Mediating Cognitive Transformation with VR 3D Sketching during Conceptual Architectural Design Process

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MEDIATING COGNITIVE TRANSFORMATION WITH VR 3D SKETCHING DURING CONCEPTUAL ARCHITECTURAL DESIGN PROCESS.

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Abstract

Communications for information synchronization during the conceptual design phase require designers to employ more intuitive digital design tools. This paper presents findings of a feasibility study for using VR 3D sketching interface in order to replace current non-intuitive CAD tools. We used a sequential mixed method research methodology including a qualitative case study and a cognitive-based quantitative protocol analysis experiment. Foremost, the case study research was conducted in order to understand how novice designers make intuitive decisions. The case study documented the failure of conventional sketching methods in articulating complicated design ideas and shortcomings of current CAD tools in intuitive ideation. The case study's findings then became the theoretical foundations for testing the feasibility of using VR 3D sketching interface during design. The latter phase of study evaluated the designers' spatial cognition and collaboration at six different levels: "physical-actions", "perceptual-actions", "functional-actions", "conceptual-actions", "cognitive synchronizations", and "gestures". The results and confirmed hypotheses showed that the utilized tangible 3D sketching interface improved novice designers' cognitive and collaborative design activities. In summary this paper presents the influences of current external representation tools on designers' cognition and collaboration as well as providing the necessary theoretical foundations for implementing VR 3D sketching interface. It contributes towards transforming conceptual architectural design phase from analogue to digital by proposing a new VR design interface. The paper proposes this transformation to fill in the existing gap between analogue conceptual architectural design process and remaining digital engineering parts of building design process hence expediting digital design process.

Keywords

Conceptual architectural design; external representation; VR 3D sketching; design collaboration; design cognition.

Introduction

This study has been motivated by the existing literature reflecting the shortcomings of current design tools in conceptual architectural design process. The literature on one hand argues that conventional manual sketching interfaces have some shortcomings in articulating new comprehensive global projects (e.g. Madrazo, 1999, Marx, 2000) and on the other hand, it indicates the failures of current CAD tools in replacing the manual sketching interfaces (e.g.

Bilda and Demirkan, 2003, Kwon et al., 2005, Meniru et al., 2003, Pour Rahimian, Ibrahim, & Baharuddin, 2008) due to their inherent problems which hinder designers' spatial cognition during the conceptual architectural design process. Hence, there are still parts of design that are handled by freehand sketches (Suwa et al., 1998) while most other parts are being done digitally. This transition is known to interrupt the continuity of a design process (Kwon et al., 2005). However, the integration of the whole building design process has since been suggested by Fruchter (1998) as she believes that it can better support collaboration among team members besides having major advantages in decreasing labor and material costs within current comprehensive production procedures. In summary the aim of this research was to facilitate digitization of conceptual architectural design process. This is expected to serve integration of whole building process besides the possibilities for improving designers' cognition and collaboration during conceptual architectural design process. As mentioned earlier, this aim was motivated by emerging challenges caused by comprehensive global building projects (Pour Rahimian, Ibrahim, & Baharuddin, 2008).

The purpose of this research was to enhance the integration of whole building process besides the possibilities for improving designers' cognition and collaboration during conceptual architectural design process. This study found some capabilities in new VR technologies to address all the above-mentioned problems. In other words, it suggested using a substitute modelling technology that is called VR 3D sketching in order to overcome the inadequacy of conventional manual design tools in articulating complex design ideas and to compensate the inflexibility of current CAD tools in intuitive design ideation. This VR based design interface is defined by the scholars as a design tool, which is easy to use, as the manual sketching besides providing a highly detailed 3D visualization environment. In defining this design interface Levet et al. (2006) use sketching metaphor and mention that in 3D sketching designers can swiftly produce 3D prototypes to exemplify the 3D objects that they have in mind. The idea of using VR 3D sketching in design is also supported by Kwon et al. (2005) since they believe that this would improve the performance of the computerized design process and speed up the incorporation of engineering requirements during the conceptual phases; i.e. applying the digital format rather than such analogue conventional formats that are currently being used.

To achieve the mentioned aim the study developed the main research question. Afterwards, in order to answer the main research question the study divided it into three Sub-RQs which are to identify: 1) the characteristics of current design media, 2) the collaborative design culture of conceptual architectural design process, and 3) the key enablers in VR 3D sketching interface that can optimize designers' cognition and collaboration during conceptual design sessions.

Research Methodology

The aim of this research was to facilitate digitization of conceptual architectural design process in order to enhance the integration of the whole building process besides developing and enhancing the current state of the design interfaces. This was expected to improve designers' cognition and collaboration during conceptual architectural design process. This aim was intended to be achieved by developing a new design methodology based on Schön's (1983a) "reflective practitioner" theory and Fitts' (1964) "motor learning" theory, then verifying its effectiveness based on collected empirical data. Schön's (1983a) "reflective practitioner" theory argues that designers are in a mutual relationship with external representations and are getting reflections from them. Whereas, Fitts' (1964) "motor learning" theory states that tangible interfaces can improve designers' cognitive actions. In this case the focus is on the integration of designers' other senses (e.g. the sense of touch) with their visual sense.

To reach to this aim, the research seeks for the current state of utilized design interfaces and the existing communication culture among designers. According to Shuttleworth (2008), qualitative case study research methodology could be an appropriate research methodology for this kind of research, which tests theoretical models by using them in real world situations. On the other hand, our research looks for the quality of the designers' cognitive and collaborative actions in using a particular design interface, i.e. 3D sketching. For this part of the research, design protocol analysis as a quantitative research methodology was chosen, since it has become the most prevailing research methodology for studying design process (Cross et al., 1996). Creswell (2002) named such a research methodology, which starts qualitatively and continues quantitatively, as "sequential mixed method research" approach.

Our early qualitative case study research (Ibrahim and Pour Rahimian, 2010) employed ethnography for data collection and artefact analysis for data analysis. Units of analyses for this part of study were design artefacts of a 2nd year architectural design studio at a local university comprising of 37 students and four studio mentors (Figure 1). Taking into account the nature of the building project that they examined, the study adopted the judgment sampling method (Kumar, 2005) to choose the sample population among available different studios. The gatekeeper during the

Figure 1: Individual and group activities of students (Source: Pour Rahimian and Ibrahim, 2008).

Figure 2: Prepared traditional (left) and 3D sketching (right) design settings.
(Source: Pour Rahimian and Ibrahim, 2009).

data collection was the Studio Master of the course. The conducted case study identified the characteristics of current design media and collaborative design culture of conceptual architectural design process. Consequently, the recommendations of the case study research helped us to develop theoretical foundations of the study.

On the other hand, the purpose of the quantitative part was to provide empirical evidence for the subjective view that proposed VR based 3D sketching interface improves the designers' spatial cognition and collaboration. In the experiment by Pour Rahimian and Ibrahim (2010), a traditional sketching toolkit was developed as a baseline to be compared with a proposed 3D sketching design interface (Figure 2). The purpose was to reveal the cognitive and collaborative impacts of the proposed design system. Five pairs of 5th year architecture students experienced with the traditional design and CAD systems were selected as participants for this experiment. During the experiment, protocol analysis methodology (Dorst and Dijkhuis, 1995, Ericsson and Simon, 1993, Foreman and Gillett, 1997, Lloyd et al., 1995, Schön, 1983a) was selected as a research and data acquisition method. The adapted methodology evaluated the designers' spatial cognition at four different cognitive levels: "physical-actions", "perceptual-actions", "functional-actions", and "conceptual-actions". It also evaluated the designers' spatial cognition in two different collaborative levels: "cognitive synchronizations" and "gestures".

Results and Analyses

The Characteristics of the Current Design Media in Conceptual Architectural Design

The conducted case study research listed three dominant types of sketching—i.e. fully manual, mixed, and fully digital—used by the students and their studio mentors. The three groups are as follow: Group 1 (Full Manual Mode—FM) uses only traditional sketching tools and abstract modelling methods, Group 2 (Mixed Mode—MM) started design using traditional methods, but later continue the process utilizing CAD modelling tools and Group 3 (Full Digital Mode—FD) started design in CAD environment and continues finalizing the design with it.

Besides, this study employed four dependent variables and three independent variables in order to identify the supportive characteristics and challenges of current external representation media. The dependent variables were solution quality, certainty of the correctness of the solution, total solution time and experienced difficulty in design problem solving while the independent variables were fully manual, mixed method and fully digital design sketching modes. This study conducted variance analysis (ANOVA) to check whether there is any significant difference among dependent variables belonging to all independent three groups or not. The results are presented in the following paragraphs.

Based on the results from the selected sample the study concluded that the design solutions by subjects using mixed traditional sketching and CAD modelling tools (MM) produce significantly higher solution quality compared to the other two groups=37. On the other hand, the entirely manual sketching subjects have significantly higher solution quality compared to those subjects who solved the problem completely in a CAD environment($n=37; \rho<0.05$). The subjects who used mixed traditional sketching and CAD modelling tools utilized manual sketching in initial design ideations and employed CAD tools in developing design ideas. Based on the findings this study posits that using CAD tools hinder designers' creativity in the early conceptual design stages. It also posits that conventional manual sketching tools are not so successful in developing design ideas particularly when the artefact becomes complicated.

However, the analysis of the second and third variables triggers more doubts about the adequacy of the conventional manual sketching in complicated design stages. Analysis of the second dependent variable revealed a significant decrease for the certainties of the correctness of the solutions of FM subjects compared to the subjects of the other two groups ($n=37; \rho<0.001$). However, the results from the survey show no significant difference among the three groups regarding their total time taken for creating their respective solutions($n=37; \rho>.05$). It implies that while the MM and FD groups had used 3D prototyping techniques to ensure that various design parts fitted and matched together, the FM group (FM) was not quite successful in convincing designers in this regard.

Since it was impossible to control the protocol size for such a huge observational data in terms of time and number of groups, the study resorted to applying subjective protocol evaluation for experienced difficulty of the design problem solving for the observed groups. Based on the subjective protocol evaluation using the narrative stories transcribed from the recorded videotapes, results indicate that subjects who had utilized mixed design media were able to pace their design processes with considerable less difficultly compared to subjects from the other two groups. The field observations (see Pour Rahimian and Ibrahim (2008)) noted that the same subjects were able to manipulate free hand sketches—as external representation tools—to solve design problems faster and easier. They were also able to use computational capabilities for solving their communicational problems either within design situations or with other designers. Results also indicate that the FM group had slightly less difficulty in producing design solutions compared to the FD group. The

Dependent variable		Solution quality		Certainty of the correctness of the solution		Total solution time	
(I) Dominant types of sketching	N	(J) Dominant types of sketching	Mean difference $(D=J-I)$	(J) Dominant types of sketching	Mean difference $(D=J-I)$	(J) Dominant types of sketching	Mean difference $(D=J-I)$
Fully manual mode	14	Mixed mode	−.43564*	Mixed mode	−1.42143***	Mixed mode	170.07
		Fully digital mode	.47755*	Fully digital mode	−1.54143***	Fully digital mode	88.49
Mixed mode (MM)	13	Fully manual mode	.43564*	Full manual mode	1.42143***	Fully manual mode	−170.07
		Fully digital mode	.91319***	Fully digital mode	−0.12000	Fully digital mode	−81.57
Fully digital mode(FD)	10	Fully manual mode	−.47755*	Fully manual mode	1.54143***	Fully manual mode	−8.49
		Mixed mode	−.91319***	Mixed Mode	0.12000	Mixed mode	81.57
Total	37	Among all groups	$f=13.3876$***	Among all groups	$f=64.535$***	Among all groups	$f=2.012$

Table 1: Comparison of the mean and standard deviation for quality of the solution, total solution time, and certainty regarding the correctness of the solution (Source: Ibrahim and Pour Rahimian, 2010).

*p<0.05 (significant difference), **p<0.01 (very significant difference), ***p<0.001 (absolutely significant difference).

results of artefact analysis are summarized in Table 1.

From the above results, the study found that among the three evaluated sketching support systems, the best external representation methodology comprises of mixing both manual and digital tools. The observations and indicative results illustrate that neither manual sketching tools nor CAD software are the better media for current conceptual design communications. This study posits that design semantic gets lost when manual design fails in articulating explicit design idea while design creativity diminishes when using arduous CAD software. The results support the earlier proposition to develop a 3D sketching methodology in VR in order to fill the gap between creative experimentation and precise manufacturing-oriented modelling supporting an integrated conceptual architectural design process.

Characteristics of the Collaborative Design Culture of Conceptual Architectural Design Process

Our second research question was: how do the novice designers collaborate in design teams during conceptual architectural design process? To deal with this question the study categorized the design communications that were observed into two groups: 1) between a designer and his or her design situation when trying to solve the design problem, and 2) between different designers during design collaboration. This study proposes calling the quality of such communications and the ways that they use to communicate as "Collaborative Culture". The observations indicate that the use of manual sketching would offer the designer the opportunity to trade off between accuracy and legibility. Hence, the manual design representation techniques do have the potential to convey design ideas more directly compared to other design support systems. The study observes that within such design projects, relationships between site plan elements were smoother when the design could be extended from the building to its site. Moreover, despite having a lower accuracy, the author noted that manual presentations exude richer emotions besides having more capability for carrying stronger design concepts. However, the works that use no digital design tools were almost raw and usually they stopped at a certain perceptive level. Regretfully, the fully manual approach ended less expressively than its initial good design concepts and intent.

The observations and protocol analysis indicate that using conventional CAD tools had shortened students' creativity and imagination during their conceptual design processes. This study proposes that this phenomenon was mainly due to many shortcomings of CAD tools in freely expressing designs ideas. In majority of their observed cases, computer-made perspectives were found to be more elaborate, had more details and were more realistic. The subjects were able to express nicer interiors with more refined details of lighting, paving, and design or colour of furniture. Yet, in most cases the author also witnessed some inconsistencies among different spaces and they lacked unity in the sense of space. The study claimed that the reason for contrast was due to different media type sketching environment.

During the digital design process, the designer saw many alternatives from perspective viewpoints rather than in plans and elevations. Hence, the perspectives could be expected to show amazing outputs compared to their final 2D elevations. The author believes that similar assumption could be applied to manually designed projects. Due to the lack of holistic consideration of the building—immersed in the perspectives—silhouettes in such cases were boring and non-artistic. Overall, the study found that the most amazing volumes did belong to computer-aided designs while the nicest conceptual spatial senses were from manual design attempts. Moreover, while most computer-generated or computer-aided works had almost similar characteristics, some of the excellent manual design solutions were unique indeed in comparison. The study found that the most successful cases were those that were designed completely manually but visualized digitally. This is because in such cases the designers would utilize the capabilities of each method to compensate the shortcomings of the other. These findings concur with the earlier conclusions from the artefact and protocol analysis that neither traditional sketching methods nor conventional CAD software are the perfect media to be used during conceptual architectural design process. Herewith, Table 2 presents a summary of challenges and benefits of each visualization method during conceptual architectural design phase.

With both ethnography and artefact and protocol analyzes suggesting no media winner between the traditional sketching method and the conventional CAD software, the study strongly recommend the need to develop an alternative design medium that could successfully transgress between both advantages. The alternative sketching tool must be able to facilitate intuitive idea expression abilities, and the excellent modelling and walkthrough capabilities while able to technically provide faster documentation process when in use.

Identifying Key enablers in VR 3D Sketching Interface That Can Optimize Designers' Cognition and Collaboration during Conceptual

Current manual sketching tools	•Flexibility in ideation due to tangible interface •Ease of use •Ease of learning •Ease of changing reforming the design alternative •Ability for using different scales of drawing and trading of between accuracy and clearness •Maintaining design idea during design process providing the ability to see all documents together and to compare	•Lower capability for shifting from micro to macro level and vice versa •More tacit information flow walkthrough •Lower details of visualisation •Fragile models and documents for editing or reviewing •Failing to add and control more details into design alternative due to weak level of visualisation •Difficulty in transition of the format when being used in the other design stages
Current CAD tools	•Easier documentation •Capability for zooming and panning for easier walkthrough •Capability for temporally omitting an object or group of objects •Capability for undoing undesired changes •More detailed, realistic, and elaborated perspectives due to high capability of visualisation	•Difficulty of obtaining ability to use •Arduousness of I/O devices which interrupt creativity of the designer •Losing consistency of spaces due to lack of ability to control ubiquitous design idea in an artistic way

Table 2: summary of challenges and benefits of each visualization method during conceptual architectural design phase(Source: Pour Rahimian, Ibrahim, & Jaafar, 2008).

Design Sessions

An experimental protocol analysis research has been conducted to identify key enablers in VR 3D sketching interface which can optimize novice designers' cognition and collaboration during conceptual design sessions (Pour Rahimian and Ibrahim, 2010). The study employed a cognitive approach to design process to articulate all aspects of the utilized medium during conceptual architectural design process. Here the traditional sketching method—which is usually appreciated by many scholars—is selected as a baseline to be compared with the proposed 3D sketching design methodology and to reveal the cognitive and collaborative impacts of the proposed design system. The experiment comprised of five main steps: 1) to conduct experiments, 2) to transcribe protocols, 3) to parse process into the segments, 4) to encode the segments based on a coding scheme, and 5) to analyze and interpret the encoded protocols. In encoding the collected data and developing the hypotheses the study categorized designers' cognitive actions into five major action categories as physical, perceptual, functional, conceptual, and collaborative. In interpreting the finding the study relied on the observations of the designers' behaviours during the experiment and also on statistical analysis of the encoded design protocols. Nevertheless, in the implications the impact of the encoded data is rather high compared to the behavioural observations.

Even though the number of participants, which is six people, seems somewhat small, the protocols included pairs' verbal accounts concurrently per experiment, therefore providing adequate data for an empirical exploratory study. Three participant groups are exactly the same number that Clayton, Kunz, and Fischer (1998) suggested to use for guaranteeing the validation of such Charrette-based experiments. Furthermore, the number of similar previous practices (e.g. Bilda et al., 2006, Kim and Maher, 2008, Menezes and Lawson, 2006) that used 2-3 pairs of designers as their participants reconfirms the facts that the utilized sample size is good enough for inferring the hypotheses via the findings.

Discussions

Overcoming the Shortcomings of Conventional Sketching Methods

Our ethnography study and the artefact and protocol analyzes on the ethnography findings (Ibrahim and Pour Rahimian, 2010; Pour Rahimian, Ibrahim, & Jaafar, 2008) concluded that there is no better winner for the choice of current media for external representation purposes. Both studies affirm the inflexibility of traditional geometric modelling tools against intuitive ideations. Moreover, both have equally observed the shortcomings of conventional manual sketching tools for further articulating design ideas whereby it had difficulties in turning tacit knowledge into explicit knowledge for collaboration purposes. On the other hand, the results have shown that neither manual sketching tools nor current CAD interfaces are the perfect media for current conceptual design communications. The alternative tool must also support all intuitive idea expression besides the precise manufacturing oriented modelling and effortless design walkthrough. This is because any new alternative need to acknowledge Griffith et al.'s (2003) idea about the tacit role of knowledge during a design process. The proposed VR tool may help designers to articulate this tacit knowledge and documenting that tacit knowledge into explicit data.

Implications for VR 3D Sketching Interface

The results of the artefact and protocol analyzes show that major barriers with conventional sketching design tools when designing complex design procedures were mainly due to their shortcomings in advanced visualization for communication purposes as the design progresses. This was particularly so for novice designers who did not know how to sketch manually very well. Current conventional sketching tools cannot be replaced directly with current geometrical CAD modelling tools since the study found that certain definite intuitive characteristics of conceptual design processes cannot be supported by existing CAD software. In brief, the inflexibility of traditional arithmetical modelling software on one hand and the restricted visualization capabilities of current manual sketching tools on the other hand are increasing the tendency for substituting manual modelling techniques with digital technique. Hence, the study proposes that an alternative 3D sketching tool becomes an intermediate sketching tool that bridges both characteristics.

In using the sketching metaphor, Levet et al. (2006) have proposed the use of some design interfaces in which designers can swiftly produce a 3D prototype to exemplify the 3D object they have in mind. Kwon et al. (2005) have considered this factor in order to improve computing performance for expediting the progress of the conceptual phase into the remaining design stages—i.e. applying the digital format as early as possible after the use of such analogue conventional tools.

Cognitive-Based Protocol Analysis Experiment for Testing Efficiency of VR 3D Sketching

The main aim of this experiment was to provide objective and empirical evidence for the subjective view that proposed VR based 3D sketching interface improves the designers' spatial cognition and collaboration during conceptual architectural design phase. In this experiment the focus was on designers' cognitive and collaborative actions and the hypotheses were being tested relying on the designers' actions. The codes assigned to the different segments were considered as the units of analysis of this study. Although this experiment was made up of three pairs of designers performing six design sessions in total, the experiment provides adequate data for observing overall designingly trends and actions. Besides, this study is guided by Clayton et al.'s (1998) recommendations in validating the results. Moreover, during the exploratory study the study has revealed consistent improvements in the main five aspects of design sessions and spatial cognition across the three pairs that further validate the claim that 3D sketching interface facilitates better quality of designing.

From the empirically collected data, the study found that in 3D sketching sessions the increased integration of the physical actions with mental perceptions and conceptions led to occurrence of epistemic actions to improve the designers' spatial cognition. Besides, relying on the literature (Kirsh and Maglio, 1994) the study posited that the epistemic actions facilitated by the rich interface offloaded the designers' mental cognition partly into the physical world, thus letting them have freer mind to create more design ideas.

Moreover, 3D sketching interface improved the designers' perception of visio-spatial features, particularly in terms of unexpected discoveries of spatial features and relationships. Based on outstanding design theories, (e.g. Schön (1983a)) the study explains how association between mental cognition with the perception of physical attributes can stimulate creativity and offload the mental load. Furthermore, the author paraphrased from Suwa et al.'s (2000) arguments to explain how unexpected discoveries can lead to more creativity and also to the occurrence of more situative inventions.

In terms of functional-conceptual actions of the design process, the study discovered that 3D sketching interface improved the designers' problem finding behaviours as well as improving their co-evolutionary conceptions of their perceptions and problem findings. Borrowing from Suwa et al.'s (2000) this study called the most important aspect of the problem finding behaviours as 'situative-inventions' and argued how the increased percentage of the co-evolutionary and situative-inventions actions can lead to improved creativity in 3D sketching design session. Further, it had the same argument about the capability of the co-evolutionary conceptions in increasing design creativity.

Lastly, in terms of the collaborative activities, the study has observed that the explicit representation ability, which is applied in the proposed 3D sketching interface, is capable to motivate the designers to share more ideas together. Moreover, the study explained how this interface is capable to change the type of conversations from ordinary clarifications to new proposals and arguments for development of the problem and solutions space. Finally, the author cited from Kim and Maher (2008) to show that emergence of this quality in design conversations can enhance the creativity of the design process.

In conclusion, this study posits that the emerging VR technologies are capable to facilitate some senses beyond the visual aspects of the design artefact by offering a new generation of promising CAD tools, which are constantly in touch with designers' cognition and collaboration during conceptual architectural design process. It also conjectures that by utilizing the same digital format during both conceptual architectural and engineering stages of the building design process—the full design integration aimed by Fruchter (1998)—can be better facilitated.

Conclusions

A sequential mixed method research comprising case study and protocol analysis studies is conducted. The case study contributes in extending theoretical foundations for improving designers' cognition collaboration during conceptual design process. These foundations became recommendations for improving and optimizing operational behaviours of design project teams. On the other hand, the purpose of the protocol analysis was to empirically evaluate and verify the role of 3D sketching using VR technology to facilitate integration between conceptual and engineering parts of building design process. The study identifies: 1) issues and challenges for multidisciplinary architecture-engineering-construction (AEC) teams in project collaborations, 2) inherent characteristics of the conceptual design process and its external representation tools, and 3) the theoretical and technical requirements of the proposed 3D sketching in VR as a new external representation tool.

The conducted empirical protocol analysis experiment compares the proposed 3D sketching design interface with traditional design methods. It explains the results of implementing the basic VR-based design interface to recommend how 3D sketching can be developed as a collaborative medium in a VR environment. Moreover, adopting a cognitive approach to design, it identifies supportive characteristics of VR in enhancing designers' cognition and collaboration in conceptual architectural design stages. The findings of this study contribute to three main areas namely architectural education, architectural profession, and integrated building industry. The following sections describe those impacts and contributions besides proposing future research on those mentioned areas.

Claimed Contributions and Impacts of the Study

i. Integrating the design process. The theoretical foundations of this study about cognitive and collaborative aspects of implementing VR 3D sketching interface contributes towards transforming conceptual architectural design phase from analogue to digital process. This study claims that this transformation can fill in the existing gap between analogue conceptual architectural design process and remaining digital engineering parts of building design process. This is because in the building industry, conceptual architectural phase is the only stage that is yet to be computerized.

Therefore, implementing VR 3D sketching interface is expected to improve the integration of the entire design process by digitization of this phase. This idea is also supported by Kwon et al. (2005) that digitization of conceptual architectural design phase can improve the integration of the whole design process.

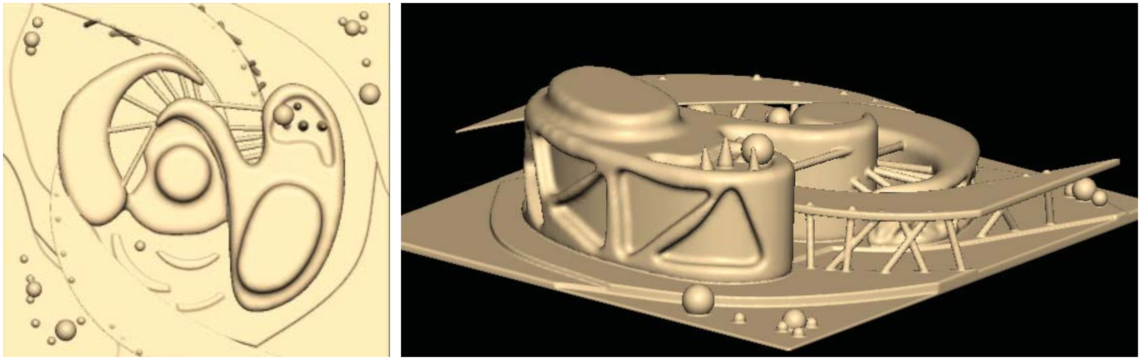

Figure 3: A 3D sketching design outcome by Group 2 (Source: Pour Rahimian and Ibrahim, 2009).

Additionally, Fruchter (1998) recommends the integration of design process since she believes that it can better support collaboration among team members besides benefiting the process by decreasing labour and material costs. Therefore, the study claims that migrating from analogue to digital conceptual architectural design process can become a stepping-stone for trans-disciplinary teamwork to share VR 3D sketching interfaces in distant locations. The author expects that this could be successful by enabling professionals to save and amplify design semantics throughout a project development lifecycle phases. Thus, advancing methodologies and technologies in the design phase that lead towards 4D construction implementation (Ibrahim, 2007) besides developing a new generation of architects who are able to work collaboratively in geographically dispersed locations (Ibrahim et al., 2007).

ii. Improving design cognition and collaboration. This study contributes to the development of theoretical foundations towards implementing VR 3D sketching interface as a more flexible and explicit conceptual architectural design interface compared to existing conceptual design interfaces. The study claims that it can improve the quality of architectural education by providing a more capable and explicit design interface. The results revealed that this interface can become stimuli for accelerating designers' creativity during design process. The findings confirm Suwa et al.'s (2000) arguments relating to more explicit design interfaces as aspect of 'learning through experience'. The study agreed that VR 3D sketching interface can become stimulus for retrieving more knowledge and accelerating inventions by articulating tacit knowledge of design. Moreover, it claims that more explicit visualization in VR 3D sketching interface can facilitate better design conversations hence improving knowledge flow between mentor and apprentice in mentoring sessions.

iii. Developing a new approach for studying design process. This study contributes to architectural design education by extending the findings of a qualitative case study research into the conducted quantitative experiment. So far, all the previous studies that dealt with architectural education either qualitatively or in some experimental laboratory conditions were not quite successful in integrating designers' cognition with their collaborative behaviours.

The adopted mixed method helps the researchers to obtain their insight into designers' needs for external representation interfaces through conducting qualitative research. It also helps them to microscopically evaluate developed theoretical constructs by adopting a quantitative approach. This study claims that extending the findings of a preliminary qualitative study can enrich the quantitative research by providing higher level of theoretical foundations for establishing assumptions and interpreting the findings.

iv. Documenting educational design process in Malaysian context. This study contributes by identifying and documenting designers' cognitive and collaborative conceptual design behaviours in the Malaysian context. This study categorized their collaborative behaviours into two major groups: 1) their collaboration with design situation, and 2) their collaboration with other team members. With regard to cognitive behaviours the study formulized Malaysian designers' collective cognitive behaviours in five major levels: physical-action, perceptual-actions, functional-actions, conceptual-actions, and collaborative-actions. The accomplished full scenario documentations during ethnography and protocol analysis research can be used as a reference for future researches in architectural design education in the Malaysian context.

Recommendations for Future Study

The results of this study are expected to help the development of cutting-edge information technologies in architectural education and profession. Therefore, this study suggests some further researches to extend the cognitive and collaborative features of the proposed VR 3D sketching interface towards creation of some professional and pedagogical programs. The created programs should involve more elaborated design practices to support new global and complicated design processes. They are also expected to consider the global and non-collocated practices during conceptual design phases. The authors believes that it can train professional graduates who are competent in multidisciplinary teamwork and equally competent in utilizing IT/ICT in delivering their building projects within the allotted time and budget.

The results and implications of this research only revealed the virtue of the new VR technology in enhancing design interfaces in term of supporting designers' cognition and collaboration. However, further research is recommended to reveal more technical and theoretical aspects for extending the implemented VR 3D sketching interface towards creating an advanced curriculum for IT/ ICT based design studio. The potential researches are listed below:

i. to test VR 3D sketching in non-collocated collaborative conceptual design projects,

ii. to seek the effects of the fully immersive interfaces on the designers' cognitive processes,

iii. to investigate the designers' collaborations when using multiple haptic design tools, and

iv. to explore higher capabilities of haptic design tools in architectural design by developing customized environments based on open source application programming interfaces.

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