A Study of the Learning Models Employed by Industrial Design Students When Learning to Use 3D Computer-Aided Design (CAD) Software

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Abstract

3D computer-assisted design (3D CAD) software is widely used in manufacturing, and the ability to use 3D CAD software is a skill that all students majoring in industrial design or related fields are expected to acquire. Very little research has been done on the methods used to evaluate student learning in this field, and even less research has been done on the learning models adopted by industrial design students whose background is in the arts or humanities. The aim of the present study is to explore appropriate methods for evaluating the learning of students studying 3D CAD, and to examine the learning models employed by industrial design students who are learning to use 3D CAD software. The key findings of the study are as follows:

1. A method is proposed for establishing a dimension-count based learning curve with respect to declarative knowledge, which can be used to

measure the impact of procedural knowledge on the learning process, and which is suitable for both simple and complex 3D model learning analysis (and as such can be applied to the evaluation of advanced learning).

2. Wright's learning curve theory is combined with dimension-count based learning appraisal to describe the learning model employed by students when studying 3D CAD. This can then be used to evaluate the development of student learning over time, facilitating the determination of the appropriate number of hours of instruction, and thereby making the teaching of 3D CAD both more economic and more efficient.
3. The most widely used 3D CAD software programs – all of which are parametric, associative feature-based, solid modeling software programs – are all based on similar modeling principles, so the measurement and evaluation approach proposed in the present study should also be applicable to other software packages.
4. The speed at which students majoring in industrial design are able to learn 3D CAD is slower than the speed at which students majoring in engineering learn to use this software. It is suggested that strengthening industrial design majors' knowledge of basic mathematical and engineering concepts might help to improve the results achieved when learning to use 3D CAD.

Key Words: ***3D CAD*, *declarative knowledge*, *procedural nowledge*, *learning curve***

1. Introduction

In 1988, Parameter Technology Corporation (PTC) launched Pro/Engineer, the world's first parametric, associative feature-based, solid modeling CAD software package. In the two decades that have elapsed since then, parametric, feature-based, solid modeling has continued to represent the mainstream of 3D CAD software development; examples of this type of CAD software include Pro/Engineer, Solidworks, Inventor, etc. This type of software integrates basic mathematical concepts, computing technology, engineering technology, spatial geometry and modeling methods; it is widely used in machinery manufacturing and in the electronics and building industries. Lin (1999) noted the important place given to 3D CAD within the computer-aided industrial design courses at the Akademie Industrial Vormgeving Eindhoven (AIVE) in the Netherlands, and in the Digital Bauhaus industrial design curriculum proposed by Germany's Hartmut Esslinger in 1990. Zhang (2003) suggested that design education today should place increasing emphasis on the learning of CAD software, to ensure that students become familiar with the software packages that are widely used in industry; Zhang also noted that impressive results that the Art Center College of Design in the U.S. has achieved in this regard, as a result of which the Art Center's graduates are widely sought after by employers.

As a result of the division of labor in industry, and because of the improvements in productivity and competitiveness that have resulted from the adoption of digital technology, 3D CAD has become a vital tool for industrial design. In universities throughout the world, 3D CAD is one of the basic skills that all students majoring in industrial design and related subjects are required to master. Thanks to the computer revolution, 3D CAD is now in very widespread use around the world, and new versions of 3D CAD software packages are being released all the time, creating significant demand for training provision. Both in industry and in the university sector, 3D CAD education and training is an important field (Desrochers, 2002; Sapidis & Kim, 2004; Rossignac, 2004), and a field which raises significant questions. However, very little research has been done on 3D CAD education and training in Taiwan, and most of the research that has been undertaken on this subject in other countries has focused on the disciplines of mechanical and electrical engineering (Kodali & Bhattacharya, 1989; McDermott & Marucheck, 1995; Sugita, 1999; Hamade, Artail, & Jaber, 2007); there has been a pronounced lack of research on 3D CAD learning by students who do not have an engineering background. The author of this paper has over ten years' experience in teaching 3D CAD, of which nearly ten years were spent teaching students majoring in industrial design or related subjects. These students generally have an understanding of aesthetics, plastic theory and design methods, but they lack mathematical knowledge, and their thinking processes are significantly different from those of students with an engineering background. There are been very little research on how this type of student approaches the learning of 3D CAD, which is heavily engineering- and mathematics-oriented. The present study explores the learning models adopted by students majoring in industrial design and related subjects when learning to use 3D CAD software, and the effectiveness of these models. It is anticipated that the results obtained in this research will constitute a useful reference for the improvement of 3D CAD teaching in the industrial design field, and will contribute to enhancing the 3D CAD capabilities of students majoring in industrial design.

2. Review of the Literature

2.1 The Main Characteristics of 3D CAD Software

The origins of CAD software can be traced back to 1962, when Ivan E. Sutherland proposed the concept of computer-aided design in his Ph.D. thesis at the Massachusetts Institute of Technology (MIT): "Sketchpad – A Man-Machine Graphical Communication System." What was originally just a doctoral thesis was to have a major and totally unexpected impact on the worlds of design and manufacturing; over time, CAD evolved to become a technology of great importance to human society. Elsas & Vergeest (1998) point out the following advantages that accrue from introducing computer-aided design at an early stage in the design process: (1) It can improve the quality of the concept design. (2) It permits the rapid creation of alternative designs. (3) It provides a basis for effective communication and appraisal in situations where several alternative designs have been developed. (4) Decisions made at an early stage in the design process can have a major impact on overall design cost; the use of CAD helps to reduce unnecessary expenditure due to errors in the early stages of the design process. Hsu (2004) notes that, whereas in the past most of the research on CAD focused on the later stages in the design process, recently there has been an increase in the number of studies focusing on the early stages of the process, and particularly on the initial design concept development. With the ongoing evolution of computer software, and of information technology in general, CAD has gradually developed into a reliable, highly effective tool for creative design work; the ability to use CAD is now a skill that all industrial designers are expected to possess.

The different 3D CAD systems that are currently available can be divided into two broad categories: surface model (such as Alias, Rhinoceros, etc.), and solid model (Solidworks, Inventor, etc.). The main focus of 3D CAD software development today is on integrating these two models (Wu, 1997). The surface model is very effective for constructing forms with complex curved surfaces, while the solid model provides precise, accurate dimension design for 3D solids. Surface model 3D CAD systems mostly employ the Non-Uniform Rational B-Spline (NURBS) model, which uses mathematical equations to define shapes. In shape design work, NURBS provides a high level of control over curves and surfaces, while at the same time ensuring that curves remain smooth. In addition, the real-time control and display capability that NURBS provides allows design to proceed without interruption. In 1989, the firm Evans & Sutherland launched CDRS, the first software package to make use of NURBS. In 1995, PTC bought CDRS from Evans & Sutherland, and integrated it into Pro/Engineer as a “Style” module. This integration of NURBS into Pro/Engineer created the world’s first parametric, associative feature-based, solid modeling CAD software package with NURBS surface-modeling capability. It used a single database for every stage from design through to manufacturing, which helped to reduce product development time (Wu, 2007). This, together with the comprehensive range of functions that it offered, has made Pro/Engineer a very widely used software package in the manufacturing sector;

Pro/Engineer enjoys particularly strong competitive advantage in terms of digital data transfer capability (Liu, 2003; Ni, 2005).

2.2 3D CAD Training

Bhavnani, John and Flemming (1999) point out that even users who have undergone formal training and have years of experience still continue to employ inefficient techniques when using complex CAD systems. Their experiments showed that the adoption of command-teaching that incorporated sketch construction strategy and the formulation of a clear layout before trying to construct the sketch led to a significant improvement in drawing efficiency, and helped to eliminate the use of inefficient techniques.

Ye, Peng, Chen and Cai (2004) combined a review of the literature with a questionnaire survey administered to leading international CAD firms that divided CAD-related personnel into four categories: CAD users, CAD application developers, CAD software developers, and CAD managers. Their results showed a need for all CAD-related personnel to acquire basic computer science, mathematical and design methodology skills in university; in addition, CAD application developers, CAD software developers and CAD managers also required other, more advanced skills training. The survey of CAD training in the electronics/communication industry by McDermott and Marucheck (1995) showed that classroom-based training provided greater familiarity with CAD technology management, while more informal training methods could be tailored to changing work requirements, but resulted in a lower level of mastery than classroom-based training.

Lang, Eberts, Gabel and Barash (1991) note that, while the job-related knowledge that CAD operators need to possess includes both declarative and procedural knowledge, most CAD training programs focus on declarative knowledge training, while neglecting procedural knowledge. Their study involved experimental analysis with respect to CAD basics, CAD system experts (users who were already familiar with the software used in the experiment), and design experts. Their results showed that, if the system experts failed to use procedural knowledge, the results that they achieved were no better than those achieved by the design experts; however, if the system experts did use procedural knowledge, then their results were superior to those of the design experts. The performance of both design experts and CAD basics with respect to declarative knowledge was poor; this was because both groups were unfamiliar with the software used in the experiment. These results suggest that procedural knowledge can be applied to different CAD software packages with different interfaces. Garcia, Santos, Quiros and Penin (2007) noted that, when Spain undertook large-scale reforms of the university curriculum in the 1990s, CAD was selected as a foundation course for many technical disciplines. Subsequently, instructors experimented with a range of different methods and different software to teach CAD. Over time, there was a gradual increase in the amount of time allocated for practical training, and instructors came to feel that giving sizeable amounts of homework was more effective than relying on traditional end-of-term exams. However, three major problems were encountered on the practical training side: (1) How to prevent students from copying other people's work? (2) How to overcome PC and software shortages? (3) Should evaluation focus on CAD knowledge or drawing skill? Many instructors felt that dedicated training software should be developed that would incorporate all of the basic commands, rather than using commercial CAD software. Most universities only teach the use of commercial software packages. Given that students may need to use these software packages in the workplace, learning how to use them is certainly important, but it should be borne in mind that the software companies concerned are constantly releasing new versions and new software packages, so that the packages students learn now may become obsolete in the future. The authors of this study suggested that universities did not necessarily need to teach specific commercial software packages; they should focus on teaching the basic principles of CAD usage. Currently, however, many university professors continue to use commercial CAD software when teaching CAD.

From the beginner's point of view, traditional classroom-based instruction is still vitally important; this type of instruction is more effective at imparting basic CAD management skills. The job-related knowledge required in 3D CAD training includes both declarative and procedural knowledge. The reason why it is so important for anyone involved with CAD to possess basic mathematical and engineering knowledge is because this strengthens their ability to acquire procedural knowledge. At the same time, there are significant differences in the knowledge required to operate different software packages; this is where procedural knowledge comes in. This is an area where attitudes in the university sector differ markedly from those in industry. University professors normally feel that the emphasis when learning CAD should be placed on procedural knowledge, whereas in industry it is generally felt that CAD training should focus on learning how to use commercial software packages. So far, there have been no examples of the successful widespread adoption of CAD software designed specifically for teaching purposes; university-level instructors both in Taiwan and overseas continue to use commercial CAD software packages for teaching CAD, because students who have learned how to use these software packages in university find it easier to get a job after graduation.

2.3 Evaluation of 3D CAD Learning

The concept of the learning curve has applications in many different fields. In the field of education and training, it can be used to evaluate student learning speed with respect to different teaching methods. From the point of view of controlling training costs, the learning curve can also help to identify the point at which student learning has progressed to the point where formal training activities can be terminated (Hamade, Artail and Jaber, 2005). Over the years, a variety of different learning curves have been proposed for capturing behavioral performance in repetitive tasks, but that proposed by Wright (1936) remains the most widely used for research purposes because of its simplicity and its ability to provide a good fit with the empirical data (Yelle, 1979; Lieberman, 1987; Jaber and Bonney, 1997; Hamade, Artail and Jaber, 2007). Wright’s learning curve equation is expressed as follows:

$$y(n) = y(1) * n^{-b}$$

$y(n) =$ production time of the n^{th} learning iteration

$y(1) =$ production time of the 1^{st} learning iteration

$n =$ number of iterations

$b = \frac{\log \phi}{\log 2}$ (learning index)

$\phi =$ learning slope $\left(0 \le \phi \le 1\right)$

The higher the learning slope (ϕ), the faster the learning speed.

Dar-El, Ayas and Gilad (1995) propose a dual-phase model that can be employed to describe most industrial work tasks (tasks that involve both cognitive skill and motor skill learning behavior). This learning curve model proposes that, in the initial phase of the learning process, cognitive skill is the most important factor. Subsequently, as the learning process progresses, learning based on cognitive skills gradually declines, and learning based on motor skills becomes dominant. Experiments were conducted to confirm this dual-phase learning curve model (Figure 1). This study also found that cognitive skill has less impact on simpler work tasks. The process of learning 3D CAD involves complex tasks where both cognitive skill learning and motor skill learning are taking place, so the dual-phase learning curve model can be used to describe this learning process. The dual-phase learning curve equation is expressed as follows:

$$y(n) = \{y_c(1) + y_m(1)\} * n^{-b} = y_c(1) * n^{-b_c} + y_m(1) * n^{-b_m}$$

$y(n) =$ the production time of the n^{th} learning iteration

$y_c(1) =$ the production time of the 1^{st} cognitive skill learning iteration

$y_m(1) =$ the production time of the 1^{st} motor skill learning iteration

$n =$ number of iterations

$b_c = \frac{\log \phi_c}{\log 2}$ (cognitive skills learning index)

$b_m = \frac{\log \phi_m}{\log 2}$ (motor skills learning index)

$\phi_c =$ cognitive skills learning slope $\left(0 \le \phi_c \le 1\right)$

$\phi_m =$ motor skills learning slope $\left(0 \le \phi_m \le 1\right)$

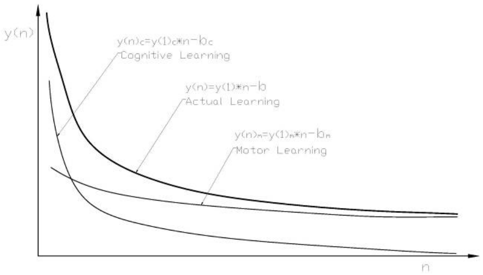

Figure 1 Dual-phase Learning Curve Model

3. Research Methodology

The present study is based on teaching implemented three hours per week for a period of one semester, using 20 students in their second year in university (from the author's department) who had already had one semester of basic training in 2D CAD (AutoCAD). The teaching materials and methods used are described below:

3.1 Teaching Materials

In the present study, the Pro/Engineer textbook *Pro/Engineer Wildfire Basics and Examples* (2007) by Lin Ch'ing-An, written specifically for university and junior college courses, was used both for in-class teaching and as a reference book that the students could use when practicing with the software on their own. The contents of this book were used during class to guide the students' learning and gauge the progress they had made, while also making use of additional teaching materials, and providing the students with video material produced by the author of this study for use in self-study.

3.2 Teaching Methods

Approaches to the teaching of 3D CAD fall into two broad categories: bottom-up and top-down. With the bottom-up approach, the instructor begins with a general introduction to the functions and applications of the different commands, before going on to introduce the construction of models for different product types, so that students can practice using the commands that they have learned to create a complete model. With the top-down approach, the learning process starts with sample product models; the students learn the different commands by seeing how the model is constructed stage-by-stage. As 3D CAD software has evolved, both the number of command types and the number of individual commands have grown dramatically, making bottom-up learning a very long and tedious process, in which it can be very difficult to keep students motivated. If the top-down approach is employed, the use of different example models (of gradually increasing complexity) can help to provide motivation and give students a sense of achievement. Today, the top-down method is more common in the teaching of 3D CAD, and it is this approach that is used in the present study.

3.3 Evaluation

Very little research has been done (either in Taiwan or overseas) on the evaluation of 3D CAD learning. The present study uses the four solid models for the evaluation of beginners proposed by Hamade, Artail and Jaber (2007) (Figure 2). The four models are all of a similar level of difficulty, but are significantly different from one another, so that students are not creating the same shapes in each model. Using similar principles, the author developed three advanced solid models (Figure 3), so as to make it possible to study the learning models employed by students when constructing both simple and complex models. Evaluation was performed in the 4th, 8th, 12th and 16th weeks of the semester. In the 4th week, only basic-level evaluation was performed; in the 8th, 12th and 16th weeks, both basic-level and advanced-level evaluation was performed. Before evaluation began, students had 1 minute to examine the model and ask questions about it. The time that each student took to construct the model was recorded.

Basic Evaluation Model 1

Basic Evaluation Model 2

Basic Evaluation Model 3

Basic Evaluation Model 4

Figure 2 Solid Models for Basic-level Evaluation

Advanced Evaluation Model 1

Advanced Evaluation Model 2

Advanced Evaluation Model 3

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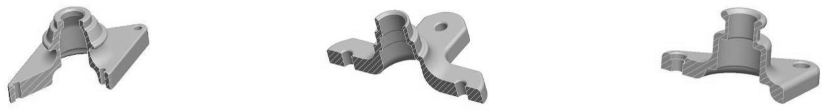


Section View of Model 1 Section View of Model 2 Section View of Model 3

Figure 3 Solid Models for Advanced-level Evaluation

Knowledge can take the form of declarative knowledge or procedural knowledge. Procedural knowledge is knowledge derived from the subject's intelligence, the education and training they have received, instinctive understanding, etc. The question of how procedural knowledge can be captured from industrial job-tasks has been a major focus of interest among researchers. Watkins, Dimopoulos, Neville and Li (1993) developed an exert system software tool for retrieving procedural knowledge, which can be applied to engineering system diagnosis and discrimination. In 3D CAD learning, the number of instructions selected from the functions list in the course of constructing the entire model is often used to measure knowledge acquisition. Lang, Eberts, Gabel and Barash (1991) use Goals, Operators, Methods, Selection (GOMS) rules to represent the information used in model construction during CAD training. This highly practicable method makes it possible to record the interaction between the CAD user and the software (including both the user's internal thought process and the visible instructions used). The study by Lang, Eberts, Gabel and Barash uses the Keystroke Level Model (KLM) to evaluate and analyze the number of picks/keystrokes and the pause time between strokes in the process of model construction. This method is difficult to use, and not sufficiently precise, as it does not take cancelled and redone operations into account. Hamade, Artail and Jaber (2007) propose an indirect measurement method that measures the time required to construct the model (including time spent undoing and redoing actions) and the number of construct features. This study found that, when students use complex, difficult instructions to create features, the number of features on the completed model was lower, and less time was required to complete construction of the model. Since this falls under the category of declarative knowledge, it can be used to distinguish between declarative and procedural knowledge, and to complete the establishment of the learning curve. However, the emphasis in the teaching of parametric, associative feature-based CAD software is on model construction strategies that combine a reasonable number of features with rapid completion time (Lin, 2004; K'ang, 2005; Kuo, 2006), rather than aiming for the smallest possible number of features. It therefore seems more reasonable to specify the geometric constraints and the required dimensions.

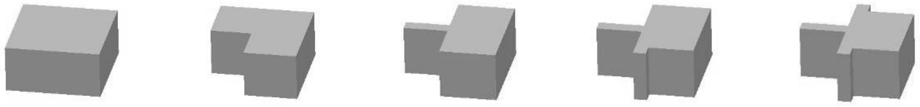
4. Results and Analysis

4.1 Learning Evaluation

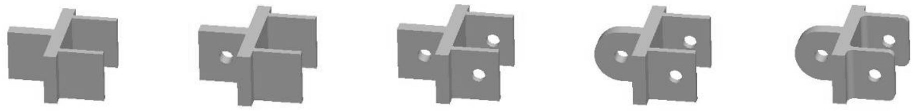
In associative, feature-based CAD models, solids are formed using protrusion, revolving, sweeping, blending, etc. Designers make use of different solid construction methods to complete the process of building the product model in line with their own construction strategy. Individual designers have varying levels of expertise, so there is considerable variation in the strategies and methods that designers use. While all of these different strategies may get the job done, in terms of efficiency some are much better than others. Taking Basic Evaluation Model 3 as an example, Figures 4 and 5 show possible procedures for constructing this model. The procedure shown in Figure 4 uses 10 features; this is the kind of inefficient method that beginners use. By contrast, the procedure shown in Figure 5 uses only two features (the smallest possible number of features). The 2D sketches for this procedure are not especially complex, and the procedure is highly efficient, mainly because of the effective application of procedural knowledge. The 2D sketches for Features 1 and 2 use 7 dimension definitions and 12 dimensions respectively (all set by the designer). The constraints used include horizontal, vertical, tangent, equal, alignment, horizontal alignment, etc.; the two features use 12 constraints and 37 constraints respectively (most of these are set automatically by the CAD system).

Figure 6 shows a procedure for Advanced Evaluation Model 1 that uses 3 features (the smallest possible number). The 2D sketch for Feature 1 of this procedure is shown in Figure 7; it uses 33 dimensions (all set by the designer) and 41 constraints. In reality, using these complex geometrical definitions reduces the efficiency of model construction, for the following reasons: (1) The geometrical shapes are so complex as to exceed the ability of most people to remember and analyze them; they violate the basic design principle that one should strive to keep things as simple as possible. (2) The definitions and constraints in the 2D sketches affect each other, creating a high risk that the designer will lose control over the shapes. (3) A correct model depends on correct geometrical forms (i.e. all of the dimensions and constraints must be correct); if any of the definitions are incorrect, the whole model will be incorrect, and feature development may fail. The use of this procedure would also make error correction more difficult and time-consuming, further reducing the overall efficiency of the procedure. Figure 8 shows an alternative procedure for constructing Advanced Evaluation Model 1. Here, Feature 1 of the previous procedure (shown in Figure 7) is broken down into Procedures 2 – 6. The advantage of adopting this procedure is that it simplifies the geometrical shapes, making them easier to control. Breaking up the feature in this way also reduces the extent to which individual dimensions and constraints affect one another, and makes error correction easier to perform. Features 3, 5 and 6 make use of rounded corner and chamfering features, and specify 7 dimensions; as shown in Figure 9, the 2D sketches for Feature 2 use 9 dimensions and 9 constraints, while the drawings for Feature 4 use 9 dimensions and 10 constraints. Although the second procedure uses more features (5 features), from the point of view of model construction it is more efficient, and the number of dimensions and constraints that need to be specified is lower. Between them, the rounded corner features 3 and 5 use only 6 dimensions, which would facilitate future design changes and feature management, without making any significant difference to the time needed for model construction. Design alterations are an inevitable part of the product development process. With the trends towards diversification of market demand and towards shorter product lifespan, the frequency of design alterations has risen, so when developing a design model, the designer needs to take the question of design alteration into consideration. Figure 10 shows the problems that can result if one fails to allow for the possibility of design alterations into consideration when creating the 2D sketches; in the worst-case scenario, it may be impossible to update the model. Figure 11 shows 2D sketches that allow for the possibility of future design alterations, and can support them, thereby reducing the risk of failure in model updating.

Here, the 2D sketch for Feature 1 uses 2 equal constraints to replace the dimensions of diameter 10 and radius 5, while the 2D sketch for Feature 2 uses 3 alignment, 1 symmetry and 3 equal constraints to replace the dimensions 80, 80, 80, 25, 35, 10, 5. It is normal practice to use constraints to allow for the possibility of design alteration, and there is an inverse relationship between the number of constraints and the number of dimensions. The impact of the 2D sketches on ease of design alteration can also be seen in Figure 12, which shows Advanced Evaluation Model 1. It can be seen from the above that the incorporation of expert procedural knowledge into model construction makes for greater efficiency, while reducing the number of dimensions that need to be used.

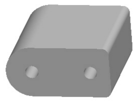


Feature 1: basic block　Feature 2: left-front cut　Feature 3: left-back cut　Feature 4: right-front cut　Feature 5: right-back cut

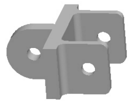


Feature 6: right-middle cut　Feature 7: left hole　Feature 8: right hole　Feature 9: left rounded corner　Feature 10: right rounded corner

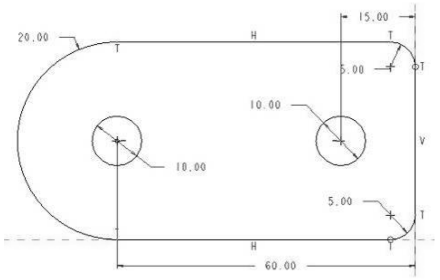
Figure 4　Procedure 1 for Constructing Basic Evaluation Model 3



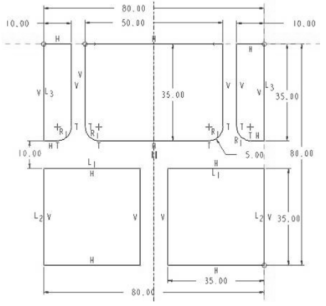
Feature 1: basic block



Feature 2: top cut



2D sketch of Feature 1



2D sketch of Feature 2

Figure 5　Procedure 2 for Constructing Basic Evaluation Model 3

Feature 1: basic block

Feature 2: cutting hole through base

Feature 3: round off all sharp corners on base

Figure 6 Procedure 1 for Constructing Advanced Evaluation Model 1

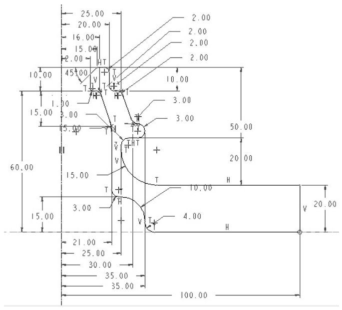
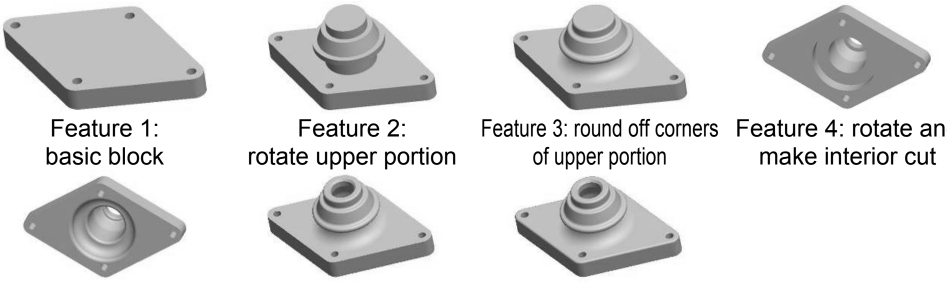


Figure 7 2D Sketch for Feature 1 of Advanced Evaluation Model 1



Feature 1: basic block

Feature 2: rotate upper portion

Feature 3: round off corners of upper portion

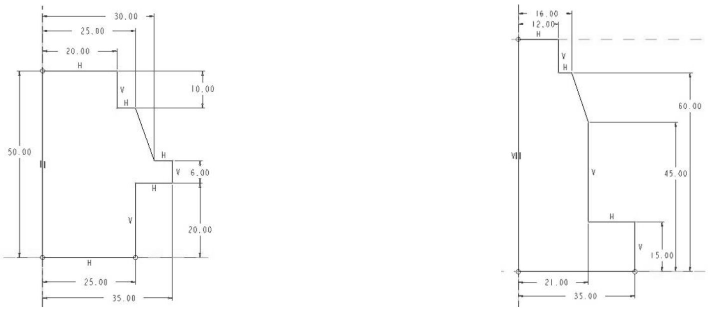
Feature 4: rotate and make interior cut

Feature 5: round off interior

Feature 6: chamfer top

Feature 7: round off corners on base

Figure 8 Procedure 2 for Constructing Advanced Evaluation Model 1



2D Sketch:
Feature 2 (rotation of upper portion)

2D Sketch:
Feature 4 (rotation and interior cut)

Figure 9 2D Sketches for Features 2 and 4 of Advanced Evaluation Model 1

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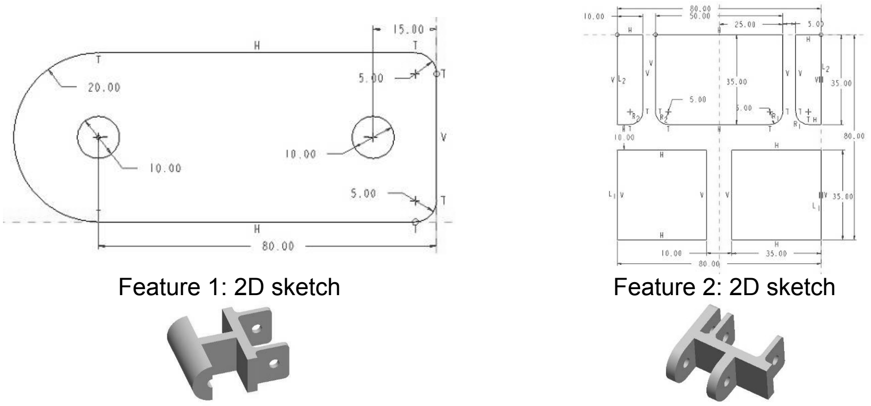


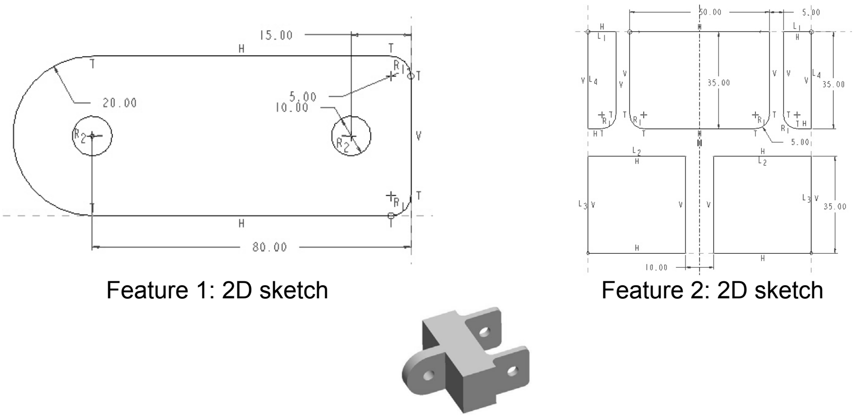
Feature 1: 2D sketch

Feature 2: 2D sketch

Design change – Result 1
(left hole distance change from 60 to 80)

Design change – Result 2
(extrusion change from 80 to 90)

Figure 10 Impact on Design Alteration of 2D Sketches that Did Not Take the Need to Allow for Design Alteration into Account

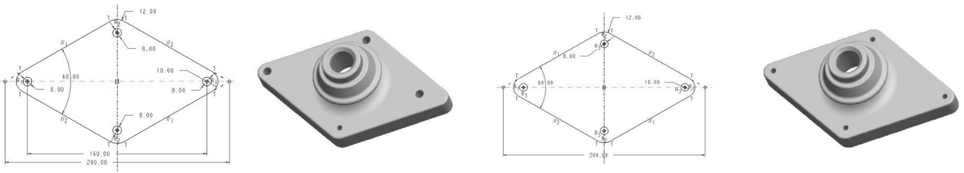


Feature 1: 2D sketch

Feature 2: 2D sketch

Design change – Result 3

Figure 11 Impact on Design Alteration of 2D Sketches that Did Take the Need to Allow for Design Alteration into Account



Possible need for design alteration not taken into consideration

Design alteration: Result 1

Possible need for design alteration taken into consideration

Design alteration: Result 2

Figure 12 Impact of 2D Sketches on Design Alteration in Advanced Evaluation Model 1

4.2 Empirical Results and Analysis

The test results obtained for Basic Evaluation Model 1 (4th Week) through to 4 (16th Week) are shown in Figure 13. Student 1 had the fastest completion time; Student 20 had the slowest completion time. With practice, the amount of time that the students needed to construct the models tended to fall. Figure 14 presents the data in four histograms, taking each evaluation model as a unit. In the histogram for Basic Evaluation Model 1 (in the 4th Week), it can be seen that the shortest time required to complete construction of the model was 18 minutes, while the longest time was 37 minutes. The average times for the evaluation tests conducted in the 4th, 8th, 12th and 16th weeks were 25.4 minutes, 17.6 minutes, 16.3 minutes and 14.5 minutes, respectively; the corresponding standard deviations were 4.838, 4.07, 3.13, and 2.819, respectively. It can be seen that completion time continued to fall over time, but that the greatest improvement was obtained early on. From the standard deviation, it can be seen that the students' completion times showed the highest degree of dispersal in the 4th Week, and that the completion times became more concentrated over time. The student of 3D CAD learning performance by students with an engineering background by Hamade and Artail (2007) found that the average completion times for Evaluation Models 1 – 4 were 27.3 minutes, 14.7 minutes, 9.6 minutes and 8.4 minutes respectively. The inferior performance of the industrial design students may reflect weaker knowledge of geometry and engineering concepts.

Figure 15 shows the results of performing regression analysis on the test data for Basic Evaluation Models. The curve that is obtained conforms to Wright's Learning Curve Equation (1), with the following values: $y(1) = 42.42$, $b = 0.3965$; regression curve fit is very good ($R^2 = 0.9543$). This curve could be used to predict the theoretical limitations on the learning performance of students with respect to 3D CAD training. It can be seen that the curve is very steep initially, representing rapid progress; as the amount of training that students have received increases, the rate of progress falls. Once the curve is more or less flat, the learning goals for that stage have been achieved; from an economic point of view, this is the time to end the training. The test results for Advanced Evaluation Models 1 – 3 are shown in Figure 16. To ensure a good

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match with the test results for the Basic Evaluation Models, ranking was performed according to the rank order shown in Figure 13. In Advanced Evaluation Model Tests 1 and 2, Student 1 had the fastest completion time, while in Advanced Evaluation Model Test 3 it was Student 9 who recorded the fastest time. Students 18 and 20 displayed the most improvement in the three Advanced Evaluation Model Tests; most students continued to display improvement in their completion time.

Figure 17 shows the histograms for Advanced Evaluation Models 1 – 3 (arranged from top to bottom). As the students received more training in the use of 3D CAD, their completion times for the Advanced Models fell; the average completion times for the three tests (in the 8th, 12th and 16th weeks) were 46.2 minutes, 36.5 minutes and 28.9 minutes, respectively, with standard deviation of 10.536, 8.733 and 5.34, respectively, showing that the students' performance became more concentrated as they received more training. These results are very similar to those presented in Figure 14 for Basic Evaluation Models 1 – 4. Over the 16-week semester, the standard deviation was 2.819 for the Basic Evaluation Model Tests and 5.34 for the Advanced Evaluation Model Tests, reflecting the greater difficulty of the Advanced Evaluation Model Tests. Figure 18 shows the learning curve for the Advanced Evaluation Model Tests; the curve presents the following values: $y(x) = 186.16x^{-0.6654}$, $R^2 = 0.9908$; this curve also displays good fit.

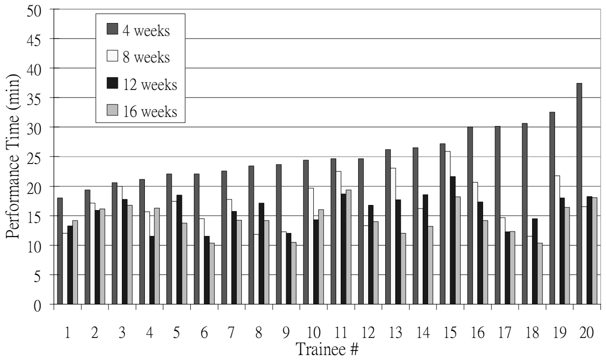

Figure 13 Test Results for Basic Evaluation Models 1 – 4

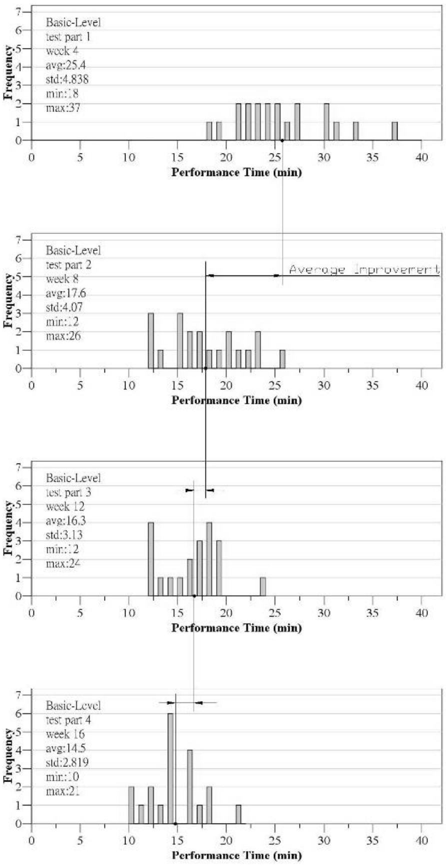

Figure 14 Histograms for Basic Evaluation Model Tests 1 – 4 (top to bottom). The dots indicate the average completion time for each test.

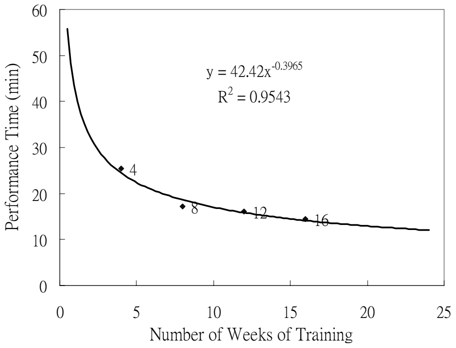

Figure 15 Learning Curve Regression Curve for Basic Evaluation Model Tests 1 – 4.

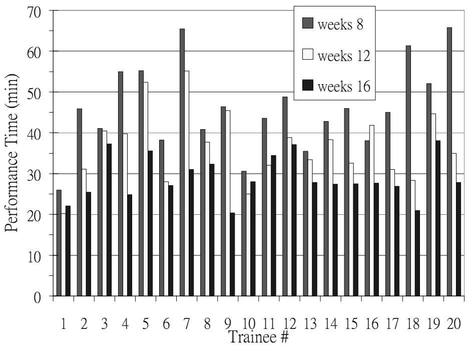

Figure 16 Test Results for Advanced Evaluation Models 1 – 3

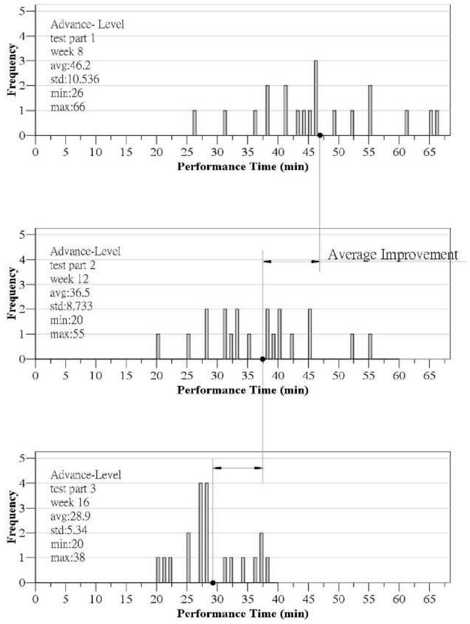

Figure 17 Histograms for Advanced Evaluation Model Tests 1 – 3 (top to bottom). The dots indicate the average completion time for each test.

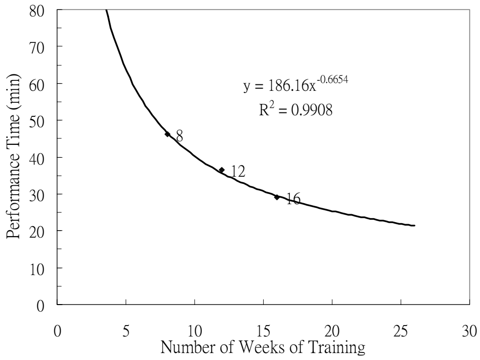

Figure 18 Learning Curve Regression Curve for Advanced Model Tests 1 – 3.

Overall learning performance includes both procedural and declarative knowledge. Procedural knowledge is access through the testee’s own internal thought processes; the question of how procedural knowledge is captured from work-tasks has been a major focus of interest among researchers. Owing to the difficulty of implementing accurate direct measurement, Hamade, Artail and Jaber (1997) proposed employing indirect measurement whereby the use of the smallest number of features would be deemed to represent the best performance; they suggest that, where students are able to complete model construction in the shortest possible time and using the smallest number of features, this represents the demonstration of acquired knowledge, and also makes it possible to distinguish between declarative knowledge and procedural knowledge. Figure 19 shows the average number of features used in each of the basic and advanced evaluation model tests. It can be seen that, while the average number of features used in the basic tests fell as the students received more training in the use of 3D CAD, this was not the case with the advanced tests. With a simple 3D model (such as those used in the basic evaluation model tests), it may be feasible to use the number of features employed to represent the student's declarative knowledge, but as the models grow more complex, the procedure that uses the smallest number of features is not necessarily the most efficient. Figure 20 shows the average number of dimensions used in each of the basic and advanced evaluation model tests. Here, the number of dimensions used tends to fall for both the basic and advanced tests as students receive more training. As the models used in the basic evaluation tests are relatively simple, the number of dimensions required is lower, and so the fall in the number of dimensions used over time is less pronounced, while the decrease is more noticeable for the more complex advanced tests; this is as might be expected. As noted above, keeping the 2D sketches simple and allowing for the possibility that design alterations may need to be made will both cause the number of dimensions used to fall. The number of dimensions used can thus be employed as an indirect means of measuring procedural knowledge for both simple and complex models; this is an appropriate method for distinguishing between declarative and procedural knowledge, and for establishing a learning evaluation model. Figures 21 and 22 show the relationship between the number of dimensions used and the completion time for the basic and advanced models respectively. It can be seen that, as the number of dimensions used falls, completion time falls too. This improvement can be attributed to the following factors:

A.Declarative knowledge factors (see Hamade, Artail, and Jaber, 2007):

1. As the training progresses, the student will build up experience in using drawing tools; this is related to motor skills.
2. Students will become more familiar with the graphical user interface and the location of the different commands within the menus.

B.Procedural knowledge factors:

1. The adoption of appropriate design strategies leads to simpler 2D sketches.
2. As students become aware of the need to allow for future design alterations, their 2D sketches become more streamlined.

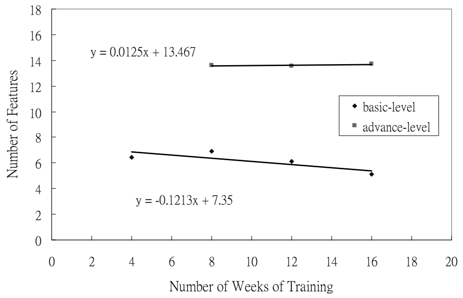

Figure 19 Average No. of Features Used in the Basic and Advanced Evaluation Tests

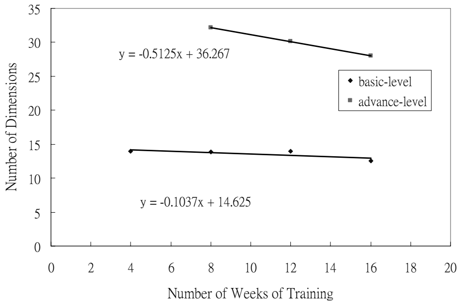

Figure 20 Average No. of Dimensions Used in the Basic and Advanced Evaluation Tests

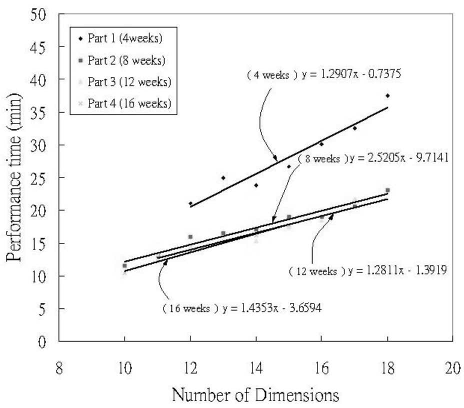

Figure 21 The Relationship between Basic Evaluation Model Test Completion Time and the No. of Dimensions Used

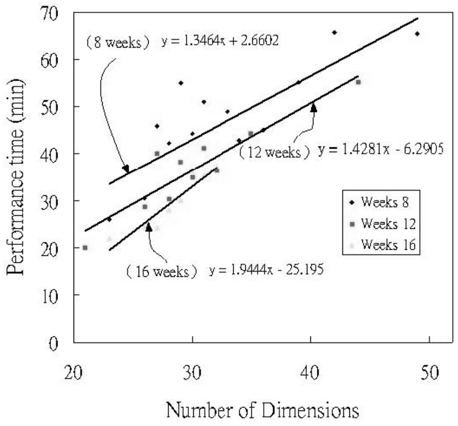

Figure 22 The Relationship between Advanced Evaluation Model Test Completion Time and the No. of Dimensions Used

The declarative knowledge learning curve can be used to segregate the procedural knowledge learning curve from the overall learning curve. Using the data from Figure 21, we made a transform-drawing of five regressive curves (with the number of dimensions remaining constant in each curve), to which was added the overall learning curve. As shown in Figure 23, the number of dimensions used for the individual curves (from bottom to top) was 10, 12, 14, 16, and 18, respectively; the slope of each curve was 0.2692, 0.3056, 0.3286, 0.3445, and 0.3561, respectively, and the value of $y(1)$ was 22.077, 30.081, 38.101, 46.127, and 54.156, respectively. All of the curves display a sharp upward rise; even when the number of dimensions is relatively large, the values of the slope and of $y(1)$ are high.

It can be seen from Figures 21 and 22 that there is positive correlation between the average time taken to construct a model and the average number of dimensions used. The smallest number of dimensions used in the model evaluation tests was 10; the student who used the smallest number of dimensions was also the student with the fastest completion time. This represents the performance of declarative knowledge. The optimal declarative knowledge learning curve for the class in question can be shown as the bottom curve in Figure 23 (with a slope of 0.2692). If this situation is expressed using the dual learning curve model of Equation (2), then the equation can be expressed in the following form:

$$y(x) = y_p(1) * x^{-b_p} + y_d(1) * x^{-b_d}$$

(Dar-El, Ayas, and Gilad, 1995; Hamade, Artail, and Jaber, 2007), where $y_p(1) * x^{-b_p}$ and $y_d(1) * x^{-b_d}$ represent the procedural knowledge learning curve and declarative knowledge learning curve respectively. Therefore:

$$y_d(1) * x^{-b_d} = 42.42x^{-0.3965} - 22.077x^{-0.2692} = 24.359x^{-0.6832} \quad \text{(Figure 24).}$$

By employing the number of dimensions used to derive a declarative knowledge learning curve and then using the inference approach outlined above, it is possible to measure the impact of procedural learning during the learning process.

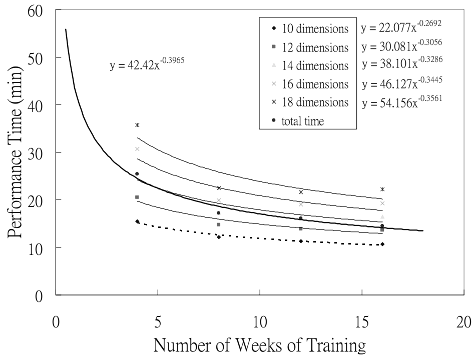

Figure 23 The Declarative Knowledge Learning Curves Corresponding to the Use of 10, 12, 14, 16 or 18 Dimensions in Model Construction

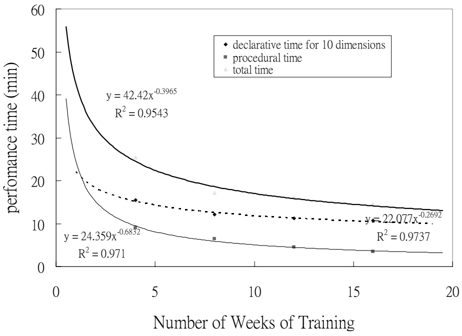

Figure 24 The Procedural Knowledge Learning Curve, Declarative Knowledge Learning Curve, and Overall Learning Curve for Basic Evaluation Model Construction

5. Conclusions and Recommendations

Today, 3D computer-assisted design (3D CAD) software is widely used in the manufacturing of industrial products, and has become a required skill for people working in manufacturing-related fields. In Germany, Hartmut Esslinger included 3D CAD in the Digital Bauhaus industrial design curriculum that he proposed in 1990. By studying the learning models that industrial design students employ when learning 3D CAD, and by establishing suitable evaluation methods, it should be possible to achieve an improvement in 3D CAD training efficiency. The conclusions reached in the present study, and the recommendations put forward, are as follows:

1. The method of using the number of dimensions to derive a declarative knowledge learning curve that is proposed in this study can be used to measure the impact of procedural knowledge on the learning process. It can be applied to the analysis of both 3D CAD learning that used simple 3D models and learning that employs more complex models, and is thus suitable for the evaluation of both basic- and advanced-level 3D CAD training.

2. By using the measurement techniques outlined above, and applying Wright's learning curve theory to describe the learning models employed by students when learning 3D CAD, the way in which students' learning develops over time can be analyzed, thereby making it possible to allocate an appropriate number of teaching hours, ensuring that the teaching is both efficient and cost-effective.
3. The most widely used 3D CAD software programs – all of which are parametric, associative feature-based, solid modeling software programs – are all based on similar modeling principles, so the measurement and evaluation approach proposed in the present study should also be applicable to other software packages (such as Solidworks, Inventor, etc.).
4. The speed at which students majoring in industrial design are able to learn 3D CAD is slower than the speed at which students majoring in engineering learn to use this software. This may be because industrial design students lack knowledge of basic mathematical and engineering concepts. One area for future research would be to analyze their needs in this regard, so as to facilitate the compilation of suitable supplementary teaching materials that could be used to improve students' learning results.

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