AC 2012-4690: A COMPARATIVE ANALYSIS OF 3D PARAMETRIC SURFACE MODELING AND FREEFORM MESH MODELING AS TOOLS FOR INVESTIGATING STUDENT LEARNING

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A Comparative Analysis of 3D Parametric Surface Modeling and Freeform Mesh Modeling as Tools for Investigating Student Learning

Abstract

This paper investigates the effectiveness with which similar outputs can be produced from two 3D CAD packages that employ different modeling approaches. The modeling approaches in question are parametric NURBS[1] (Non-Uniform Rational B-Spline) surface modeling and polygonal freeform modeling. The former refers to the creation of organic geometry using 2D sketches and building standalone faces between sketches [fig1], the latter refers to taking an existing geometric shape and "sculpting" it into a desired form with manipulation of faces and edges[fig2]. The advantages and dis-advantages of parametric and freeform modeling of organic, complex shapes are numerous and disputable. Parametric surface modeling is advantageous in creating well defined functional geometry but is not considered to easily allow for design iteration[2]. Freeform mesh modeling alternatively allows a more flexible approach in design but commonly results in unusable geometry from a manufacturing or rapid prototyping perspective. There are various software packages that facilitate one or sometimes both modeling approaches. This study aims to investigate these approaches to 3D modeling using third level Product Design students as test subjects. As suggested by software companies and existing research, each approach has its merits in visualisation, manufacturability and difficulty to achieve design intent. The central aim of this study is to evaluate the two modeling approaches.

Introduction

[Students in the study participated in 2 design tasks, the first to create a design using the parametric approach, and the second task using the freeform mesh modeling approach. Each task involved the creation of similar real world objects that employ organic form. Both design tasks required the students to produce digital 3D models to visually represent their concepts. A separate 3D modeling software package was used for each task. The concept of organic surface creation was new to each participant, all of whom had 3D graphical experience exclusively in solid geometric modeling. Through the paradigm of Project Based Learning, a scaffolded approach encouraging student exploration and experimentation was employed across the study.

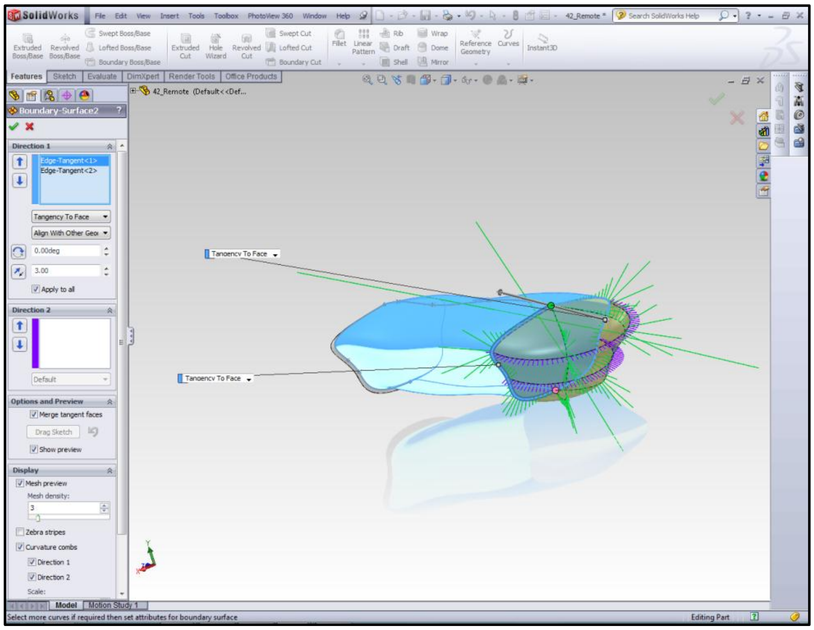


Figure 1 - Parametric surface modeling

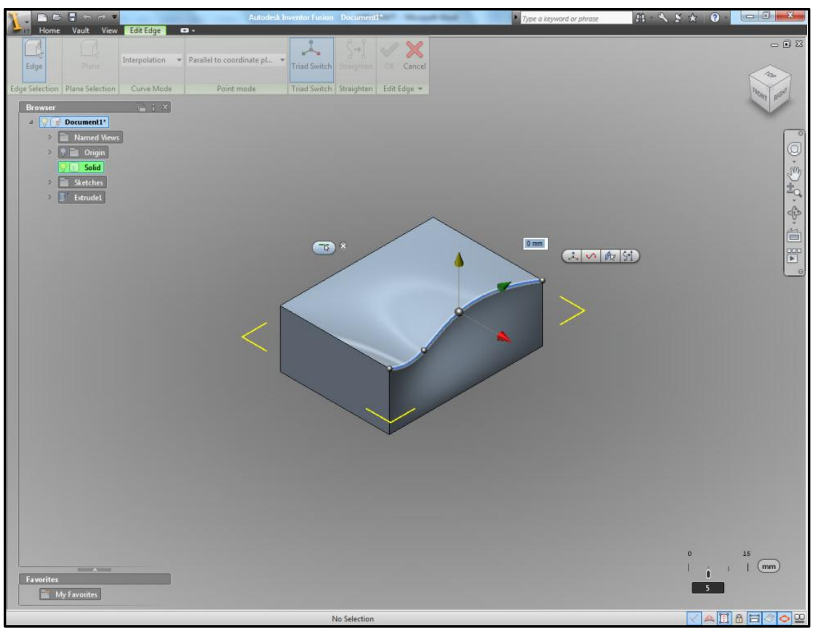
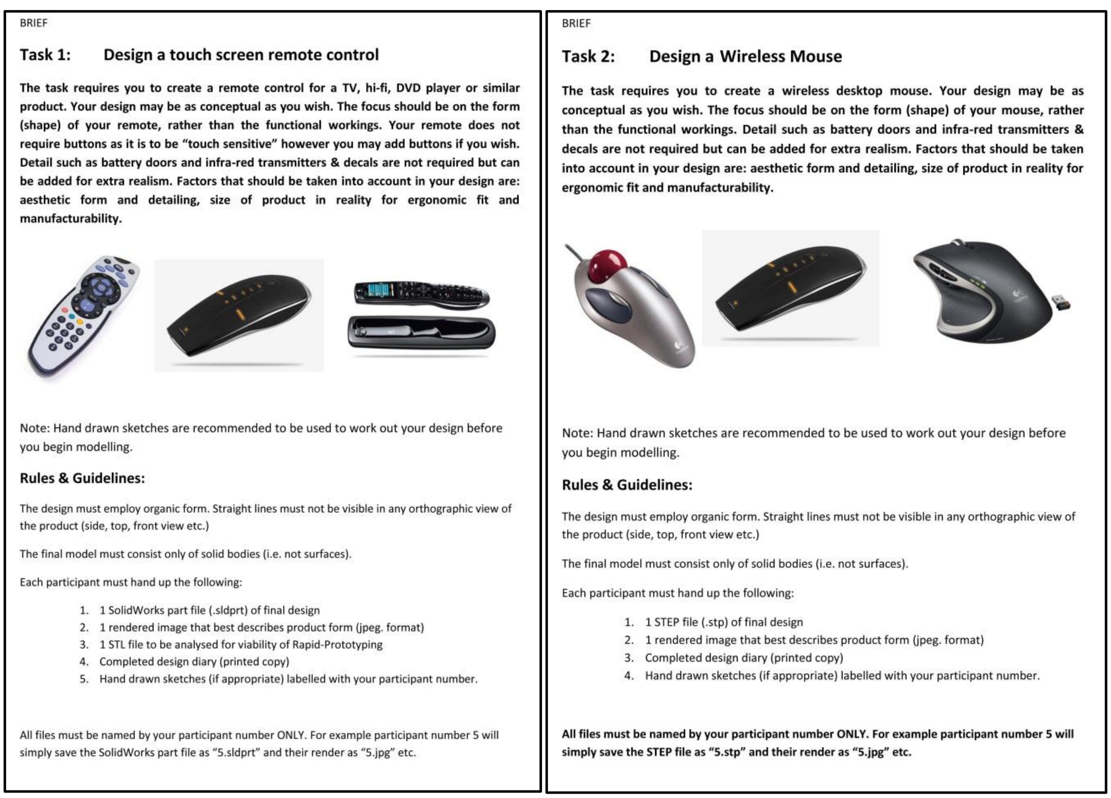


Figure 2 - Freeform Polygonal modeling

The choice of software for each task was based on marketing material analysed from a range of software and claims on what they are designed to do, in addition to the researcher’s experience having had success with both for similar design tasks. The parametric surface modeling program chosen for the study was SolidWorks 2011. For the freeform modeling task, Autodesk Inventor Fusion 2012 was selected. SolidWorks is an engineering software package and is capable of bringing a design to a production stage, including such functionality as draft analysis, mold creation and FEA (Finite Element Analysis). For this task, SolidWorks’ tools were used only to create a conceptual digital model that could be used to create a rapid-prototype. Inventor Fusion however, is much more limited in its overall functionality with regards to stages of the design process for which it caters. It is designed to serve two main purposes; direct manipulation of geometric model forms created in other software packages and the rapid creation of organic shapes. The latter suggests that this software is ideal for this task. It is worth noting that there is a freeform tool in SolidWorks and theoretically a freeform approach can be taken but Inventor Fusion was deemed more suitable for the task due to its more organic approach.

Methodology

The study was conducted using a group of Product Design students during their third year of a four year undergraduate degree programme. Participation in the study was voluntary and anonymous. Ethics approval was acquired. Seventeen students completed all parts of the study. Students were randomly assigned participant numbers (using a shuffled deck of numbered playing cards). A questionnaire was given to each student at the beginning of the study to obtain information on gender, age and information on previous CAD training/experience. Of this group there were ten males and seven females, with the group ranging in age from nineteen to twenty three years old. All students had identical previous formal training and similar experience in 3D CAD. All participating students completed a module in the previous semester where they studied the modeling of solid geometric shapes in SolidWorks. The study consisted of two separate design tasks, both of which all seventeen students attempted. Each project or task had a similar brief [fig3] and identical timeframe allocated for completion.


BRIEF

Task 1: Design a touch screen remote control

The task requires you to create a remote control for a TV, hi-fi, DVD player or similar product. Your design may be as conceptual as you wish. The focus should be on the form (shape) of your remote, rather than the functional workings. Your remote does not require buttons as it is to be "touch sensitive" however you may add buttons if you wish. Detail such as battery doors and infra-red transmitters & decals are not required but can be added for extra realism. Factors that should be taken into account in your design are: aesthetic form and detailing, size of product in reality for ergonomic fit and manufacturability.

Note: Hand drawn sketches are recommended to be used to work out your design before you begin modelling.

Rules & Guidelines:

The design must employ organic form. Straight lines must not be visible in any orthographic view of the product (side, top, front view etc.)

The final model must consist only of solid bodies (i.e. not surfaces).

Each participant must hand up the following:

1. 1 SolidWorks part file (.sldprt) of final design
2. 1 rendered image that best describes product form (jpeg. format)
3. 1 STL file to be analysed for viability of Rapid-Prototyping
4. Completed design diary (printed copy)
5. Hand drawn sketches (if appropriate) labelled with your participant number.

All files must be named by your participant number ONLY. For example participant number 5 will simply save the SolidWorks part file as "5.sldprt" and their render as "5.jpg" etc.

BRIEF

Task 2: Design a Wireless Mouse

The task requires you to create a wireless desktop mouse. Your design may be as conceptual as you wish. The focus should be on the form (shape) of your mouse, rather than the functional workings. Detail such as battery doors and infra-red transmitters & decals are not required but can be added for extra realism. Factors that should be taken into account in your design are: aesthetic form and detailing, size of product in reality for ergonomic fit and manufacturability.

Note: Hand drawn sketches are recommended to be used to work out your design before you begin modelling.

Rules & Guidelines:

The design must employ organic form. Straight lines must not be visible in any orthographic view of the product (side, top, front view etc.)

The final model must consist only of solid bodies (i.e. not surfaces).

Each participant must hand up the following:

1. 1 STEP file (.stp) of final design
2. 1 rendered image that best describes product form (jpeg. format)
3. Completed design diary (printed copy)
4. Hand drawn sketches (if appropriate) labelled with your participant number.

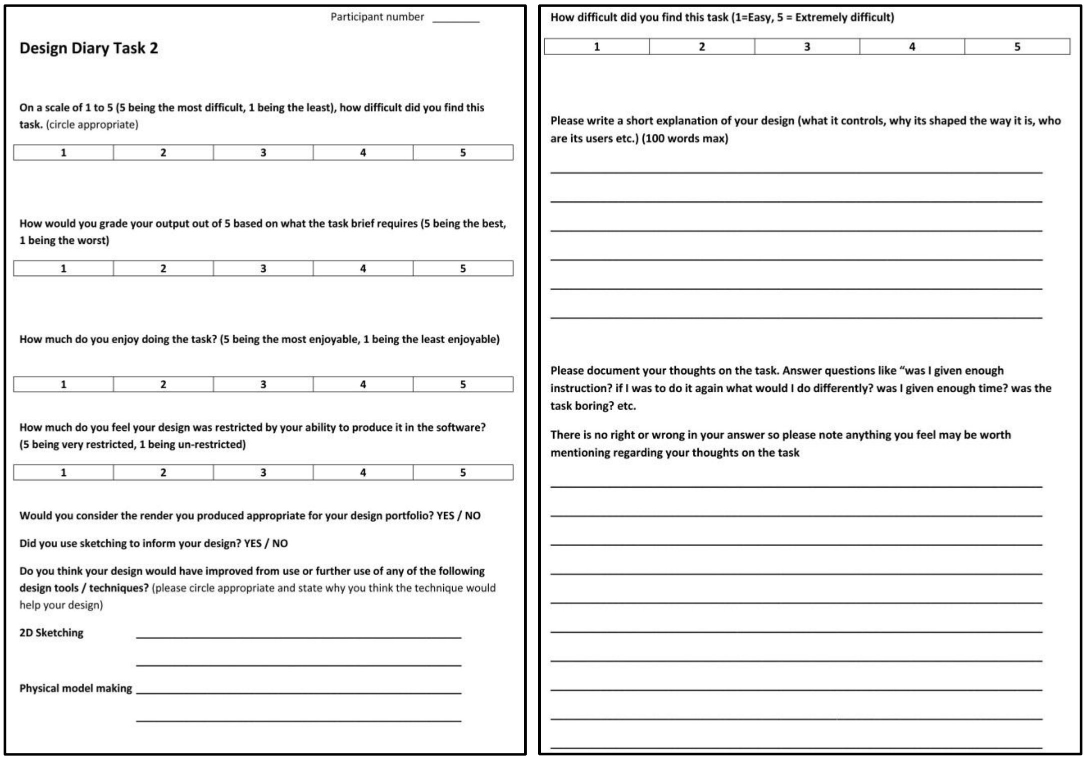
All files must be named by your participant number ONLY. For example participant number 5 will simply save the STEP file as "5.stp" and their render as "5.jpg" etc.

Figure 3 - Design briefs for Task 1 and Task 2

The briefs, for both tasks, were designed to have a similar level of difficulty and complexity in the requested outcome. The deliverables were set so either brief could have been attempted in either of the chosen software packages. Designs produced were to be conceptual in that they proposed only a design concept i.e. an aesthetic digital mock-up. Aesthetic appeal was the main focus of each design however students were instructed to be conscious of keeping realistic scale and viability of manufacture in their designs. From an analysis of existing consumer products it was determined that a touch screen remote control and a wireless desktop mouse were appropriately similar for the purposes of this study. A touch sensitive remote control was chosen opposed to a remote control with several buttons. This was to allow the students to explore the form of the product instead of allocating too much time modeling numerous small details such as buttons which can be very time-consuming in a 3D CAD package. Typically a mouse does not share this characteristic but a wireless mouse was requested for the same reason (to reduce detail). Each brief stressed the use of organic form in the solution and that extra detail such as buttons and scroll wheels were not essential. Also included in each brief was a set of images to give examples of existing products in the category. Each brief also included the parameter that straight lines could not be visible in any orthographic view of each design. This restriction was added to each brief to ensure that students explored organic, complex form rather than employing familiar geometric shapes to their designs. Students were required to submit the relevant CAD file as well as a 2D photorealistic rendered image of their solutions in each case. Hand drawn sketches were also submitted if students chose to employ them.

The study was conducted over four weeks and consisted of four, four hour computer laboratory sessions (one session per week). Each task took two laboratory sessions to complete. All seventeen students attended the four sessions. The first of the two sessions in each task consisted of instruction on using the surfacing tools in each applicable software package. Students were required to complete the model demonstrated in the first session of each task before the design stage commenced. This acted as a bridge assignment so students engaged with the software and new techniques in their own time prior to stage two of each task. The design brief was not introduced until the beginning of the second session in each task. This allowed students four hours (one full session) to work on each design, applying the knowledge gathered in the first session of each task. Students were allowed one week after the design session to work on their designs in their own time. A pilot study was conducted with four separate participants with similar CAD experience (to the seventeen students) prior to the study to confirm that the time allowed was enough to complete the task. At the beginning of the design stage in each task, students were given:

- Drawing paper, pens, pencils & markers (to use for sketching their designs if desired)
- Rulers & vernier callipers (to use as a reference for dimensioning as they designed)
- Blank design diaries



Participant number ________

Design Diary Task 2

On a scale of 1 to 5 (5 being the most difficult, 1 being the least), how difficult did you find this task. (circle appropriate)

1	2	3	4	5

How would you grade your output out of 5 based on what the task brief requires (5 being the best, 1 being the worst)

1	2	3	4	5

How much do you enjoy doing the task? (5 being the most enjoyable, 1 being the least enjoyable)

1	2	3	4	5

How much do you feel your design was restricted by your ability to produce it in the software? (5 being very restricted, 1 being un-restricted)

1	2	3	4	5

Would you consider the render you produced appropriate for your design portfolio? YES / NO

Did you use sketching to inform your design? YES / NO

Do you think your design would have improved from use or further use of any of the following design tools / techniques? (please circle appropriate and state why you think the technique would help your design)

2D Sketching ________________________________

Physical model making ________________________________

How difficult did you find this task (1=Easy, 5 = Extremely difficult)

1	2	3	4	5

Please write a short explanation of your design (what it controls, why its shaped the way it is, who are its users etc.) (100 words max)

Please document your thoughts on the task. Answer questions like "was I given enough instruction? if I was to do it again what would I do differently? was I given enough time? was the task boring? etc.

There is no right or wrong in your answer so please note anything you feel may be worth mentioning regarding your thoughts on the task

Figure 4 - Design diaries

Design diaries[fig4] were used for documenting students' thought processes and providing qualitative feedback to the researcher on the study. A separate but identical diary was used by each student for each of the two tasks. Students did not submit the diaries until one week had elapsed following each task. This allowed reflection on the task subsequent to its completion in addition to providing the researcher feedback on their thoughts whilst working in their own time. The diary included questions relating to the difficulty and enjoyment experienced as well as what they felt might have helped to enable them to perform better at the task.

Task 1

The first four hour session of Task 1 entailed instruction on surfacing techniques and relevant features in SolidWorks. The session was held in a computer lab where each student had a workstation running SolidWorks 2011 and the instructor operated SolidWorks from the front of the room on two large projector screens. A sample design of a remote control was modeled as a demonstration for the group. The sample remote control was created in SolidWorks employing all standard surfacing tools, namely:

- Surface Extrude
- Surface Loft
- Surface Sweep
- Boundary Surface
- Fill Surface
- Freeform Surface

- Planar Surface
- Trim Surface
- Knit Surface

Secondary features such as mirror, fillet and shell were also demonstrated. Each feature was explained thoroughly as it was being used, including creation of relevant sketch geometry. Temporary secondary parts were opened to explain how each of the features could be used for different modeling scenarios. Students modeled a remote similar to what was being demonstrated and questions were allowed and encouraged throughout the session. Included in the tutorial was a demonstration on “knitting” surfaces together to form solid geometry and how to avoid difficulties with this. The design task required all surface geometry to be converted to solid geometry. By requesting that each file was submitted in Stereolithography (STL) format, it was insured that each student produced solid geometry as an STL would not save successfully if the part contained only surface geometry. A Stereolithography file is a format that is common to most 3D CAD packages and is frequently the output format utilised by rapid prototyping machines.

The second four hour session for Task 1 was the time allotted for students to design their own remote control. The brief was given only at the start of this session. Students were permitted to ask questions if struggling with modeling a particular surface. If a similar problem occurred twice or more, a short demonstration was given to the entire group on how to address it.

Task 2

The second task was run with identical format to the first i.e. four hour tutorial in the first session followed by a four hour design session one week later. For both tasks, no formal contact time in between sessions occurred but help and advice was given on request by the researcher. This help ranged from replying to emails or informally meeting students in the computer laboratory. The tutorial session introduced the interface of Autodesk Inventor Fusion, including instruction on how it differed from the SolidWorks interface that they had familiarity. All necessary tools and features for creating an organic shape like a mouse were demonstrated. This included sketch creation and secondary features like mirror, fillet/chamfer in addition to the following primary features:

- Extrude
- Edit Edge
- Assign Symmetry

Again, the second session of Task 2 was the time allowed for students to design their own mouse. Autodesk Inventor Fusion produces only solid geometry in this case but STL files were also submitted for comparison to the submissions from Task 1.

To perform quantitative analyses on the outputs from each task a grading scheme was generated that was common to both tasks. This grading reviewed each student’s output on a scale of 1 to 5 (1 = poor, 5 = excellent). Outputs (3D models and 2D renders) were analysed and graded as appropriate under the following criteria:

- Aesthetic styling

  The brief required each student to produce a digital 3D conceptual mock-up representative of their product. When grading under this innately subjective criteria, good marks were awarded for forms that flowed consistently, were balanced in appearance and were generally good to look at. Poor marks were given for designs that lacked logical flow, like having sharp bodies running into smooth faces. Both the mouse and remote are hand held products and as such should not contain sharp edges on faces that the user interacts with. This consideration also fell under the aesthetic styling criteria for the purposes of this study.

- Realistic scale

  Designing/modeling in CAD can be misleading in relation to the real world scale (size) of a product or component. Students were advised to be aware of this. Using the measurement tools in each program, 3D models submitted were analysed as to what dimensions they would have in reality.

- Manufacturing viability

  Although both tasks required a conceptual mock-up students were to take into account manufacturing viability assuming that their designs would be injection moulded plastic parts. Good grades were awarded for parts that could be shelled (by the researcher) to a thickness of 1mm without making modifications to the STL file. Poor marks were awarded for models that required extensive work to perform a shell operation, particularly those that contained extremely sharp edges and badly intersecting geometry.

A third study was carried out with separate Product Design students. This study was carried out in the same format with four hours tutoring and four hours designing for each task. These five participants however, completed Task 2 before Task 1 was introduced. This study was added as a measure to detect if the Order Effect[3] would impact how participants performed having done one task before the other.

Results

	Task 1				Task 2			
Participant #	Aesthetic styling	Realistic Scale	Manufacturing viability	Avg. Score	Aesthetic styling	Realistic Scale	Manufacturing viability	Avg. Score
2	4	5	3	4.0	3	2	1	2.0
4	5	1	3	3.0	2	3	3	2.7
6	4	5	4	4.3	2	3	1	2.0
7	3	4	2	3.0	1	2	1	1.3
9	5	5	5	5.0	1	1	1	1.0
16	5	5	5	5.0	2	2	1	1.7
20	4	2	3	3.0	5	5	4	4.7
26	3	2	3	2.7	4	3	3	3.3
29	2	2	4	2.7	1	1	1	1.0
32	4	3	3	3.3	4	4	1	3.0
34	3	5	5	4.3	2	1	1	1.3
36	3	4	5	4.0	2	2	2	2.0
39	4	1	3	2.7	1	1	1	1.0
42	3	1	5	3.0	4	3	4	3.7
44	5	4	1	3.3	4	4	2	3.3
48	4	5	5	4.7	1	3	3	2.3
51	4	5	5	4.7	3	2	1	2.0

Table 1

		Sum of Squares	df	Mean Square	F	Sig.
Aesthetic Styling	Between Groups	15.559	1	15.559	12.231	0.001
	Within Groups	40.706	32	1.272		
	Total	56.265	33			
Realistic scale	Between Groups	8.5	1	8.5	4.219	0.048
	Within Groups	64.471	32	2.015		
	Total	72.971	33			
Manufacturing Viability	Between Groups	32.029	1	32.029	22.512	0
	Within Groups	45.529	32	1.423		
	Total	77.559	33			

Table 2

Table 1 above displays the grades awarded in both tasks for all seventeen participants. On analysing the grades achieved by each student on both tasks, it was apparent that the majority of students performed significantly better overall on Task 1 than Task 2. Only two students of the seventeen performed better overall on the second task. The group as a whole scored at least 20% better under each of the grading criteria on Task 1 than Task 2.

An ANOVA (Analysis of Variance) test was run on SPSS (Statistical Package for the Social Sciences). Results are displayed in Table 2 above. There was a high significant difference in “aesthetic styling” and “manufacturing viability”. A significant difference was observed from the “realistic scale” criteria. All results suggest that Task 1 (parametric surface modeling) was a better modeling approach for both tasks under the selected criteria.

The design diaries [fig4] from each student were analysed for both tasks. Having established that the vast majority of students performed better in Task 1, it was interesting to learn from their diaries that fifteen of the seventeen students found Task 2 more enjoyable. One student commented:

> “I knew how to do all the things to change the shape and I knew what I wanted it to look like but I just couldn’t get it to look the way I wanted.”

A lack of experience and practice in creating organic shapes in both approaches stifled the group as a whole and affected their design intent. In many cases designs produced were similar to the design that students had envisaged but were not entirely accurate:

> “I was just unsure on what feature to use when I had the reference sketches done, even though I know how to use all the features, I was almost there, I just couldn’t get it perfect”.

Students were asked to rate on a scale of 1 to 5 how much they felt their designs were restricted (5 = Extremely influenced, 1 = Not influenced) by their ability to use the software. For Task 1 the average rating was 3.6 and Task 2 resulted in significantly high average of 4.3. This result provides noteworthy evidence that students were restricted in both modeling approaches.

The parametric nature of SolidWorks did allow students to change geometry created numerous steps back, but on many occasions caused inveterate errors when changes were made retrospectively:

> “It previewed fine, but I when I hit return I just got error messages”.

The ability to use the history tree (in the parametric approach) to make slight changes to reference sketches was deemed useful and helpful by fourteen students. If changes more drastic than altering the weight or direction of a spline were required, the history tree was not considered useful. The lack of history based functionality in Inventor Fusion caused many students difficulty, with one student commenting:

> “I decided to change one of the curves I had messed around with before but I couldn’t go back to change it because I had changed something after it”.

The ability (in freeform modeling) to see what is happening to the entire model as changes are made undoubtedly contributed to the enjoyment of using this approach, highlighted by one student commenting:

> "With SolidWorks when I did anything I had to be thinking ten steps ahead but with Fusion I could see what was happening to the whole shape as I was doing it."

The argument whether CAD in general should be used as a recording/documentation tool or a design tool has been extensively and inconclusively documented[4] and its intricacies is beyond the scope of this paper. It is interesting however that in both tasks, all seventeen students commented that they would have found the task easier had a physical foam model first been created. A common theme from student feedback is reflected in the following statement:

> "I didn't really know where I was going next as I had nothing to go on".

Interestingly, this student had not attempted to sketch out an idea before beginning to model in either task but rather chose to use CAD as a design tool in both modeling approaches even though they were aware of the difficulty this approach posed. In Task 1, twelve of seventeen students chose to use sketching before beginning to model and only one student out of seventeen made any attempt to sketch their idea for Task 2. This may be due to apparent ease of the interface and ability to iterate in Inventor Fusion. Throughout the study it was not made mandatory, but rather encouraged to use sketching, as sketching has been documented as the ideal tool to facilitate the learner to visualise when modeling in CAD[5,6.] Although having never used the surfacing techniques in SolidWorks before the study, all students were familiar with the interface as a result of previous experience in its use for solid modeling. The interface of Inventor Fusion, although covered in the tutorial session was unknown to the students prior to this study. Twelve students commented (in their design diaries) that they had issues with Inventor Fusion's interface. For example, they had issues with trying to remember where certain buttons were on screen but this was less of an issue in SolidWorks. The interface of Inventor Fusion could be considered much simpler to that of SolidWorks, mainly because of the number of tools available on-screen. When tutoring the group on the tools required for the tasks, SolidWorks consisted of nine new tools whereas Inventor Fusion had only three (all available on the on-screen toolbar):

> "I had to hover over the buttons every time I wanted to do something because I couldn't remember what each one did".

In this instance, the student was referring to the explanation that appears when each on-screen button is hovered over with the cursor. It came as a surprise that students found Inventor Fusions interface difficult to navigate even though there were so few buttons on screen compared to SolidWorks (using default un-customised display setups in both cases).

Conclusions

From conducting the study it cannot be conclusively argued that one approach to modeling is better than the other for producing 3D digital concept mock-ups. Statistically students performed better overall at Task 1 (parametric modeling) than Task 2 (freeform modeling). However, almost all students commented that Task 2 was more enjoyable. This suggests that it is a more enjoyable approach to alter existing geometry than it is to create geometry face by face. This appears to be due to the fact than one can see how the finished part will look as one is doing it, without having to visualise what subsequent faces will appear (in parametric modeling). The study also demonstrated that familiarity with software's interface is extremely important. Although new tools and approaches were introduced in both packages, students performed better using the interface they had been familiar with, despite assumptions that freeform modeling was easier[2]. This finding may be because the concept of polygonal mesh modeling is further removed from solid geometry modeling than parametric surface modeling. These findings have given the researcher a better understanding of Product Design students and the characteristics they share towards the learning of approaches to CAD. A better understanding on the pros and cons of both approaches to modeling has also been gained and has led the researcher towards developing this study further by considering alternative demographics, software packages, modeling approaches and methods of analysis.

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