Exploring the Role of CAD and its Application in Design Education

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Abstract. Mixed media design, which includes both pencil sketching and computer-aided design (CAD) modelling, is frequently used in both the design industries and design schools. Research suggests that mixed media design environments provide several advantages over design environments that use singular media. Although a common outcome of CAD modelling is design documentation, researchers have argued that CAD modelling could support conceptual design. In our study four experts were invited to complete different design tasks. They were asked to sketch first and then model their designs using CAD. A Function-Behaviour-Structure coding scheme was adopted to analyse their cognitive actions. The empirical evidence collected shows that being dissatisfied with sketches resulted in the entire CAD design phase becoming uncertain. Thus, an optimal solution may not be achieved after the use of one design medium. This means that subsequent design sessions need to support designers to refine their designs by evaluating alternatives. The main contribution of this study is for teaching CAD design. A model was developed for the phenomenon of CAD modelling to support conceptual design or design documentation in mixed media design environments.

Keywords: CAD modelling, conceptual design phase, design education, uncertainty.
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1 INTRODUCTION

Contemporary design practice encompasses a range of visual representations including sketching, computer-aided design (CAD) modelling, manually sketched models and physical models. Designers use these media for multiple purposes, such as reducing cognitive load, and as triggers to communicate ideas and explore design problems. Previous research [29,38] has investigated the roles of visual representations in enhancing designers' problem-solving processes. Romer, Pache, Weißhahn, Lindemann and Hacker [31] found that the two most frequently used design media in both the design industry and design schools, were sketching and CAD modelling. Sketches are ambiguous but allow designers to explore alternatives, while CAD models accurately specify the dimensions of objects and their relationships with each other.

Due to the increased globalisation of architecture, engineering and construction projects, current research has shifted from individual design environments to integrating different design environments to improve design outcomes [18]. When Ibrahim and Rahimian [20] compared traditional sketching, CAD modelling and mixed media to assess their influences on design cognition and activities, they found that mixed media design environments improved the quality of the design process as well as of the ultimate product design. Many researchers [21,38] have proposed different types of design research studies to improve understanding of design activities. Even though the stereotypical outcome of CAD modelling is primarily documentation [40,41], researchers have argued that CAD modelling could support conceptual design [1,8]. Our research question is what factors drive uncertainty when CAD modelling is used in mixed media design environments? This paper builds on previous mixed media studies with an empirical exploration of sketching and CAD modelling in an architectural design process. An initial critical review of relevant design works including the roles of different design media and design research studies is provided. In the next section, the design of the protocol analysis used for this study is described. Finally, our findings are presented.

2 LITERATURE REVIEW

In the last few years, research has shifted from single design media to the influence of mixed media on cognitive activities during the conceptual design phase. Evidence for the use of mixed media comes from Sachse, Leinert and Hacker [33] who surveyed more than 100 expert designers who used sketching prior to and concurrently with CAD modelling. Their study identified three positive outcomes of this approach: improved solutions, faster task completion, and fewer processing steps to develop CAD models. A similar result was found by Chen [8] who studied design creativity when conventional and digital media were used simultaneously. Chen found that as designers move from sketching to digital tools, creativity is stimulated. This is because designers have opportunities to re-think previous ideas and to improve the quality of their designs. Ibrahim and Rahimian [20] argued that the CAD software available at the time did not facilitate the intuitive aspects of conceptual design. They introduced mixed media, using sketching first, followed by CAD modelling. The overall design outcomes were superior to either CAD modelling or sketching using this approach.

Sketching plays a pivotal role in the initiation and development of creative ideas during the early design phase. Designers rely on it to support and focus their visual reasoning when exploring spatial relationships through diagrams. Different types of seeing ('seeing-as and seeing-that') stimulate the cognitive process of evaluation when designers re-interact with vague and ambiguous sketches [17]. However, CAD modelling also has the potential to enhance design cognition and creativity [18-19]. It can be used to continually develop, iterate, and refine a form without having to delete a previous version. It gives designers alternative and realistic ways to improve their designs [24]. The use of CAD modelling during the early design process has several advantages: (1) It allows for faster generation of design alternatives; (2) It improves design communication in terms of design collaboration; and (3) It avoids costly errors.

Although researchers have argued that CAD modelling can support conceptual design by exploring design alternatives, the stereotypical outcomes of CAD modelling are primarily documents [40,41]. It is clear that CAD modelling plays two roles in the conceptual design phase: exploration of design alternatives and the production of design documentation.

2.1 Reducing Uncertainty through Co-evolution

Providing solutions that effectively meet the requirements of a design brief is a designer's ultimate goal. A creative design process is best defined by its output – creative design processes produce great design outcomes [36]. Teaching students creative design processes is a common goal of many architectural design courses worldwide. Having a comprehensive understanding of the processes that lead to creative designs is of great interest to academics, designers as well as design researchers. In earlier descriptions of creative engineering design, Buhl [5] described design as a linear sequence involving the following steps: (1) preparation, (2) analysis, (3) synthesis, (4) evaluation, and (5) presentation. Similarly, Isaksen et al. [21] described creative approaches to a problem-solving activity as a linear sequence of: (1) framing a problem, (2) exploring data, (3) generating ideas, (4) developing solutions, and (5) appraising tasks.

The development of creative design processes is traditionally viewed as a sequence of activities involving the formulation of a problem, leading to the synthesis of solutions [25]. However, design problems are often ill-defined [35], meaning there is no definitive formulation of the design outcomes. Creative designers thus constantly generate design alternatives to redefine uncertainties. In practice, a designer develops and redefines both the formulation of a problem and his or her ideas for solutions, iterating between the design processes, the design requirements and the final outcomes.

An alternative model is Gero's Function-Behaviour-Structure (FBS) framework developed in 1990 [13] and refined over the last two decades. The process represented by the FBS model (Figure 1) transforms design requirements into a design artifact. This model contains six design issues and eight design processes that describe all designed artifacts, irrespective of the specific design discipline. The six design issues include requirement (R), function (F), expected behaviour (Be), behaviour derived from structure (Bs), structure (S) and documentation (D). A design description is never transformed directly from the function but undergoes a series of design processes related to the FBS design issues. The primary advantage of the FBS coding scheme is that it clearly shows the relationships between the eight design processes. They are formulation (R>F & F>Be), synthesis (Be>S), analysis (S>Bs), evaluation (Be>Bs), documentation (S>D), reformulation I (S>S), reformulation II (S>Be), and reformulation III (S>F). Many studies [23,27] have used FBS as a uniform coding scheme to explore designers' behaviours. The FBS coding scheme is thus a proven approach and has been adopted for this study.

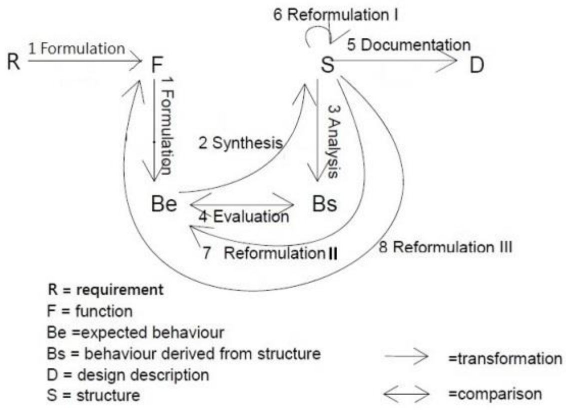

Figure 1: FBS design model [14].

Research in cognitive psychology has revealed that uncertainty is central to solving complex problems [34]. Indeed, uncertainty is important in the earliest stage of problem solving because how a problem is initially discovered and structured is a vital precursor to problem solving [28]. Design tasks are concerned with ill-structured or wicked problems, where the solutions are unknown throughout the design process [9]. Exploring different ideas under conditions of uncertainty is a natural occurrence [3]. As a consequence, uncertainty becomes a means to help designers explore design alternatives. Within the early design stage, designers also engage with the iterative design process of evaluation to gain valuable insights into the boundaries of the original problem [12].

In reality, many possible solutions are generated when designing to meet specific requirements. This process involves redefining problems and developing solutions called co-evolution by Maher and Poon [26] (Figure 2). This model fits Dorst and Cross's design creativity study [12] in that they argue that creative design is not a matter of first defining a problem and then searching for a satisfactory solution. Creative design is a matter of the interchange of information between problem and solution spaces.

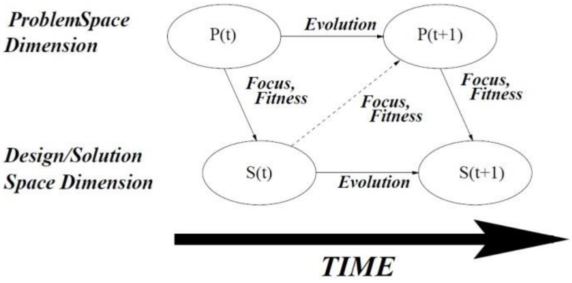

Figure 2: The co-evolution design model [26].

Gero and Kannengiesser [14] also argued that there is no direct transformation from a problem to a solution. Designers need to continually evaluate expected behaviours (Be) and behaviours derived from structures (Bs) until the structure performs its desired function. For instance, when a designer wants to design a structure to support a floor lamp, s/he will think of several possible solutions first (expected behavior, Be), design them (structure, S), and then iteratively test (behaviour derived from structure, Bs) whether or not to they achieve their goal (evaluation, Be⇆ Bs). Uncertainty (problem space) and evaluation (co-evolution) form a unique relationship, which together with design alternatives (solution space) can be mapped onto the FBS model (Figure 3). Similarly, Tracey and Hutchinson (2016) argue that 'Uncertainty is central to design, and designers seek to reduce it via problem-solution co-evolution' (p 91). Our research question is what factors drive uncertainty when CAD modelling is used in mixed media design environments?

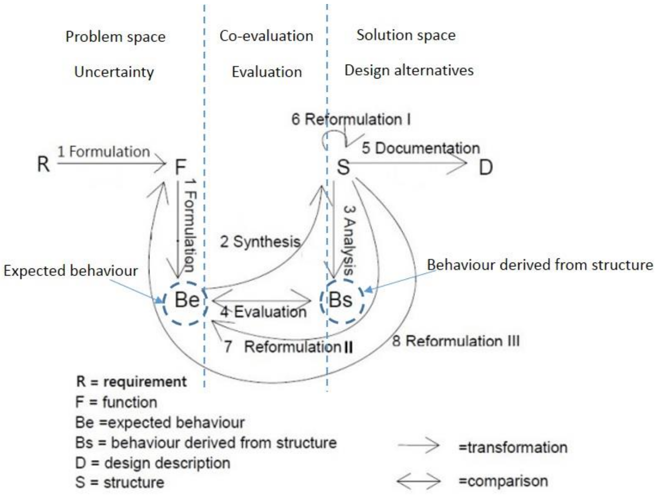

Figure 3: The mapping of uncertainty (problem space), evaluation (co-evolution) and design alternatives (solution space) into the FBS model, adopted from Gero and Kanengiesser [14].

3 METHODOLOGY

The credibility of a study depends upon the research method chosen and the way in which the research is conducted. Different approaches have been taken to study designers [9] including interviews with expert designers [7,10] observations and case studies [16], simulation trials (Akin, 1993) and protocol studies [6,30]. The research question in this study is to determine the factors that lead to uncertainty when using CAD modelling in mixed media design environments. Protocol analysis was selected as the most appropriate method because it offers a potentially effective technique for the controlled observation and experimental analysis of cognitive behaviour [2,37]. A coding scheme for a mixed media study was developed from the FBS design model to distinguish between the design activities that occur in sketching and in CAD modelling (Figure 4). Based on the FBS coding scheme, the sketching environment consists of six design issues (Rs, Fs, Bes, Bss, Ss, and Ds) while the CAD modelling environment also involves six design issues (Rc, Fc, Bec, Bsc, Sc and Dc). These distinctions enable different distributions of design issues to be collected and analysed.

Four architectural designers were recruited and a FBS coding scheme [13] was adopted to analyse their cognitive actions [22,32]. These designers were identified from those who satisfied the selection criteria. To be included, they needed: (1) competence in both sketching and CAD modelling; (2) a tertiary degree in architecture with a minimum of two-year of professional architectural practical experience; and (3) competence in practising and communicating design in English. Architectural designers often design buildings and this study provided a basic floor plan with its CAD model. Participants were asked at random to use this model to design a building for different purposes: an architectural office, a dream house and an art gallery. These tasks were appropriate because the task could be completed in approximately 75 minutes. Participants worked on the 2D layout by sketching, followed by CAD modelling (Figure 4). Because of this reliability rating, our study adopted Bilda et al's [4] approach.

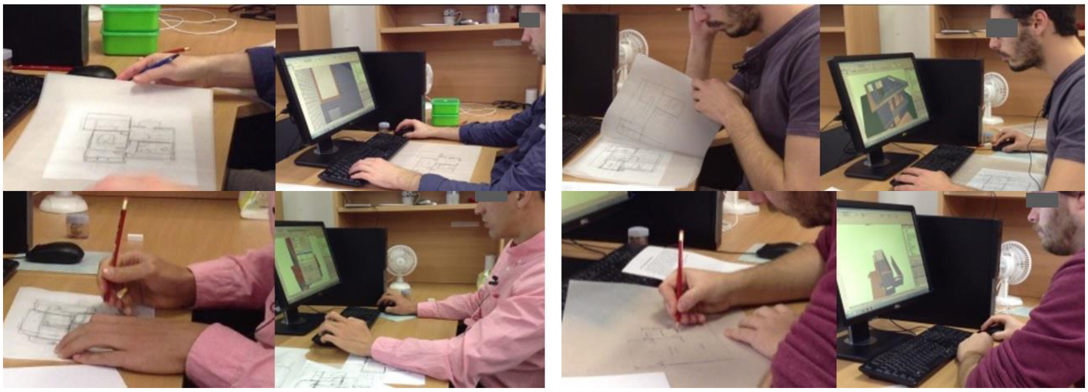

Figure 4: Four participants used sketching followed by CAD modelling.

4 DATA ANALYSIS AND DISCUSSIONS

All participants completed and satisfied the design briefs, and their design activities were videoed, covering between 153 and 355 FBS design issues. Sketching design activities occupied between 56 and 89 FBS design issues and CAD modelling design activities occupied between 97 and 271 FBS design issues. The average number of cognitive efforts in CAD modelling was thus approximately 2.5 times that of sketching. This indicates that the CAD design phase required more cognitive effort, resulting in more FBS coding than the sketching session. Due to the varied quantities of each participant's segmentations in sketching and CAD modelling, the occurrences of design issues and design processes were normalised as percentages of the total issues and processes, as described in the following sections.

4.1 Distributions of Design Issues and Design Processes in Mixed Media Design Environments

Results indicated that the four participants shared a similar distribution of design issues (Figure 5). The majority of cognitive effort was expended in reasoning about the structure and the behaviour derived from the structure (Bs) (>20%). The design issue of requirement (R) had the lowest cognitive focus (<6%). Noticeable differences were observed among the participants on the issues of requirement (R) (5% difference between participant A and D), function (F) (8.6% difference between participant A and D), expected behaviour (Be) (6.2% difference between participant B and C), behaviour derived from structure (Bs) (16.3% difference between participant C and D), structure (S) (18.8% difference between participant B and C) and description (D) (6.7% difference between participant C and D). Participant C's design behaviour differed to others in terms of (Be), (Bs), (S) and (D).

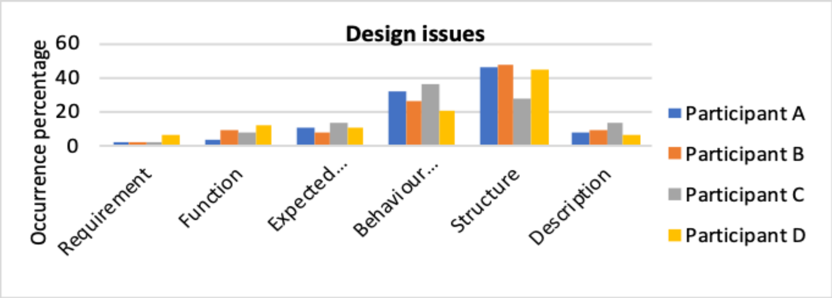

Figure 5: Four participants used sketching followed by CAD modelling.

4.2 Distributions of Design Issues and Design Processes in CAD Modelling

A syntactic design process is one that presumes all segments are cognitively related to their immediately preceding segment. They are design processes which transform from one segment to the other [42]. In this study, participants shared a similar design process distribution (Figure 6). The majority of time spent was in the design process Reformulation I. However, participant C spent the most time on evaluation. The following sections analyse participants' FBS distributions in terms of design issues and design processes in CAD modelling to understand the roles of CAD modelling in mixed media design environments.

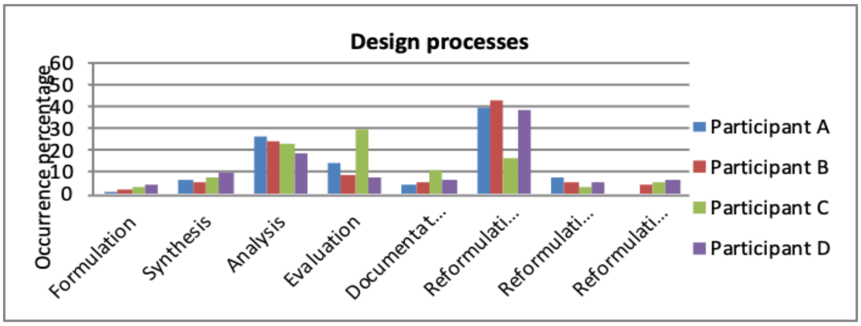

Figure 6: Participants' FBS distributions of design processes in mixed media design environments.

Protocol analysis can be used to help understand the designer's design process, the knowledge they use, the cognitive behaviour they adopt, and the strategies they adopt. We established that design activities in sketching and CAD modelling can be coded differently using the coding structure developed for this study. While (Rs) refers to sketching and (Rc) refers to CAD modelling, other examples of coding segments for sketching and CAD modelling are shown in Table 1:

Number	Utterance	Code by environments
58	Say about 600, five and two meters for each of those.	Ss
59	and the smoking area out of just the roof terrace	Ss
60	Just going to review afterward make sure I think everything is going to work when it's drawn to scale.	Bes
61	I think that looks okay.	Bss
133	2600. That's …	Sc
134	See how it works in 3D.	Dc
135	It's not accurate but it works.	Bsc
136	I was going to get rid of it anyway, so, lose that.	Dc

Table 1: Examples of coding segments for sketching and CAD modelling.

In the CAD modelling design environment, it was observed that participants expended the majority of their cognitive effort considering design issues related to structure (approximately 30~52%) and behaviour derived from structure (23~38%) (Figure 7), as well as design processes of reformulation I (19~47%) and analysis (21~33%) (Figure 8). This suggests that most participants focused mainly on modelling the solution structures of their final designs. However, only participant C spent the majority of his cognitive effort on the design process of evaluation (30%) which concerned expected behaviour (Be) and behaviour derived from structure (Bs). This indicates that participant C's reasoning processes were different to other participants in CAD modelling (Figure 8). The next section applies Markov chains to analyse the events that follow (Be) and (Bs).

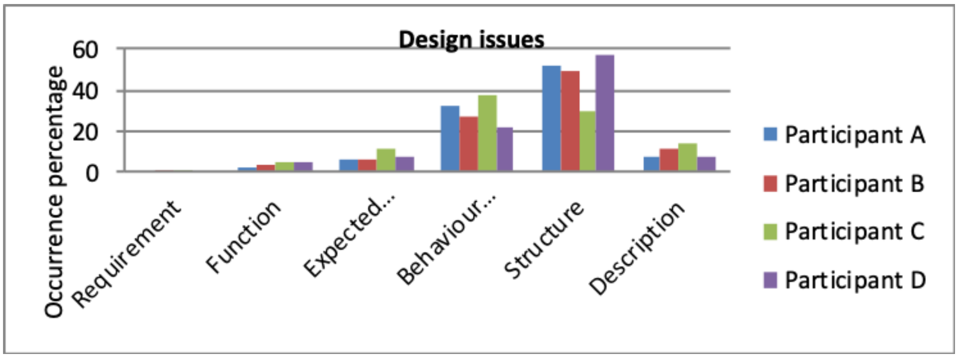

Figure 7: Participants' FBS distributions of design issues in CAD modelling.

4.3 Using Markov Chains to Describe the FBS Transition in CAD Modelling

The above analyses of FBS distributions found that those of participant C differed to the others in the CAD design phase. Traditional protocol analysis often assumes that each segment is an independent event, while Markov chains examine the sequence of events describing the probability of one event leading to another [23]. McNeill, Gero and Warren's protocol study [27] found that the most likely event after analysis is an evaluation event.

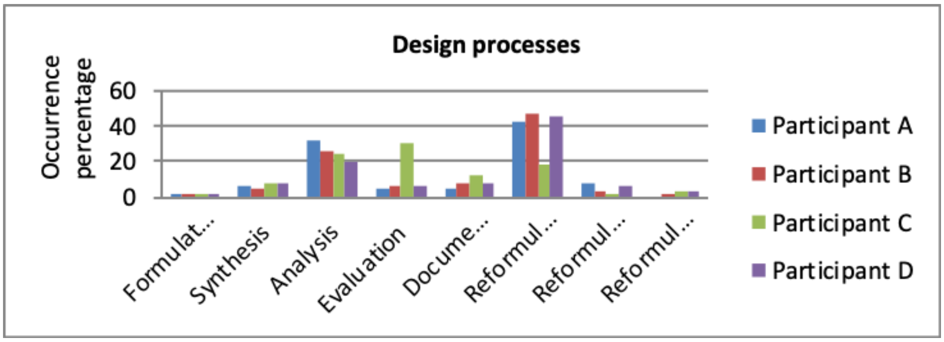

Figure 8: Participants' FBS distributions of design processes in CAD modelling.

According to Kan and Gero's study [23], each segment code can be viewed as one design event, one design move, or one unit. Markov chains not only summarise the transitions between the FBS design events (Table 2-5) but also describe the probability of one design event leading to another. These can be viewed as behavioural patterns using the linkoder software developed by Gero, Kan and Pourmohamadi [15]. As mentioned above, the iterative processes of evaluation between problem and solution spaces have the potential to turn routine design processes into creative ones.

Understanding evaluation as a bridge linking uncertainty to design alternatives leads to two directional process: (Be→Bs) and (Bs→Be). Participants' probable future design events after (Be) and (Bs) were illustrated and compared (Table 2-5). If the current event is (Be), participant C's probable future events will be (Bs) (evaluation, 0.55) and synthesis (Be→S). From the probable future event after (Bs), participant C also will have the highest probability (0.23) among others: participant D (0.1), participant B (0.08) and participant A (0.03). This means that participants D, B and A mainly focused on documenting their designs from sketches in the CAD design phase. Participant C was more concerned about design problems and solutions and evaluated them through the CAD design phase. The next section uses dynamic models to visualise the design processes involved in CAD modelling.

Participant-A	Syntactic					
	R	F	Be	Bs	S	D
R						
F	0.00	0.00	0.25	0.25	0.50	0.00
Be	0.00	0.00	0.00	0.25	0.67	0.08
Bs	0.00	0.03	0.03	0.16	0.64	0.13
S	0.00	0.00	0.09	0.37	0.48	0.05
D	0.00	0.07	0.00	0.80	0.13	0.00

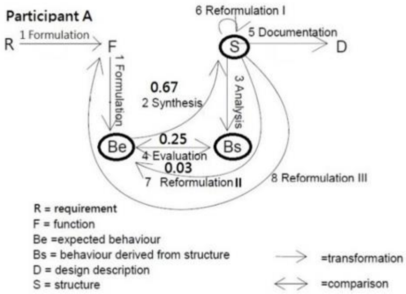

Table 2: Markov chains for participant A.

Table 2 shows that the probable future event of participant A after (Be) is (S) (synthesis, 0.67) and the iterative design process of evaluation is 0.28 (0.25 plus 0.03). Table 3 shows that the probable future event of participant B after (Be) is (S) (synthesis, 0.46) and the iterative design process of evaluation is 0.39 (0.31 plus 0.08). Table 4 shows that the probable future event of participant B after (Be) is (Bs) (evaluation, 0.55) and the iterative design process of evaluation is 0.78 (0.55 plus 0.23). Table 5 shows that the probable future event of participant B after (Be) is (S) (synthesis, 0.71) and the iterative design process of evaluation is 0.39 (0.29 plus 0.1).

Participant-B	Syntactic					
	R	F	Be	Bs	S	D
R	0.00	0.00	0.00	0.00	1.00	0.00
F	0.00	0.00	0.10	0.10	0.70	0.10
Be	0.00	0.08	0.08	0.31	0.46	0.08
Bs	0.00	0.08	0.08	0.22	0.45	0.17
S	0.00	0.02	0.05	0.30	0.54	0.09
D	0.00	0.07	0.07	0.21	0.46	0.18

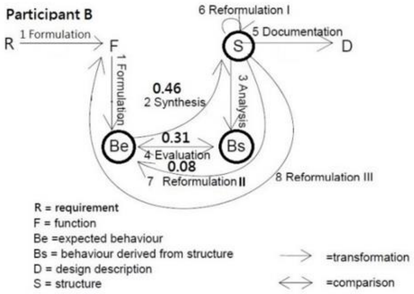

Table 3: Markov chains for participant B.

Participant C	Syntactic					
	R	F	Be	Bs	S	D
R	0.00	0.00	0.00	1.00	0.00	0.00
F	0.00	0.18	0.18	0.55	0.09	0.00
Be	0.00	0.03	0.00	0.55	0.35	0.06
Bs	0.01	0.06	0.23	0.26	0.32	0.12
S	0.00	0.06	0.02	0.41	0.31	0.20
D	0.00	0.00	0.08	0.45	0.26	0.21

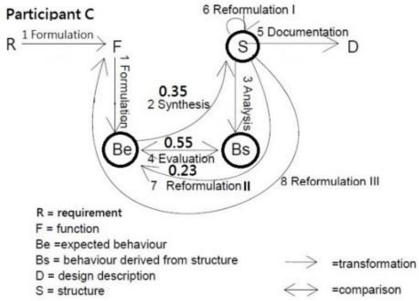

Table 4: Markov chains for participant C.

Participant-D	Syntactic					
	R	F	Be	Bs	S	D
R						
F	0.00	0.20	0.20	0.20	0.20	0.20
Be	0.00	0.00	0.00	0.29	0.71	0.00
Bs	0.00	0.05	0.10	0.20	0.60	0.05
S	0.00	0.04	0.08	0.25	0.55	0.09
D	0.00	0.00	0.00	0.14	0.86	0.00

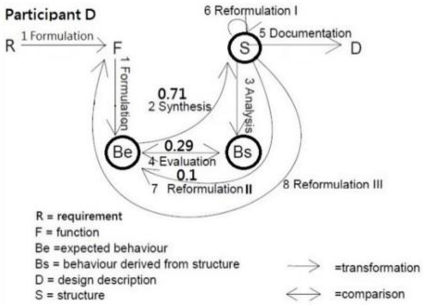

Table 5: Markov chains for participant D.

4.4 Dynamic Models to Visualise the Design Processes in CAD Modelling

As we discussed in the previous section, participants A, B and D had a similar pattern during the CAD modelling so participants B and C were selected to visualise and compare their design processes. Figure 9 and 10 shows the dynamic models of participants B and C during the CAD design process. Dynamic models using the linkoder software [15] make it possible to visually describe design moves using different colours. Fig. 9 shows that participant B produced 256 segments in the CAD design process and that these clearly focused on reformulation I (light blue, S→S) and analysis (yellow, S→Bs). The two peaks are caused by reformulation I and analysis around segments 26 and 100. This shows that participant B mainly focused on structure-related issues such as object dimensions and material selections in CAD modelling.

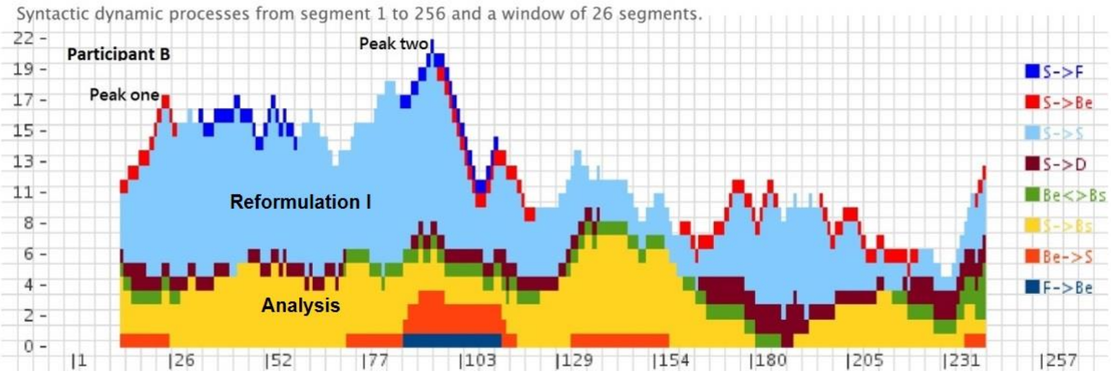

Figure 9: Participant B, dynamic model of CAD process.

Figure 10 shows that participant C produced 280 segments and spent the majority of his reasoning on the design processes of evaluation (green, Be→Bs) and analysis (yellow, S→Bs). The two peaks result from evaluation, analysis and reformulation I around segment 84 and 230. This reveals that participant C mainly focused on the design process of evaluation between problem and solution spaces.

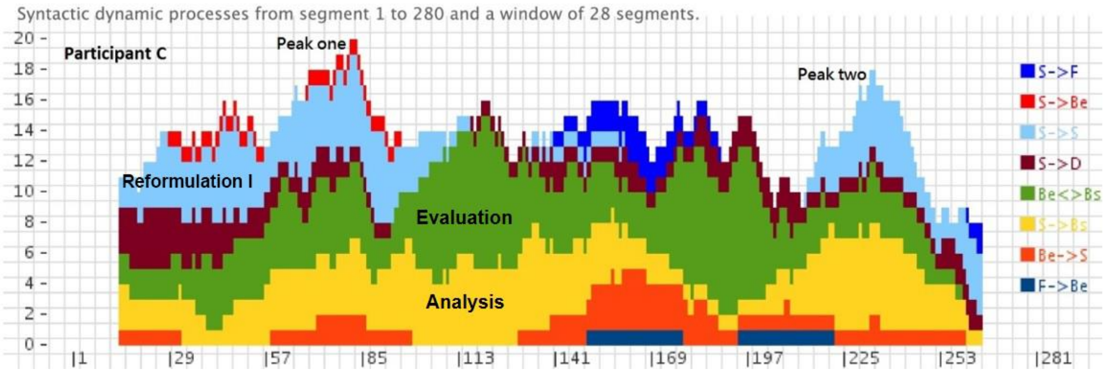

Figure 10: Participant C, dynamic model of CAD process.

4.5 Uncovering Uncertainty through Dissatisfaction with Sketches

To explore the factors that changed the roles of CAD modelling in mixed media design environments, it was informative to look at the participants' design protocols of segmentations at the end of the sketching sessions. A review of every segment indicated that participants A, B, and D were satisfied with their sketches. Only participant C was dissatisfied with his sketches so his CAD modelling design phase remained uncertain (Figure 11). Although the majority of his effort was devoted to evaluating his design alternatives, participant C was nevertheless dissatisfied with his sketching, stating:

> *Okay, so I'm done with the drawings, I think. I don't like it. I like going back to the drawing, so - but I understand the exercise, so now I'm going to try, from what I have drawn - from what I have drawn which is very rough, to make it work on the model, which should be easy enough.'*

Although participant C was dissatisfied with his sketches, he tried to build a CAD model based on his rough sketches and thought this would be easy. This illustrates Participant C's uncertainty justification for this assertion follows. Markov chains and dynamic models empirically support Tracey and Hutchinson's argument which is that when uncertainty arises during a design task, producing new solutions to a problem involves a process in which missing information is recovered from the design alternatives. This phase involves the iterative process of evaluation to reduce uncertainty [39]. Although the findings are limited by the small sample size, the empirical evidence provides strong reasons for the role changes in CAD design processes.

Figure 11: Participant C was dissatisfied with his sketches.

Participants provided comments on completion of their experiments. These pointed to a single solution which is integrating sketching into the CAD modelling design process, as shown below.

> *'By restricting the process to the sketching as design and then CAD as documentation only and no allowance to switch between them the capacity of each form is limited. Some design will always happen in the CAD environment, and some documentation (even if only for the designers' own records) will happen best with pencil and paper, so assuming that the division is clear and discreet is wrong. It is generally not possible to memorize a design and then CAD it up correctly, so referring to the sketch is vital' (Participant A).*

> *'Without being able to switch it took too long to try different design combinations if the first design didn't fit within the building properly. Then I was left to try to design straight into CAD which is much less intuitive then sketching' (Participant D).*

> *'I personally found the design process more difficult as once I had sketched my ideas and then placed them in CAD I could not sketch further ideas. The problem of this approach is the practitioner need to 'fix' encountered problems on the screen and not draw by hand possible alternative solutions. This process is much slower then returning to the 'thinking hand' for developing new ideas' (Participant B).*

After reviewing participants' design segments, participant A mentioned that he wanted to use sketching during the CAD modelling process when sketches and CAD models did not match each other (Table 6). Whatever the mechanism, the assumption is that uncertainty with current designs stimulates new solutions to solve problems using different design environments.

No.	Utterance	Code
177	'I hope that would be a solution enough. Well … okay. Let's think about reconfiguring our reception area. If we had a bathroom on the outside of this building … that won't work.'	Bsc
178	**'Okay this is the point in time when I want to take out a pencil and start sketching again.'**	Dc
179	'The reception desk … a little there some chairs that are not working here.'	Bsc

Table 6: Participant A's design protocol during CAD modelling.

Lastly, from empirical evidence, we confirmed that dissatisfaction with prior sketches resulted in CAD modelling being used to support conceptual design. Being dissatisfied with sketches, the whole CAD design phase became uncertain. This played a key role driving designers to new solutions and involving considerable cognitive effort on evaluation. This aligns with Christensen and Schunn's [11] study because higher uncertainty occurred at the beginning of the design process (e.g., sketching). Once designers are satisfied with their sketch outcomes, the following CAD design phase mainly entailed documentation because uncertainty was lower. This phenomenon is illustrated below (Figure 12):

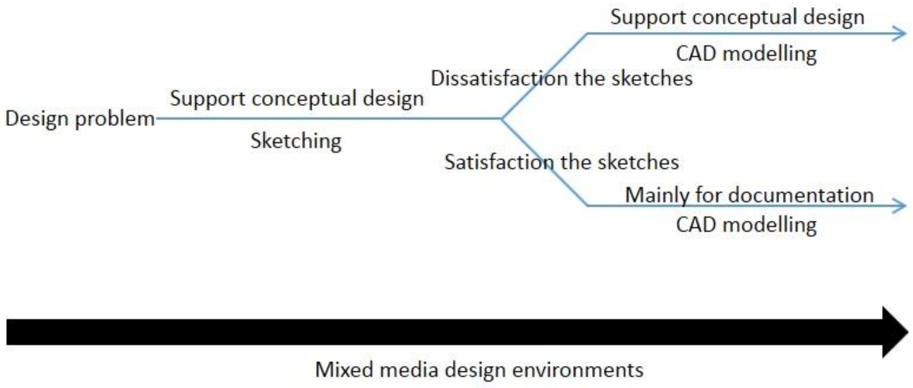

Figure 12: A diagram showing how CAD modelling is used differently in mixed media environments.

5 CONCLUSIONS

This paper has examined the effect of different design media in the conceptual design phase, i.e. sketching and CAD modelling. Although they support conceptual design, the normal understanding of CAD modelling is that it is mainly used for documentation. In addition, most research in this area is based on single design media to explore designers' cognitive reasoning processes. However, solving a design task using a single design medium does not address the increasing complexity of design problems. As a result, we proposed an approach where CAD modelling is gradually integrated with sketching in mixed media design environments.

To understand the relationship between uncertainty and evaluation, different creative design models were critically reviewed. Complicated and ill-defined design problems make the design process uncertain. This uncertainty drives designers to explore other design alternatives. To produce optimum solutions for design problems, the design process involves co-evolution between problem and solution spaces to reduce uncertainty. As the design process of evaluation is iterative (not sequential), the FBS design model was applied. The relationships between different creative processes map to the FBS design model and this mapping has been provided above.

We identified designers' cognitive actions that occurred in sketching and CAD modelling and defined them using the FBS coding structure. The justifications for applying protocol analysis, the think aloud protocol and the FBS coding scheme were also provided. Our results show that designers produce 2.5 times more FBS segments in CAD modelling than in sketching. This means that the designers spent the majority of their effort in reasoning during the CAD modelling session which had a significant influence on the overall FBS design issues and process distributions.

We conducted protocol analyses with four expert designers. We explored how they interacted with mixed media and focused on the use of CAD in the design phase. Participant A, B and D spent the majority of their cognitive effort on the design process of reformulation I (S→S). This suggests that they were using CAD modelling for documentation because many segments were coded according to the design issue of structure (S) for building components or selecting materials. However, participant C spent the majority of his cognitive effort on the design process of evaluation (Be⇆Bs). This suggests that he was using CAD modelling to support conceptual design because it refers to co-evolution for reducing uncertainty. The Markov chains and dynamic model analyses also provided empirical evidence of this.

A crucial point was reached when designers wanted to shift from sketching to CAD modelling. The contents of the design protocols that occurred at the end of the sketching sessions were examined to identify the factors that triggered this change. One factor was dissatisfaction with the sketches, and this turned the CAD design phases into a creative design process. This occurred because dissatisfaction increased the degree of uncertainty at the beginning of the CAD modelling sessions. The main contribution of this study is for teaching architectural design. Due to the increased complexity of design tasks, different technical design media are used to facilitate design processes. However, each design medium has its advantages and disadvantages. Thus, an optimal solution may not be achieved after the use of one design medium. This means that the following design sessions (e.g., CAD modelling) need to support designers to refine their prior designs (e.g., in sketching session) by evaluating alternatives.

One of the limitations of protocol research is the time required for both data collection and analysis [32]. It proved difficult to recruit participants who were competent in both sketching and CAD modelling, and who were interested in conceptual architectural design tasks. However, a sample size from one to three is acceptable in most protocol design studies [22]. In addition, the experimental set-ups were carefully considered and the approach of using mixed media was based on previous mixed media studies [8,20]. These statements confirm the validity of this study.

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