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Assessing Mechanical Engineering Undergraduates' Conceptual Knowledge in Three Dimensional Computer Aided Design (3D CAD)

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Abstract

Research on the relation between conceptual and procedural knowledge showed that interaction between them will enhance understanding of domain knowledge. At the university, the emphasis on teaching and learning of CAD is on the procedural knowledge, thus some students might not be aware of the concepts underlying the procedure used in 3D CAD. The question is do the students have the conceptual knowledge before entering the workforce. This article discusses the concept of developing 3D CAD models, identifies different categories of the concepts and provides assessment method for teaching and learning. It will address the implementation of Concept Map to assess students' conceptual understanding on 3D modeling technique.

Keywords: Conceptual Knowledge; 3D CAD; Concept Map; Mechanical Engineering; 3D modelling

1. Introduction

CAD software is the prime tool to support Mechanical Engineering courses in higher institutions throughout the world. It was initially used only as a tool to replace hand drawn engineering drawing. Then, as the software and hardware further developed, this has made the systems more affordable and higher institutions started incorporating the system into their curriculum. Extensive use of the system to support teaching and learning in Mechanical Engineering programme materialize as the systems are capable of producing three dimensional virtual objects. 3D models developed by the system are used in teaching engineering design subjects where

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graduates can visualize and present their design ideas. A university in Malaysia is known to use the software as supporting tools for its Mechanical Engineering undergraduates throughout their years at the faculty. Specifically, in producing engineering drawing at freshmen year, presenting design ideas during second year of study, presenting and representing design project in Engineering design subject in third year of study and using the software for capstones design project. Similarly, other higher institutions do integrate the software in their Mechanical Engineering curriculum. For instance, Garcia et al. (2005) and Hamade et al. (2008), reported that they have CAD subjects in their mechanical engineering curriculum, whilst some faculties teach them as Engineering Design or Computer Graphics subjects (Sung et al., 2002; Devon, 2007; Sorka-Bizon, 2007).

However, at UTM knowledge in the use of CAD software are taught along with Engineering drawing subject without any specified time dedicated for teaching and learning of the software. The undergraduates are taught the principles of engineering drawing and consequently produced the relevant output in the form of CAD generated drawings. Procedures and methods in developing 3D CAD models are explained in dedicated CAD computer laboratory. Engineering drawings are generated from the models and presented to instructors for assessment. The teaching and learning on the models are primarily focused on procedural knowledge where uses of related commands are emphasized. The emphasis placed by the instructors is on assessing students' outcomes in engineering drawing subject and not on their knowledge or skills in developing 3D CAD models. However, this is the only formal training the students have in using the software, and they are expected to use it to solve problems in other domain subjects.

This leads to the following study: What is the students' level of understanding on the fundamental concepts in the process of developing 3D CAD models? Of interest is in dentifying the possible conceptual knowledge requirements of 3D CAD tasks. Implications from this study will be beneficial to instructors in assisting students by providing adequate support of model development techniques within product development activity.

2. Related Research in knowledge of CAD

Research on CAD education began when two dimensional version of the software were introduced. Advances of computer software and hardware results in 3D CAD capabilities that shift the research to focus on utilization of 3D CAD tools in design and product development process (Wang et al., 2002). Researchers started examining students' skills and capabilities in using the software while producing computer generated engineering models (Hamade and Artail, 2008). Lang et al. (1991), and identified knowledge in CAD as declarative and procedural knowledge. They state that declarative knowledge consists of the facts of the situation and include knowledge on the object being drawn and knowledge about the particular commands which can be used on particular CAD system. Bhavanani et. al. (2000), explained the meaning of declarative knowledge in CAD as knowing what the software is all about and what it can produce. While Chester (2006), proposed a declarative command knowledge which is concerned with specific procedures used by individuals to secure familiar objectives such as extrude and revolve. He states that it is knowledge about the commands or algorithms that are available within 3D CAD.

CAD procedural knowledge as mentioned by Lang et al. (1991), is similar to a subroutine that processes the particular information always in the same way depending on the situation. They suggested that the strategies or procedures used for CAD tasks should be independent of the CAD platform and usable on virtually any machine. Similarly, Chester (2006), proposed the term as specific procedural command knowledge which is concerned with specific procedures used by individuals to secure familiar objectives such as extrude and revolve. Bhavnani et al. (2000), used the term command knowledge which refers to knowledge of the commands (algorithms or tools) and procedures to be adopted by those tools within CAD software. It is related to knowledge of knowing the relevant software command to achieve desired output. Meanwhile, Chester (2006), reconceptualized command knowledge as specific procedural command knowledge which is the knowledge of how to execute the commands by the system to get desired output. This knowledge enables the operator to execute the necessary commands within specific CAD software. Bhavnani et al. (2001), stated that expertise in complex computer applications such as CAD may be differentiated on the basis of 'command' and 'strategic' knowledge with expert employing greater amounts of the later knowledge. He explained that strategic knowledge is concerned with knowledge of the alternative methods by which specific tasks may be achieved and the process by which a choice may be made. Chester (2006), refers to strategic knowledge as the knowledge necessary to choose and apply the appropriate command knowledge in a manner that efficiently produces model and allows future design variation.

As CAD system becomes more complicated with various development of virtual models, essentials concepts on how to develop the models need to be recognized. However, there has been little study of conceptual knowledge in 3D CAD modeling and the emerging requirements of the knowledge. Therefore, this research investigate conceptual knowledge in 3D CAD modeling. The advantages of understanding this type of knowledge, according to Tabaran et al. (2007), are longer-term retention of information due to more elaborated cognitive representation of the knowledge, and the ability to transfer the knowledge to novel situation because the knowledge is not tied to specific rote situations and procedures. Adopting such a perspective, fundamental concepts in developing 3D CAD models will be addressed, specifically in Mechanical Engineering domain.

3. Concepts of Model Construction in 3D CAD

Construction of 3D CAD models involved numerous steps users should understand as it is concerned with the development in virtual environment. The models are developed by employing set of concepts along with utilizing the right command of the software. Basically, general shapes of the models are initially identified. Then, two dimensional projection profiles are drawn on a construction plane (or working plane) for the formation of basic structure or part of the model to be drawn. Applying suitable procedures to the profile will produce a basic feature of a model to be drawn. This semi-completed model is then further developed by adding desired features. The model and their associated features can be modified or manipulated by using appropriate procedures. Combinations of models or parts are then assembled to form complete assembly visualization. Mechanical engineers use these virtually assembled products for the purpose of evaluating and examining design ideas.

4. Conceptual Knowledge and 3D CAD

Conceptual knowledge is defined by Groth and Bergner (2006), as a connected web of knowledge; a cognitive network in which relations between nodes are as important as the discrete pieces of information constituting these nodes. While Bloom defined conceptual knowledge as the interrelationships among the basic elements within a larger structure that enable them to function together. In the case of 3D CAD, the technology itself has become more complicated by having various modeling techniques with different capabilities to carry out different functions. Knowledge in the interrelationships of this technology within and between them is important as the systems are nowadays being used as essential tools in product development process. According to Hiebert and Lefevre (1986), this knowledge is needed to identify problems and generate new strategies or adapt known strategies to solve original problems.

Constructivism and *Schemata* are two important ideas that underpin learning issues in relation to conceptual knowledge (McCormick, 1997). Constructivisms in 3D CAD focus on individuals building up representation of their understanding of the systems' model development process. Students gradually develop their understanding of model development process by initially building up basic models of part to a more complicated model structure, and eventually form complete assembled models. They will attempt to fit their understanding of the concepts during model development process. Prior conceptual knowledge is essential during this process as it develops over time.

Schemata described by cognitive psychologists as the knowledge structures that exist in students' memory which they construct from experience and instruction (McCormick, 1997). Students were generally taught how to develop basic 3D CAD models in computer laboratory by means of some command and procedural knowledge. They are further required to develop complete models as an exercise. Requirements of related domain subjects such as engineering design to produce and present design ideas using CAD models generate deeper understanding of the system. Through these experiences their concepts of model development process were constructed and are structured within their engineering domain.

Research in Mathematics education show that understanding the concepts may enhance procedural knowledge and performance (Rittle-Johnson et al., 2001 and Nevin Mahir, 2008). It helps students to identify key features in a problem based situation. Students' understanding of the concepts would improve when they can determine or identify problems and subsequently produce successful solution (Hiebert and Lefevre, 1986). According to Fisher and his colleagues (1993), effective problem solving is closely associated with concept learning, making inferences and categorization, which represent distinct components of engineering skill. Tabaran et al. (2007), stated that conceptual and procedural knowledge are two mutually-supportive factors associated with the development of engineering skill. McCormick (1997) explained that conceptual knowledge consists of ideas that give some power to think about technological activity.

5. Concept Map for the assessment of Conceptual Knowledge

Concept maps visually represent students' knowledge structures and meanings in a particular knowledge domain (Jonassen and Merra, 1994). It was initially introduced by Novak and Gowin (1985) to see how students linked hierarchical material together in biology. According to Nicoll (2001), the use of concept mapping is becoming an important technique for analyzing student understanding in other disciplines. He clarified that concept maps are built by placing terms, which represent the concepts to be mapped, in structures called nodes. The nodes are then linked together into propositions.

This research is aim to better understanding of how Mechanical Engineering undergraduates represent their 3D CAD knowledge structure in relation to their domain using concept map. According to Biggs and Tang (2007), the map can serve as an indication of how the student sees the way in which individual concepts relate to each other and how it presents an overall picture, a holistic representation of a complex conceptual structure. It provides rich insights into organization and cognitive structure (Kinchin et al., 2000; Hay and Kinchin, 2006). Zele and his colleagues (2004), explained that a concept map represents a person's structural knowledge about a certain concept or subject and present a more informative and complete picture of students' understanding. Upadhyay et al. (2007), reported that concept map methodology has been integrated successfully to develop a visual pattern of structure of various pre-identified concept elements for a quality engineering education. Application of the method help decision-makers, planners and administrators understand the necessary linkages in the complex and co-evolving system of engineering education.

6. Categories of 3D CAD Conceptual Knowledge

To identify essentials concepts of 3D CAD in mechanical engineering, categories of concepts are developed for this study. The conceptual knowledge are classified into five major categories: Model Creation, Manipulation, Exploratory Visualization, Model Transfer and Collaboration. The meaning of each category are as follows:

- Concepts of 3D CAD Model creation process. Understanding of the system models creation techniques to develop models in virtual environment.
- Concepts to manipulate modeled object to produce alternatives and preferred solution. Knowledge on the systems' capabilities that facilitate variations to be explored would enhance creativity and support problem solving activity.
- Concepts to Visually Explore models during the process of models development. This knowledge would enhance models creation process by assisting the users to visually navigate through complex models structure.
- Concepts to share data (model transfer) for the purpose of obtaining the desired output. Understanding of this function to perform proper data exchange across various platforms is essential in product modeling process.
- Concepts of collaboration in model development process. Understanding or recognize that internet and intranet technology has transformed the system to facilitate concurrent engineering in product development process.

In order to further develop this conceptual model, we need to operationalize and define the categories. Each category is discussed next in detail.

6.1. Model Creation

In 3D CAD, modeling activity starts with defining datum or construction plane that serves as the base plane to create the base profile. The construction of the base profile utilizes geometric entities, such as lines, arcs, splines, which are drawn as vectors in a single open or closed profile that will form base part (Silva et al., 2002). Constraints are added at this point to the profile if parametric modeling is chosen for the modeling techniques. Further development on the models' subpart are constructed by employing the same part creation sequence through creating and positioning the construction plane at appropriate location. The user can add features to the parts' features. Completed model are treated as a single part in assembly modeling and additional parts can be further developed either in the same or separate files. Standard engineering part can also be constructed through third party software or special programming script by specifying required parameter. These parts are then assembled using suitable software's specific command procedures. Models are regularly rotated and positioned in preferred location during the development process to assist interaction between the user and the models. Items associated with this category are as listed in Table 1.

6.2. Manipulation

Manipulation is a modeling activity where variations on the models is developed (Baba et al., 1998).The models is manipulated by means of modifying the geometry or features. The systems' facilities has great potential in reducing design time and design mistakes, enhancing consistency and ease of documentation. Knowing this knowledge reduce the amount of time spend modifying designs ideas, subsequently helping design to manufacture more quickly (Wang et al., 2008). Any change made on any part or assembly is automatically generated in all associated parts and drawing sheet, so that all the related files will simultaneously been changed as the main part is being manipulated. Items for this category are as listed in Table 1.

6.3. Exploratory Visualization

Understanding of CAD systems' visualization facilities would help users to speed up model development process (Fitzmaurice et al., 2008). It is necessary for the user to be able to navigate through simple or complex models structure such that features can be added or modified to form complete object (Jong et al., 2008). For instance, users can make use of feature manager to select directly desired entities in a complex model structure which would enable users to speed up modifying or correcting unintentional error. Concepts included in this category are as listed in Table 1.

6.4. Data Transfer

Understanding and knowing data transfer in 3D CAD models development process is essential to every CAD users as created models are used for downstream applications (Pratt et al., 2001; Kim et al., 2008). The process of developing the models should include the needs of other users. Models would not be useful if it cannot be transferred to another platform. For example, related software system could not read the data due to inappropriate use of geometry or topology to develop a 3D model. Therefore, it is important to develop models that can be in use throughout the organization. Table 1, illustrate essential concepts for to this category.

Table 1. List of items of each category of the knowledge

		Concepts/Items		Total No. of Items
Categories of 3D CAD Conceptual Knowledge	1. 3D CAD Model Creation	1. Drawing 2. Parts 3. Assembly 4. Modeling Techniques 5. Geometrical Entities 6. Reference plane 7. Sketch profile 8. Free form geometry	9. Surface creation methods 10. Rules for the creation of surface 11. Models Translation and Rotation 12. Model position and orientation 13. Parametric Layout to capture design intent 14. Standard parts in assembly modeling 15. Programming	15
	2. Manipulation of Modeled object	1. Sub model 2. Engineering Drawing 3. Dress up features 4. Connections of edges 5. Level of model manipulation	6. Manipulation of non geometric entities 7. Parent child relationship 8. Perform design changes 9. Exploration of design	9
	3. Exploratory Visualization	1. Model viewpoint 2. Switching between 2D and 3D mode 3. Appearance of surface 4. Interaction with geometric entities 5. Producing 3D CAD layout	6. Visualizing features 7. Models hierarchies 8. Features manager 9. Navigation 10. Expand and Collapse	10
	4. Model Transfer	1. Handling of geometric and non geometrical entities 2. Different CAD platform 3. Data throughout company 4. Data to related company	5. Data as communication with consumers 6. Data as design review 7. Data as design verification 8. Data as illustration 9. Data as sharing of design	9
	5. Collaboration	1. Formal design report 2. Visual output 3. Reverse engineering 4. Use of internet	5. Concurrent engineering 6. Implement Real time design 7. Perform online design 8. Design activity of different time zones	8

6.5. Collaboration

The framework of collaborative CAD in product development facilitates creation of a hierarchical product structure, with single and compound components by assigning tasks to team members (Janardanan et al., 2008). Each team member can have his own specific view on the product which is kept consistent by using a central product model. The actual design of a single component is supported by a web-client specialized in part design, whereas the specification of assembly relations among components is supported by a web-client specialized in assembly design (Bidarra et al., 2002). Some commercial CAD systems are incorporating functionality for multi-user facilities using client-server architecture in collaborative modeling. Items related to this category are as shown in Table 1.

7. Method

The participants of this study were 33 final year Mechanical Engineering undergraduates from the university. All of the participants are studying Mechanical Engineering as main area without any specific subjects on CAD or CAM. Procedures for Concept map assessment test were based on steps proposed by Ruiz-Primo et al. (2001). Students were taught the basic structure and classifications of concept map the first twenty minutes followed by a simple exercise. They were asked to develop a simple concept map as an exercise to familiarise with the method. The students were then provided with a sheet of A3 paper with the following instruction printed along the top edge of the page: “What do you know about three dimensional Computer Aided Design (3D CAD)?”. Five categories of the conceptual knowledge were labeled along 3D CAD word with linking lines. No propositions were labeled along these lines. A set of essential concepts randomly arranged in A4 page was attached to the sheet. The total number of listed items for each category is as shown in Table 1. This list of concepts was given such that their internal knowledge representation would converge as anticipated by the researcher. The tasks were administered in a normal lecture day for the duration of thirty minutes. Most students only come across the construction of concepts maps once the researcher introduces it.

8. Scoring Method

A criterion from Blooms’ (1956) characterization of conceptual knowledge which was reported by Nightingle et al. (2007), was used to form the basis of the assessment. The assessment criteria are on the understanding of items *classification*, formation of logical conceptual *model* and the *structure* of the items forming the model. Briefly, maps were scored with the following point assignment for each valid component:

- item links to categories (1 point each)
- 3 connected items forming logical conceptual model (3 point each)
- logical structure of the model (3 point each)

The marking scheme is used to measure students’ understanding of components of conceptual knowledge categories as described in previous section. A table of scored marks for each student was established to identify their level of knowledge. The table consists of criteria of conceptual knowledge (Classifications, Models, Structure) and the knowledge categories (Model Creation, Manipulation, Exploratory Visualization, Model Transfer and Collaboration). All the data were then statistically examined and analyzed y using SPSS version 17.

9. Results of Study

The purpose of this study was to examine students’ understanding of 3D CAD modeling techniques through the construction of concept maps. Scoring procedures were applied to assess the relationship of the students’ concept maps to a reference map developed by the researchers. The data set used here is the outcome of concept map scores outlined previously (n = 33). Descriptive statistics were used to describe distribution of Scores. The data were also assessed for normality and nonparametric means of Spearman’s rho and Friedman’s test were used for skewed distribution in comparisons of the scores.

There are three criteria in this dataset that address undergraduates’ conceptual knowledge: score on Classifications (scale), score on developed Models (scale) and score on the models’ structure (scale). Preliminary examination on the concept maps reveals that majority of the students were unable to construct logical structured models of the concepts as most of the items were drawn in a chain like connections. The connections were drawn without any linking words in almost all the maps. Initial investigation of the data indicates that all five categories of the conceptual knowledge received low or zero scores for all the criteria, as illustrated in Table 2. Criteria for classification demonstrate some variation of scores for all the categories. Therefore, only results of these criteria will be presented in the following section.

Further analysis on classification criteria were carried to give an impression of the diversity within the group of students. The relative frequencies of the criteria were tested for normality with Kolmogorov-Smirnov procedure. All the attributes were found to be not normally distributed, however attribute of Model Creation is fairly close to a normal distribution. This give an impression that most of the students only being able to classify the items into this variable, which indicates that the students were only familiar with concepts of developing 3D CAD models within the boundary of a single basic CAD system. The highest score in this category is 8 with a mean of 3.90 and a standard deviation 1.86. Figure 1 shows the frequency distribution of this variable. Other variables show distribution of scores skewed (i.e. positively skewed) toward the low end of the scale.

The frequencies of the various categories of classification criteria were determined in order to give an impression of the diversity within the students. Figure 2 shows the cumulative percentage distribution of classification criteria. From the chart it was found that the scores of all the attributes were evenly distributed at low marks. More than three quarter of the students' scored below 3 for all the attributes except for the category of model creation. This indicates that students tend to understand more concepts or items for models creation compared with other attributes.

Table 2. Descriptive statistics of the concept map scores

		Criteria of Conceptual Knowledge											
		Classification				Models				Structure			
		Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum
Attributes Of Conceptual Knowledge	Model Creation	3.90	1.86	.00	8.00	.73	1.51	.00	6.00	.52	1.15	.00	4.00
	Manipulation	1.94	1.27	.00	6.00	.00	.00	.00	.00	.00	.00	.00	.00
	Exploratory Visualization	1.33	.92	.00	3.00	.00	.00	.00	.00	.00	.00	.00	.00
	Model Transfer	.38	.66	.00	2.00	.00	.00	.00	.00	.00	.00	.00	.00
	Collaboration	1.39	.92	.00	3.00	.48	1.56	.00	8.00	.30	1.05	.00	5.00

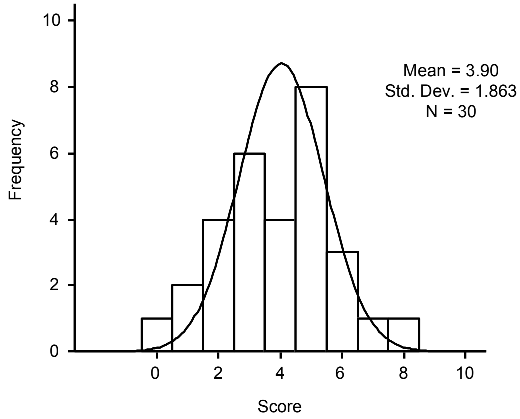

Fig. 1. Frequency distribution for *Model Creation*.

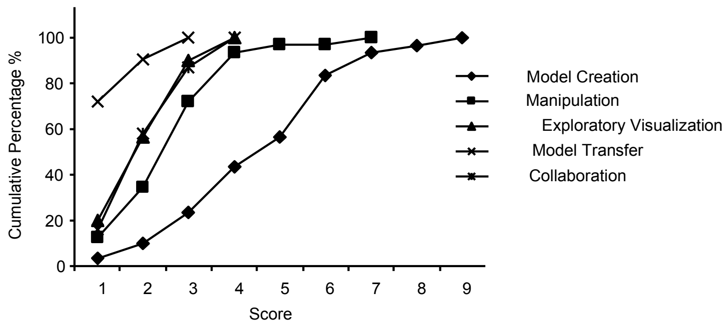

Fig. 2. Cummulitive percentage across scores.

They were inclined to utilize all available items for this category. This suggested that they are quite comfortable utilizing the software only to achieve desired objectives. In other word, they still regard the system as basic supporting tools in their own domain subjects.

Non parametric test of the variables revealed that the correlation between Manipulation and Collaboration was found to be significant (Spearman's rho=0.096, n=30, p=0.049). This monotonic relationship means that the two variables are associated but only in a general sense. It give insight that the students did not understand the meaning of manipulation by not manipulating modeled object for the purpose of finding alternatives and they did not have any ideas on how to develop CAD models collaboratively.

Friedman's test for comparison of scores resulted in $\chi^2(3) = 63.61$ and $p < 0.001$. The lowest score was Model Transfer. Multiple comparisons indicate that there was no significant difference of scores in Model Creation and Model Transfer, but there were significant difference between Manipulation and Exploratory Visualization, Manipulation and Collaboration, and Exploratory Visualization and Collaboration. This gives an indication that the students appreciate the items used in Model Creation and Model Transfer, but not in the other variables. The result indicates that there are some patterns of students' understanding of the software which will be further investigated.

10. Discussion

This study explains how concept map might be use to explore students' understanding of essential concepts in 3D CAD. Initial results of the map have provided the researcher understanding of the undergraduates' knowledge structure about the software. The results have shown a relatively low understanding of 3D CAD modeling within their own domain area. Understandings of the concepts are found to be scattered across multiple components of the knowledge. Further investigation of the constructed concept maps reveals that the students were unable to form logical structured models of the concepts.

Supplementary items or concepts which were made accessible by providing students with a random list of crucial concepts have proved to assist evaluators to investigate certain aspects of domain subject appropriately. Structural elements, generated by a numerical analysis of generated map were found to create important qualitative data about how the students construct their understanding of anticipated concepts. The maps also provide manageable means of generating qualitative data about 3D CAD abstract concepts. The results point out what the students know about 3D CAD and how they construct the knowledge in their learning experiences.

These insights are useful for educators to introduce conceptual knowledge within the systems' procedural, command or strategic knowledge while delivering instruction to students.

This study is largely explanatory, attempting to build foundation on which to base more comprehensive investigations with larger student samples for future work. A more complete picture of each student's understanding might emerge by incorporating aspects such as the shortcomings and considering the content and structure of the concept map. It will assist researchers to comprehend potential misconception about the utilization of software within a specific domain.

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