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USING SITUATED FBS ONTOLOGY TO EXPLORE DESIGNERS' PATTERNS OF BEHAVIOR IN PARAMETRIC ENVIRONMENTS

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SUMMARY: *Current literature suggests that there is limited empirical evidence supporting the understanding of designers' behaviour or processes in parametric design environments (PDEs). This study explores designers' patterns of behaviour in PDEs. To achieve this, we introduce the situated function-behaviour-structure (FBS) model to develop a customized coding scheme for protocol studies. The situated FBS model has been suggested to be able to capture most of the meaningful design processes and indicate clear transition between design events. In the customized coding scheme, this situated FBS ontological model has been adapted to reflect the characteristics of parametric design by categorizing designers' activities both from design knowledge and rule algorithm. In order to test the coding scheme and explore patterns of designers' behaviour in PDEs, a pilot study is conducted in which two designers are involved to complete a design task using parametric tools. We propose to apply the results of the protocol analysis in identifying three levels of design behaviour patterns: behaviour patterns derived from three worlds (internal, expected and external worlds), behaviour patterns derived from design processes (the eight design processes indicated in FBS model) and those derived from the two levels of parametric design activities (design knowledge based activities and rule algorithm based activities). Preliminary results show that the customised coding scheme based on the situated FBS ontology is capable to capture most of designers design activities and explore designers' patterns of behaviour form various aspects. Furthermore, some patterns in terms of the three levels of behaviour in PDEs are identified and discussed.*

KEYWORDS: *parametric design, FBS ontology, design behaviour patterns.*

REFERENCE: *Rongrong Yu, Ning Gu, Michael Ostwald (2012)* Using situated FBS ontology to explore designers' patterns of behavior in parametric envrionments, *Journal of Information Technology in Construction (ITcon), Vol. 17, pg. 271-282, http://www.itcon.org/2012/17*

1. INTRODUCTION

Parametric design has become increasingly popular in the architectural design industry in recent years. According to Kolarevic (2003), this change is characterized by a rejection of static solutions in conventional design systems and the adoption of intelligent systems which have rendered design processes more flexible and productive. As argued by Woodbury (2010), design processes in parametric design environments (PDEs) are different from those in other design environments due to the unique characteristics of PDEs. Analysis of literature further shows that there is a lack of empirical evidence supporting the understanding of designers' behavior in PDEs. The overarching question therefore is what are the typical design activities in a parametric design process? For instance, in PDEs, what are the characterized patterns of a designer's behavior? What methodology best favors design process and knowledge transfer? Aiming to answer these questions, this study starts by exploring design behavior patterns in PDEs using protocol analysis.

To prepare for the protocol analysis, we adopt Gero's and Kannengiesser's (2004) situated function-structure-behavior (FBS) ontology model to form a customized coding scheme in order to reflect the characteristics of designing in PDEs. The model has been applied in a variety of cognitive design studies and is potentially capable of capturing 92% of meaningful design processes (Kan and Gero, 2009). Moreover, as reported by these authors, the situated FBS ontology model indicates clear transitions between design events. Therefore, the situated FBS ontology provides a reasonable foundation for developing an appropriate coding scheme for our research. Moreover, in protocol studies, the coding scheme has to be suitable for the design environment being studied; this means it should reflect the characteristics of parametric design in this particular study. Based on related works in parametric design such as those by De Boissieu et al., (2011), Aranda et al.,(2008) and Woodbury (2010), there are two levels of typical activities in parametric design process: activities based on *design knowledge* and activities based on *rule algorithms*. It is also possible to suggest that designers' behavior in PDEs shifts between these two levels. Therefore, these two levels of parametric design activities have been combined with the FBS ontology for developing our coding scheme. To test the coding scheme, a pilot study in which two designers are involved to complete a design task using parametric tools is conducted. To conclude the paper, some preliminary results regarding patterns of designers' behavior from the pilot study have been explored and discussed.

2. BACKGROUND

2.1 Parametric design

Parametric design is a dynamic, rule-based process controlled by variations and constraints, in which multiple design solutions can be developed in parallel. According to Woodbury (2010), it supports the creation, management and organization of complex digital design models. By changing parameters of an object, particular instances can be altered or created from a potentially infinite range of possibilities (Kolarevic, 2003). In the architecture design industry, parametric design tools are utilized mainly on complex building form generation, multiple design solution optimization, as well as structural and sustainability control.

Previous studies on designers' behavior in PDEs show that parametric tools advance design in a variety of ways. For instance, evidence shows that the generation of ideas is positively influenced in PDEs. Particularly, in Iordanova et al.'s (2009) experiment on generative methods, ideas were shown to be generated rapidly while they also emerge simultaneously as variations. Moreover, Schnabel (2007) shows that PDEs are beneficial for generating unpredicted events and can be responsible for accommodating changes. However, researchers have typically studied design behavior in PDEs (Schnabel, 2007, Iordanova et al., 2009, Qian et al., 2007) mostly by observing students interactions with PDEs in design studios or workshops. Arguably, this approach can hardly provide an in-depth understanding of designers' behavior in PDEs. This lack of empirical evidence regarding this issue will be addressed in the present study by adopting the method of protocol analysis, a method widely used for cognitive design studies.

2.2 Situated FBS ontology

Since its publication, Gero's (1990) original FBS model has been widely used as a theoretical foundation to study designers' behavior in cognitive design studies. The FBS model contains three classes of variables: Function (F), Behavior (B) and Structure (S). Function represents the design intentions or purposes; behavior represents how the structure of an artifact achieves its functions; structure represents the components that make up an artifact and their relationships. There have been many design cognitive studies that develop and apply coding schemes based on the FBS model to study design cognition in different environments. These include collaboration in virtual environments and in face-to-face design settings (Kan and Gero, 2009), free hand sketch and online virtual digital sketch (Tang et al., 2009), as well as in digital and traditional sketching environments (Tang et al., 2011). Like any research method, coding schemes based on the original FBS model have their limitations as they focus more on designers' intentions and often use the "thinking aloud" method, both of which are criticized as overtly influencing participants' perceptions (Suwa and Tversky, 1997, Ericsson and Simon, 1993).

Gero and Kannengiesser (2004) further developed the FBS model by introducing interaction in three worlds：the external world, interpreted world and expected world (FIG. 1). The external world means the world which "is composed of representations outside the designer or design agent". The interpreted world is the world "that is built up inside the designer or design agent in terms of sensory experiences, percepts and concepts". The expected world is the world where "that the imagined actions of the designer or design agent will produce" (Gero and Kannengiesser, 2004, p. 337-338). As shown in figure 1, there are four types of transition among the three worlds: focusing, push-pull process, transformation and comparison. The situated FBS ontology divides the variables into 10 classes and establishes 20 design processes. This situated FBS ontology is allegedly capable of capturing 92% of meaningful design process compared to only 66% in the original FBS model. Furthermore, it is claimed to be a universal coding scheme which can be adapted for a variety of design processes (Kan and Gero, 2009).

There are eight main processes in this revised situated FBS ontology: ① Formulation process: processes 1, 2, 3, 10; ② Analysis process: process 14; ③ Synthesis process: process 11; ④ Evaluation process: process 15; ⑤ Documentation process: processes 12, 17, 18; ⑥ Reformulation Ⅰ process: processes 6, 9, 13; ⑦ ReformulationⅡ process: processes 5, 8, 19; ⑧ Reformulation Ⅲ process: processes 4, 7, 16, 20. In terms of the eight design processes in the situated FBS ontology, the reformulation processes have been suggested to be of benefit for evoking design creativity by introducing new variables (including new variables of function, behaviour and structure) or new directions (Gero, 1990).

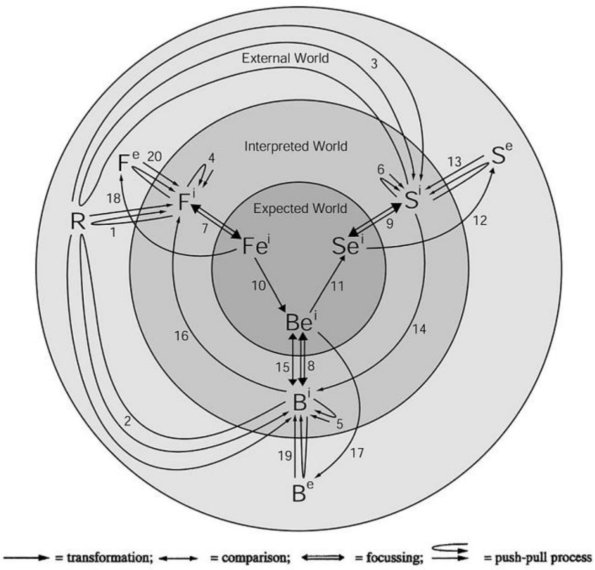

FIG. 1:The situated FBS ontology (Gero and Kannengiesser, 2004)

3. CODING SCHEME DEVELOPMENT

Protocol analysis is a method widely used for cognitive studies into designers' behaviour during design processes (Cross, 2001, Cross et al., 1996, Ericsson and Simon, 1980). After collecting protocol data from such design experiments, a particular coding scheme will be applied to categorise the collected data, enabling a detailed study of the design process in the chosen design environment(s). In this section, we present a coding scheme based on the situated FBS ontology and for the purpose of encoding design processes in PDEs.

3.1 Design behaviour in parametric design

In comparison to traditional design environments, in PDEs designers are not only modelling geometries, but also defining the rules and their logical relationships. Parametric design "requires a deeper understanding of how it can support our intentions as architects" (Sanguinetti and Kraus, 2011, p. 47). In this design process, PDEs play an important role in calculating, evolving and generating design solutions using computational algorithms to support the process. Meanwhile, the architect "is still ultimately responsible for design intention and needs to be able to look at the big picture to decide which factors to parameterize to give limits to the parameters, assign a weight to each factor and determine method of the information modelling process" (Ottchen, 2009, p. 23). Therefore, the balance between algorithmic thinking and architectural thinking is very important in the parametric design process: architects are familiar with architectural design thinking, but how should algorithmic thinking be developed to be integrated with architectural thinking in a PDE? One of the biggest differences between parametric and traditional design is that rule-sets become basic design procedures in PDEs (Abdelsalam, 2009): while building models, designers set variations, design data flow routes, adjust the values of parameters and revise rules. Additionally, through the control of logical relationships there are more possibilities for design solutions (Hernandez, 2006, Karle and Kelly, 2011). Aranda and Lasch (2008) believe that parametric design communicates between two worlds, one entirely abstract and coded from which complex spatial worlds could emerge through very simple mathematical expressions governed by parameters; the other is very real and alive, as that we find through our interactions every day with people, communities and cities. Therefore, we conclude that in the typical parametric design process, there are two levels of design activities: design knowledge based activities and rule algorithm based activities. As shown in FIG. 2, designers' activities will be transferred between these two levels throughout the parametric design process.

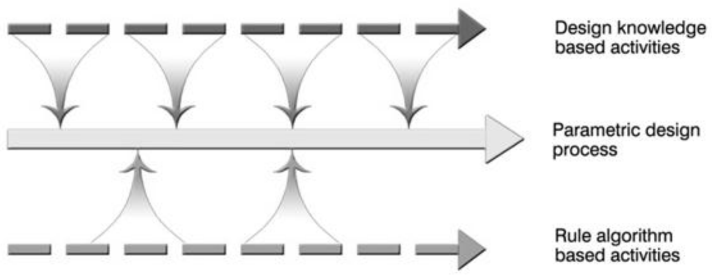

FIG. 2: Two levels of parametric design activities

In the design knowledge based activities level, architects make use of their innate professional knowledge, such as how to make the building adapt to the environment, how people will use the building, how to satisfy the requirements of clients, etc. While in the rule algorithm based activities level, designers focus on the operation of parametric design tools. At this level, their design behaviour includes defining the rules and their logical relationships, choosing the component suitable for a particular purpose, setting and changing parameters, etc.

3.2 Proposed coding scheme

Based on the analysis of design activities in PDEs, the following coding scheme is proposed. The main category is function (F), behavior (B), and structure (S) based on Gero's (1990) definition. The subcategory is defined by three worlds: internal worlds (F^i, B^i, S^i), external world (F^e, B^e, S^e), and expected world ($F_{e^i}, B_{e^i}, S_{e^i}$). In each category, two levels of designers' activities will be coded: design knowledge based level and rule algorithm based level. Additionally, particular parametric design actions are introduced to form the coding scheme. Designers' behavior includes their design intentions and design actions. Intentions inspire design actions, while actions are reflections of design intentions (Schön, 1992). Because designers' cognitive behavior are influenced by the design environment (Mitchell, 2003), we expect to reveal the role parametric tools plays on affecting designer's behavior.

Variables in the function category describe "what the design is for", which is mostly from the design knowledge based level. TABLE. 1 is the function category of the coding scheme.

TABLE. 1: Function category

Category	Subcategory	Name	ID	Description
R	Design knowledge	Requirement	R-KI	Consider or revisit the requirement.
F^i	Design knowledge	Intention	F^i-KI	Interpreted function from designers' own experience or their concepts or percepts
F^e	Design Knowledge	Intention	F^e-KI	External representation of function perception on existed behavior.
F_{e^i}	Design knowledge	Intention	F_{e^i}-KI	Definition of the expected function from the interpreted function.

Variables in the behavior category describe "what it does". The rule algorithm based activities consist of intensions, relationship set/change, and parameters set/change; while design knowledge based activities consist of design intention only. The rule algorithm category in interpreted behavior (B^i) represents design actions based on a consideration of how the algorithm rules achieve certain behavior interpreted from requirements or structures. In this context, relationship means the connection between different variables, parameters, route of data flow, ext. TABLE. 2 is the behavior category of the coding scheme.

TABLE. 2: Behaviour category

Category	Subcategory	Name	ID	Description
B^i	Design knowledge	Intention	B^i-KI	Interpreted behavior from designers' experience or concepts/percepts
	Rule algorithm	Intention	B^i-RI	Interpreted behavior serving for the rule algorithm purpose
B^e	Design knowledge	Intention	B^e-KI	External representation of behavior derived from design knowledge or perception on existed behavior
	Rule algorithm	Intention	B^e-RI	External representation of behavior derived from rule algorithm perception on existed behavior
		Relationship	B^e-RR	Set relationship from consideration of behavior
		Relationship change	B^e-RRc	Change relationship from consideration of behavior
		Parameter setting	B^e-RP	Set parameter from consideration of behavior
		Parameter changing	B^e-RPc	Change parameter from consideration of behavior
B_{e^i}	Design knowledge	Intention	B_{e^i}-KI	Define expected behavior, predicted behavior goals to achieve from design knowledge
	Rule algorithm	Intention	B_{e^i}-RI	Define expected behavior, predicted behavior goals to achieve from rule algorithm

Variables in the structure category describe "what it is". This class of variables contains mostly design actions related to geometry making. The rule algorithm based activities consist of intension, relationship set/change, and parameters set/change; while design knowledge based activities consist of design intention and geometry make/change. TABLE. 3 is the structure category of the coding scheme.

TABLE. 3: Structure category

Category	Subcategory	Name	ID	Description
S^i	Design Knowledge	Intention	S^i-KI	Interpreted structure from designers' experience or concepts/percepts
	Rule algorithm	Intention	S^i-RI	Interpreted structure serving for the rule algorithm purpose
S^e	Design knowledge	Intention	S^e-KI	External representation of structure derived from design knowledge or perception on the existed structure
		Geometry	S^e-KG	Model geometry
		Geometry change	S^e-KGc	Chang geometry
	Rule algorithm	Intention	S^e-RI	External representation of structure derived from rule algorithm or perception on the existed rules
		Parameter	S^e-RP	Set parameters due to the consideration of structure
		Parameter change	S^e-RPc	Chang parameters due to the consideration of structure
		Relationship	S^e-RR	Set relationship due to the consideration of structure
		Relationship change	S^e-RRc	Chang relationship due to the consideration of structure
S_{e^i}	Design knowledge	Intention	S_{e^i}-KI	Define expected structure, predicted structural goals to achieve from design knowledge
	Rule algorithm	Intention	S_{e^i}-RI	Define expected behavior, predicted structural goals to achieve from rule algorithm

4. A PILOT STUDY

4.1. Experiment setting

Aiming to examine the effectiveness of the developed coding scheme for better understanding of designers' behavior in PDEs, this study develops a pilot study explore designers' behavior patterns. In devising an experiment to collect protocol data from PDEs, 2 students are recruited to complete a design task using commercial parametric design software (Grasshopper in this study) in 60 minutes. Both of participants, are masters of architecture students, have had at least two years of parametric design experience.

The experiment environment includes a computer installed with the parametric design software, pen and paper, and two video cameras. The design task is to generate a conceptual form for the tower part of a high-rise building. During the design process, both "think aloud" and "retrospective method" are applied to collect protocol data. Designers' verbalization and design actions are video-recorded for protocol analysis.

4.2. General observe action

Generally, the two students show sound ability of manipulating forms as well as taking advantages of the parametric design tool. However, their design strategies are quite different—designer A uses a 'top-down' method (in which the designer considers mainly the façade of the building) and designer B adopts a 'bottom-up' (in method which the designer considers hotel rooms as a unit and focus on the combination of these units generating in the overall tower form).

In the design process, most of the verbalized protocols were accompanied with non-verbalized moves; designers rarely used sketches so that almost all their actions happened on computers; both designers switched between the script interface (grasshopper interface) and the geometry interface (Rhino interface) frequently.

4.3. Protocol analysis results

The segmentation is according to the semantic meanings of function, behaviour and structure. There are respectively 186 and 179 segments from the two protocol data and over 90% of the meaningful design processes are coded. Student 1 spent 36 minutes to finish the design task while student 2 spent 49 minutes. TABLE. 4 shows that both students have the highest percentage of "structure" segments coded around 50%, followed by the behaviour coding and the function coding.

TABLE. 4: General protocol analysis results

	Design time	**Number of segments**	**Coded segments**	**Coded percentage**	**F**	**B**	**S**
Student1	36 minutes	186	172	92.5%	12.2%	38.1%	49.7%
Student 2	49 minutes	179	161	90.0%	15.3%	30.4%	54.4%

FIG. 3 shows the distribution of coding in the situated FBS categories. The vertical axis represents the percentage of each category coding occupies in all the coded segments. From FIG. 3, both students have highest percentages in external structure (S^e) and external behavior (B^e). It may because external world is the main platform where design actions happen. Meanwhile, internal behavior (B^i) has around 10% of the coding –which has the second highest percentage. This suggests that designers often consider the method to achieve their structure or function in PDEs.

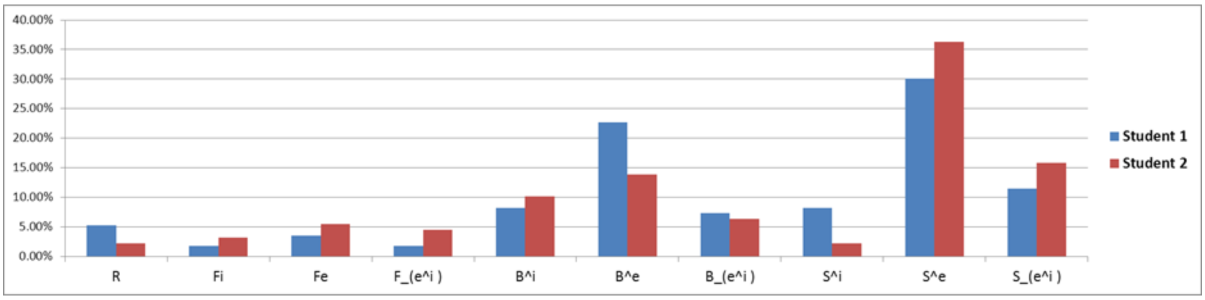

FIG.3: Distribution of coding in the situated FBS categories

5. DESIGNERS' BEHAVIOR PATTERNS IN PDES

Alexander et al.(1977, p.x) states that a design pattern "describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such way that you can use this solution a million times over". Generally, a design pattern consists of a design problem, its context and a specific solution which can be followed and reused. In this study, designers' behavior patterns are defined as those operations or procedures which the designer repeatedly applies in a certain period/process of design. They consist of a pattern name, a simple description and a specific transition. Because in the future main study of this research, there will be a much larger number of participants, the behavior patterns will be extracted from those that most participants share and repeat. In the protocol analysis, there are three levels of behavior patterns being proposed: those derived from the three worlds, from the overall design processes, and from the two levels of parametric design activities.

5.1. Behaviour patterns derived from the three worlds

In this level, behavior patterns are explored from the perspective of the three worlds defined in the situated FBS ontology--- internal world, external world and expected world (definition of three worlds see section 2.2). Internal world includes categories of internal function (F^i), internal behavior (B^i), and internal structure (S^i); external world includes categories of external function (F^e), external behavior (B^e), and external structure (S^e); expected world includes categories of expected function (F_{e^i}), expected behavior (B_{e^i}), and expected structure (S_{e^i}). The proposed pattern will help us understand the transition between these three worlds during parametric design.

FIG. 4 and FIG. 5 respectively demonstrate the distribution of the coding in the three worlds of each student. The vertical axis represents the percentage. The horizontal axis represents the time span. From FIG. 4 and FIG. 5, we can observe that external world contain most coding and all three worlds have more coding in the middle of design process, which means that designers are more active in the middle of design session.

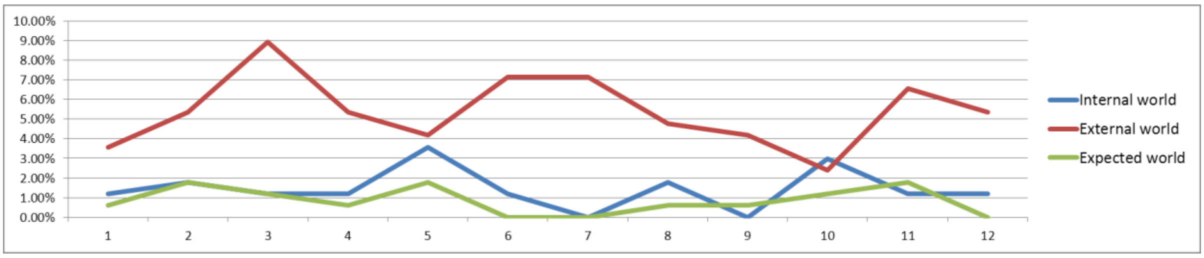

FIG.4 Design process of student 1 distributed in the three worlds

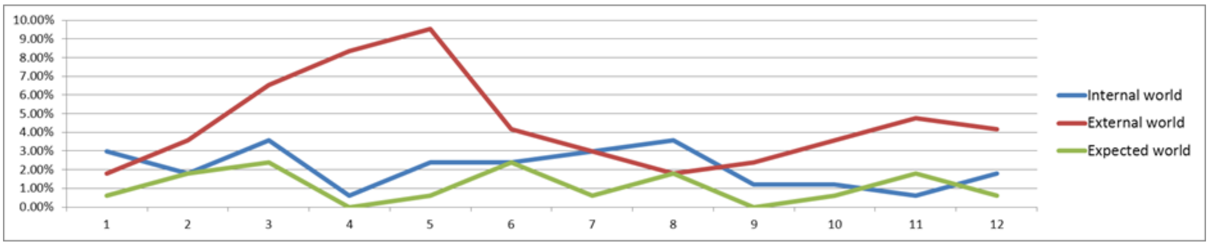

FIG.5 Design process of student 2 distributed in the three worlds

TABLE. 4 demonstrates the transition among the three worlds according to Gero's definition: focussing, push-pull process, and transformation. It illustrates the distribution of all transitions. Meanwhile, the transitions shared by both designers are highlighted in TABLE. 4.

The focussing process represents the connection between the internal world and the expected world. From TABLE. 4, both students show pattern of B_{e^i}-RI>B^i-RI and B_{e^i}-KI=B^i-RI. This means designers have more consideration focusing on the interaction between the internal and the expected worlds. The most common pattern of the focussing process is B_{e^i}-KI=B^i-RI, this is, a comparison between internal behaviour and expected behaviour, which means the designer often evaluates what they expect to achieve and their intention of how to achieve it.

The push-pull process represents the interaction between the internal and the external worlds as well as within the internal world itself. The pattern shared by both designers are S^e-RPc>S^i-RI and S^e-RPc>S^i-KI. Which means the typical patterns of push-pull process is structure related; especially the action of changing parameters that potentially lead to the formulation of new structural intention (from both the design knowledge and rule algorithm level).

The transformation process represents the transition from the expected world to the external world. Most of the process is structure related. Transformation process is where most actions happen. Here the common pattern is S_{e^i}-RI>S^e-RR, which means the expected structure often followed by a set of structural rules (in this experiment is the set of a component).

TABLE. 4: Transitions between the three worlds

Focusing (transition between the internal world and the expected world)	Student 1	S_{e^i}-KI>S^i-RI	B_{e^i}-RI>B^i-RI	B_{e^i}-KI=B^i-RI	B_{e^i}-RI=B^i-RI	S^i-KI>S_{e^i}-KI
		0.6%	0.4%	4.1%	2.7%	3.1%
	Student 2	B_{e^i}-RI>B^i-RI	B_{e^i}-KI=B^i-RI	------	------	------
		1.8%	4.3%	------	------	------
Push-pull process	Student 1	S^e-RPc>S^i-RI	B^e-RPc>B^i-RI	S^e-RPc>S^i-KI	S^e-RI>S^i-KI	S^e-RPc>S^i-KI

(interaction between the internal and the external world as well as within the internal world itself)		5.1%	8.2%	2.6%	2.7%	1.9%
	Student 2	B^e-RPc>B^i-KI	S^e-RPc>S^i-KI	S^e-RI>S^i-RI	S^e-RPc>S^i-RI	B^i-KI>B^i-RI
		8.2%	3.6%	4.2%	8.4%	2.1%
Transformation (Transition from the expected world to the external world)	Student 1	S_{e^i}-RI>S^e-RR	S_{e^i}-RI>S^e-RP	S_{e^i}-KI>S^e-RPc	B_{e^i}-RI>B^e-KI	------
		7.1%	3.2%	4.2%	2.2%	------
	Student 2	S_{e^i}-RI>S^e-RPc	S_{e^i}-KI>S^e-KGc	B_{e^i}-RI>B^e-RP	S_{e^i}-RI>S^e-RR	------
		2.1%	4.3%	5.9%	6.3%	------

5.2. Behaviour patterns derived from the overall design processes

In this level, design behavior patterns are explored in terms of eight design processes in the situated FBS ontology: formulation, analysis, synthesis, evaluation, documentation, reformulation Ⅰ, reformulation Ⅱ and reformulation Ⅲ. The patterns will help us understand what kind of transition appears most frequently, how much time each transition takes and when it appears.

FIG. 6 demonstrates the percentage of the eight design processes of the two students. The vertical axis represents the percentage of particular design process against all processes. From FIG. 6, we can see that the most frequently happened process is documentation. Reformulation has the second highest percentage, which means that designers also constantly reconstruct their concepts or ideas which potentially give the design new directions (Gero and Kannengiesser, 2004). The same as previous studies in sketch and CAD environments (McNeill et al., 1998), reformulation Ⅰ in PDEs is the predominant reformulation type. Additionally, there is very rare reformulation 3 appears.

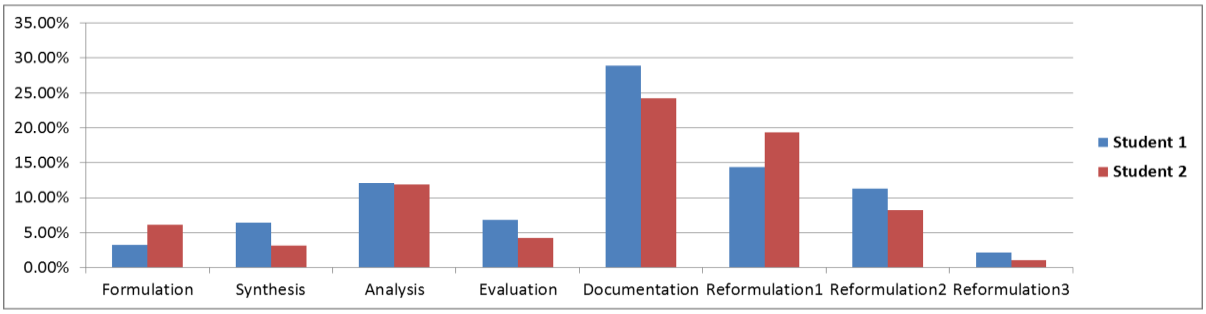

FIG.6 Distribution of coding in the eight design processes

TABLE. 5 shows typical patterns happened in the eight design processes in terms of transitions, where the numbers indicate the percentages of transitions between different processes. We can observe that: 1) as highlighted in TABLE. 5, six of the eight design processes have patterns shared by two designers 2) most of the patterns are structure related, which means designers consider elements of geometry frequently 3) Rule algorithm structure related coding has the high percentage among the transitions, especially rule making and parameter changing categories.

TABLE. 5: Behaviour of patterns in terms of the transition between the eight design processes

Formulation	Student 1	R>B^i-RI	S_{e^i}-KI>S^i-RI	B_{e^i}-RI>B^i-RI	Student 2	B_{e^i}-RI>B^i-RI	R>F^i-KI	B^i-KI>B^i-RI
		1.1%	0.6%	0.4%		1.8%	1.2%	2.1%
Synthesis	Student 1	B_{e^i}-KI>S_{e^i}-KI	------	------	Student 2	B_{e^i}-KI>S_{e^i}-RI	B_{e^i}-KI>S_{e^i}-KI	------
		6.4%				1.1%	2.0%	
Analysis	Student 1	S^i-KI>B^i-RI	S^i-KI>B^i-KI	------	Student 2	S^i-KI>B^i-KI	------	------

		7.7%	4.4%			11.9%		
Evaluation	Student 1	B_{e^i}-KI=B^i-RI	B_{e^i}-RI=B^i-RI	------	Student 2	B_{e^i}-KI=B^i-RI	------	------
		4.1%	2.7%			4.3%		
Documentation	Student 1	S_{e^i}-RI>S^e-RR	S_{e^i}-RI>S^e-RP	S_{e^i}-KI>S^e-RPc	Student 2	S_{e^i}-KI>S^e-KGc	S_{e^i}-RI>S^e-RR	B_{e^i}-RI>B^e-RP
		7.1%	3.2%	4.2%		4.3%	6.3%	5.9%
Reformulation 1	Student 1	S^e-RPc>S^i-RI	S^i-KI>S^i-RI	S^i-KI>S_{e^i}-KI	Student 2	S^e-RPc>S^i-KI	S^e-RI>S^i-RI	S^e-RPc>S^i-RI
		5.1%	2.9%	3.1%		3.6%	4.2%	8.4%
Reformulation 2	Student 1	S^i-KI>B^i-RI	B^e-RPc>B^i-RI	------	Student 2	B^e-RPc>B^i-KI	------	------
		3.1%	8.2%			8.2%		
Reformulation 3	Student 1	B^i-KI>F^i-KI	------	------	Student 2	F^i-KI>F^i-KI	------	------
		2.1%				1.1%		

5.3. Behaviour patterns derived from the two levels of parametric design activities

In this level, transitions between the two levels of parametric design activities - design knowledge based and rule algorithm based - are explored. The behavior patterns will help us understand how the designers' activities transfer between these two levels, what proportions do each level of activity take up and how do the two levels of activities distribute in the overall time span.

FIG. 7 and FIG. 8 show how the two levels of design activities distribute along the overall time span for each student. The vertical axis represents the percentage of coding. The horizontal axis represents the design time. From FIG. 7 and FIG. 8, we can observe that: 1) the two levels of activities share the similar patterns between the two students. 2) Designers shift between the two levels during their design processes. 3) Both students considered more design knowledge at the beginning and the end of the design session. In the beginning, they considered design requirement and start to form their design concept from the requirement; while in the end of the design session, they frequently evaluate their models, which led to more coding at the design knowledge level.

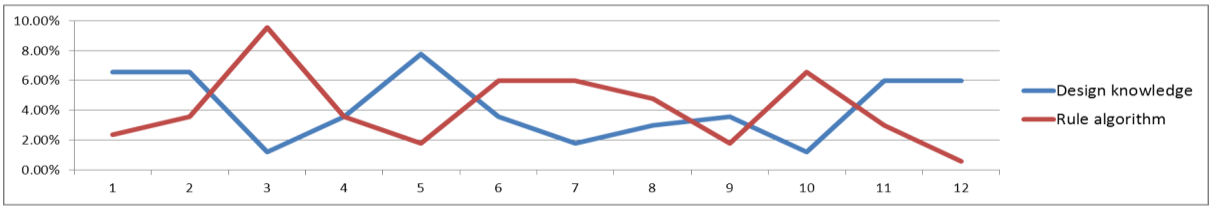

FIG.7: Two levels of activities by student 1

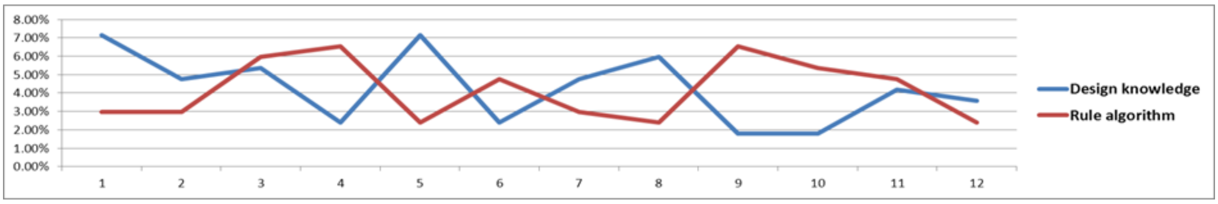

FIG.8: Two levels of activities by student 2

TABLE. 6 summarize the transitions between the two levels of activities. The four most frequent transition types of each student are listed. The patterns transferring from the rule algorithm level to the design knowledge level shared by the two designers is S^e-RPc>S^i-KI. This means that from changing parameters, designers create new directions of forming structure intention (design knowledge related). The pattern transferring from the design knowledge level to the rule algorithm level shared by the two designers is S_{e^i}-KI>S^e-RPc. This means that designers' intentions on structure (design knowledge related) are potentially follows by changes of parameters.

TABLE. 6: Transition between the two levels of activities

Transition from rule algorithm to design knowledge	Designer A	B_{e^i}-RI>B^e-KI	S^e-RPc>S^i-KI	S^e-RI>S^i-KI	S^e-RPc>S^i-KI
		2.2%	2.6%	2.7%	1.9%
	Designer B	S^e-RPc>S^i-KI	B^e-RPc>B^i-KI	S^e-RPc>S^e-KGc	S^e-RPc>S^e-KI
		3.6%	8.2%	1.3%	1.2%
Transition from design knowledge to rule algorithm	Designer A	S^i-KI>S^i-RI	S_{e^i}-KI>S^e-RPc	S^i-KI>B^i-RI	S^i-KI>B^i-RI
		2.9%	4.2%	3.1%	7.7%
	Designer B	B_{e^i}-KI>S_{e^i}-RI	S^i-KI>S^e-RP	S_{e^i}-KI>S^e-RPc	B^i-KI>B^i-RI
		1.1%	3.1%	2.1%	2.1%

6. CONCLUSION AND FUTURE WORK

This study proposes a new coding scheme, based on the situated FBS ontology, and further adapted to the characteristics of parametric design. A pilot study is conducted to test the coding scheme. From preliminary analysis, the proposed coding scheme are suggested be able to analyses designers' behavior patterns from the different levels. The next stage of this work is to conduct a main study to refine and further the research using larger number of participants. Results of the main study will further test the validity of the developed coding scheme and explore the associated levels of behavioral patterns in greater details.

In the main study, the future work includes: 1) further test the validity of coding scheme based on the experiment results, that is, specific actions and intentions in PDEs; 2) Exploration of patterns of designers' behavior based on a larger sample of protocol analysis results; 3) illustration of those patterns of designers' behavior in a formal form, which includes a pattern name, a specific transition, and a simple description of the context where those patterns possible to appear; and 4) further investigation of the theory of design creativity and situated FBS ontology; correlate the identified patterns of designers' behavior with creativity to explore those patterns potentially beneficial for design creativity.

7. REFERENCES

Abdelsalam, M. (2009). The Use of the Smart Geometry through Various Design Processes: Using the programming platform (parametric features) and generative components, *Proceedings of the Arab Society for Computer Aided Architectural Design (ASCAAD 2009)*, Manama, Kingdom of Bahrain, 297-304.

Alexander, C., Ishikawa, S.and Silverstein, M. (1977). *A pattern language : towns, buildings, construction,* New York, Oxford University Press.

Aranda, B.and Lasch, C. (2008). What is parametric to us. *In: From control to design : parametric/algorithmic architecture,* (Sakamoto, T. & Ferr, A., editor). Barcelona ; New York: Actar-D.

Cross, N. (2001). Design Cognition: Results from Protocol and other Empirical Studies of Design Activity. *In: Design Knowing and Learning: Cognition in Design Education,* (Charles, E., Michael, M & Wendy, N., editor). Oxford: Elsevier Science.

Cross, N., Dorst, K.and Christiaans, H. (1996). *Analysing design activity,* Chichester ; New York, Wiley.

De Boissieu, A., Lecourtois, C.and Guéna, F. (2011). "Operation of parametric modelling" and/or "operation of architectural conception"?: Expressing relationships in parametric modelling, *Proceeding of 29th eCAADe Conference,* University of Ljubljana Slovenia, 530-538

Ericsson, K. A.and Simon, H. A. (1980). Verbal reports as data, *Psychological Review,* Vol. 87, No. 3, 215-251.

Ericsson, K. A.and Simon, H. A. (1993). *Protocol analysis : verbal reports as data,* Cambridge, Mass., MIT Press.

Gero, J. (1990). Design prototypes: a knowledge representation schema for design, *AI Magazine,* Vol. 11, No. 4**,** 26–36.

Gero, J.and Kannengiesser, U. (2004). The situated function-behaviour-structure framework, *Design Studies,* Vol. 25, No. 4**,** 373-391.

Hernandez, C. R. B. (2006). *Design procedure: A computational framework for parametric design and complex shapes in Architecture.* Doctor of Philosopgy in Architecture, Massachusetts institute of technology.

Iordanova, I., Tidafi, T., Guité, M., De Paoli, G.and Lachapelle, J. (2009). Parametric methods of exploration and creativity during architectural design: A Case study in the design studio, *Processdings of CAADFutures 2009*, 423-439.

Kan, J. W. T.and Gero, J. S. (2009). Using the FBS ontology to capture semantic design information in design protocol studies. *In: About: Designing. Analysing Design Meetings,* (Mcdonnell, J. &Lloyd, P., editor). CRC Press.

Karle, D.and Kelly, B. (2011). Parametric Thinking, *Proceedings of ACADIA Regional 2011 Conference*, 109-113.

Kolarevic, B. (2003). *Architecture in the digital age : design and manufacturing,* New York, NY, Spon Press.

McNeill, T., Gero, J. S.and Warren, J. (1998). Understanding conceptual electronic design using protocol analysis, *Research in Engineering Design,* Vol. 10, No. 3**,** 129-140.

Mitchell, W. J. (ed.) (2003). *Beyond Productivity: Information Technology, Innovation, and Creativity,* Washington, D.C.

Ottchen, C. (2009). The Future of Information Modelling and the End of Theory: Less is Limited, More is Different, *Architectural Design,* Vol. 79, No. 2**,** 22-27.

Qian, C. Z., Chen, V. Y.and Woodbury, R. F. (2007). Participant Observation Can Discover Design Patterns in Parametric Modeling, *Proceedings of the 27th Annual Conference of the Association for Computer Aided Design in Architecture*, Halifax, Nova Scotia, 230-241.

Sanguinetti, P.and Kraus, C. (2011). Thinking in Parametric Phenomenology *Proceedings of ACADIA Regional 2011 Conference*, University of Nebraska-Lincoln Lincoln, USA, 39-48.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation, *Knowledge-Based Systems,* Vol. 5, No. 1**,** 3-14.

Schnabel, M. A. (2007). Parametric Designing in Architecture, *Proceedings of the 12th International Conference on Computer Aided Architectural Design Futures*, Sydney, Australia, 237-250.

Suwa, M.and Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies,* Vol. 18, No. 4**,** 385-403.

Tang, H.-H., Lee, Y.-Y.and Chiou, W.-K. (2009). Is an on-virtu digital sketching environment cognitively identical to in-sity free-hand sketching?, *Proceedings of the 14th International Conference on Computer Aided Architectural Design Research in Asia*, Yunlin, Taiwan, 473-482.

Tang, H. H., Lee, Y. Y.and Gero, J. S. (2011). Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function-behaviour-structure coding scheme, *Design Studies*, Vol. 32, No. 1**,** 1-29.

Woodbury, R. (2010). *Elements of Parametric Design*, Taylor and Francis.