Title:
Exploring the Role of CAD in the Conceptual Design Phase

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Introduction:
Mixed media design, which includes both pencil sketching and computer-aided design (CAD) modelling [4] and 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 [1], researchers have argued that CAD modelling could support conceptual design [6]. In our focused 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 [3] was adopted to analyse their cognitive actions, and 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 the following design sessions need to support designers to refine their prior 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 used to support conceptual design or design documentation in mixed media design environments.

Methodology:
Protocol analysis with think-aloud method was used for this study. Four architectural designers were recruited for this study and a Function-Behaviour-Structure coding scheme [3] was adopted to analyse their cognitive actions. These designers were identified from those who satisfied the selection criteria. To be included, the participants needed: (1) a tertiary degree in architecture with a minimum of two-year of professional architectural practical experience; (2) competence in both sketching and CAD modelling; 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 1).

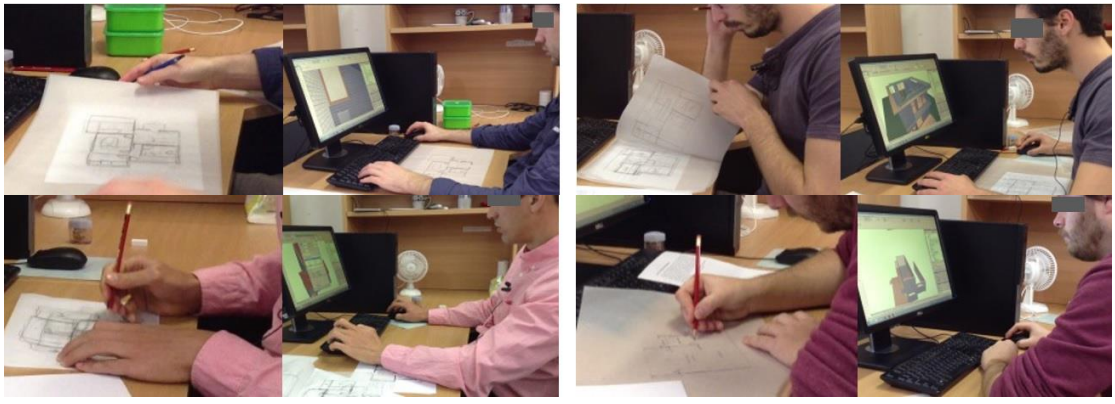

Fig. 1: Four participants used sketching followed by CAD modelling.

Discussions:
When using CAD modelling, 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 2a), as well as design processes of reformulation I (19~47%) and analysis (21~33%) (Figure 2b). 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 10). The next section applies Markov chains to analyse the events that follow (Be) and (Bs).

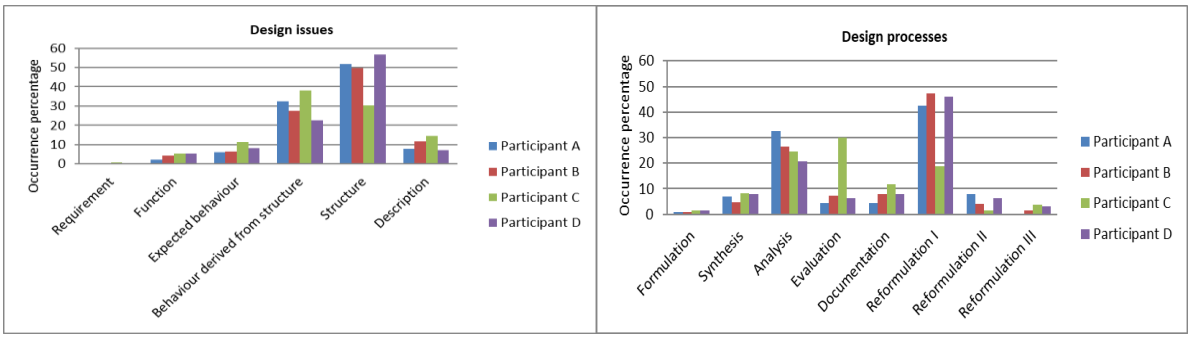

Fig. 2: (a) Design issues' distributions using CAD; (b) design processes' distributions using CAD.

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 3, in the next page). 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' (Participant C).

However, participant C was dissatisfied with his sketches, but tried to build a CAD model based on his rough sketches and thought this would be easy. This illustrates Participant C's uncertainty which turned the CAD design phase into a creative design process. Based on our protocol analysis in terms of the FBS distributions, (Markov chains and dynamic models will discuss in the full paper) empirically support Tracey and Hutchinson's argument: 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 [5]. Although the findings were generalised by the small sample size, the empirical evidence makes sense answering the reason of role changes in CAD design processes.

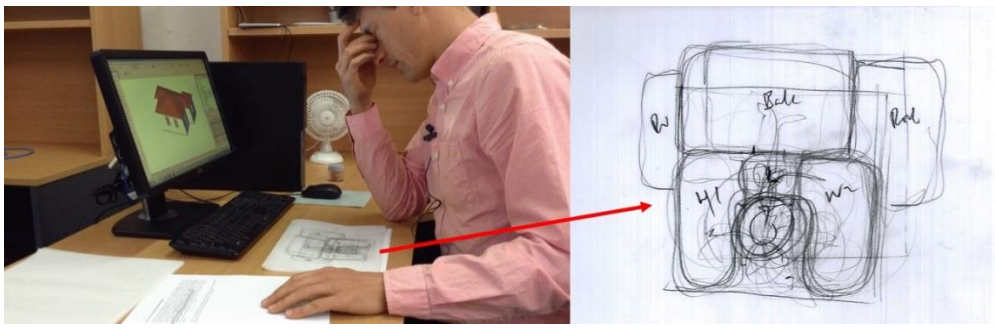

Fig. 3: Participant C was dissatisfied with his sketches.

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

'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 1). 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

Tab. 1: 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 also fits Christensen and Schunn's study [2] because higher uncertainty occurred at the beginning of the design process (e.g. here is sketching). Once designers satisfied their sketch outcomes, the following CAD design phase was mainly for documentation because uncertainty became lower. This phenomenon is illustrated below (Figure 4):

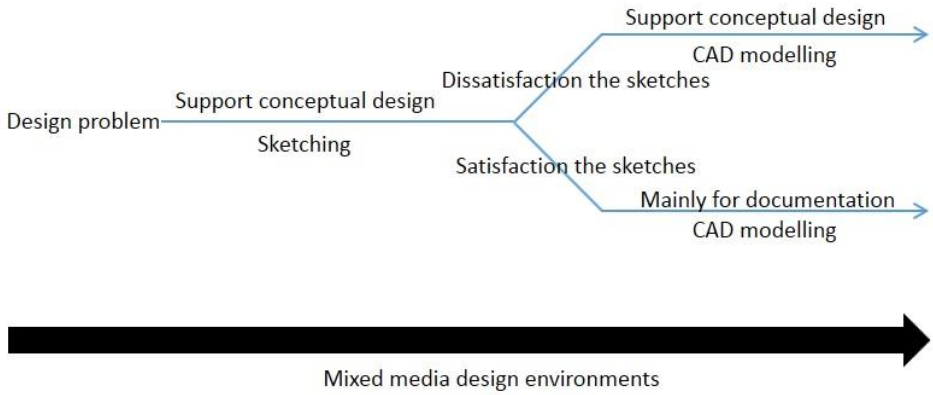

Fig. 4: A diagram showing how CAD modelling is used differently in mixed media design environments.

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 propose 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 the best solution for the design problem, the design process involves co-evolution between problem and solution spaces to reduce uncertainty. The design process of evaluation is iterative (not sequential) so 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.

The 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 reasoning effort 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 CAD 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.

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