3D CAD AND MENTAL SCALING IN THE PRODUCT DESIGN PROCESS: EXPLORING THE CREATIVITY POTENTIAL IN DESIGN EDUCATION

Harald SKULBERG
Institute of Design, The Oslo School of Architecture and Design (AHO), Norway

ABSTRACT
This paper explores the potential of using technology as a tool for creativity in design education. The gap between research and practice in the design field requires a stronger emphasis on research on design methodologies, and investigating the influence of technology in this context seems appropriate. In particular, this paper explores the relation between the use of parametric Computer-Aided Design (i.e. CAD) software and mental scaling - or mental elasticity. Mental scaling describes the ability to mentally fluctuate between divergent and convergent thinking through the design process. This is a case study where a group of industrial design students without previous experience with using this software were asked to document their own physical model during an assignment by building their own virtual 3D model. Through the use of photo documentation, observations and a written questionnaire, this study explains how CAD may constitute a catalyst for mental scaling by turning the initial documentation process into an extended design process through added iterations.

Keywords: Design methodology, Computer-Aided Design, mental scaling, virtual 3D model, case study

1 INTRODUCTION

As the design field moves towards immaterial media and conceptualization, we acknowledge that a stronger emphasis on research on design methods is required, and this paper aims at bridging the gap between research and practice within the design field. Due to demands from industry, the teaching and utilization of digital media have become increasingly essential in academia. The versatility of recent computer aided design software has become an important asset for industrial designers and product designers in particular, as the use of CAD has become an essential skill for the development, optimization and documentation of solutions within products and systems. The development of effective design methods utilizing the creativity potential inherent in CAD is therefore highly relevant in design schools. The potential to use CAD not only as a construction tool but also as a creative and stimulating design tool for exploration should be exploited in a broader manner than experienced today, and this study aims at investigating this potential.

1.1 The scope and design case

The scope for this study is a design case introducing 3D CAD - SolidWorks (i.e. SW) - to a group of first year industrial design students at the foundation level of a Master program in industrial design. The design assignment was divided in two parts, where the first part -Physical model- was the foundation for the second part -3D CAD model. After going through basic introductory tutorials under competent supervision, the design students were asked to develop their own virtual 3D model. The two assignments were defined as follows:

- **Assignment Part 1, Physical model:** "Give shape to a new object to be made of wood, plastic or metal. Examine a formal question or formal challenge you find interesting in relation to the material's inherent properties. In addition to the selected main material you will use one additional material of the three materials mentioned. This will enable you to plan and solve a joining between two different materials in your object. Object's maximum dimensions: Height 20 x Width 20 x Depth 20 cm".

- **Assignment Part 2, 3D CAD model:** "Transform the formal properties observed in the artefact in part 1 into a virtual 3D model using SolidWorks. Develop and clarify the visual qualities observed in your artefact by exploring and utilizing the functional possibilities in the Solid Works software".

1.2 Research question and hypothesis

In this particular context, the term creativity is comprehended as the ability to transform and develop visual and formal qualities found in the physical object into a virtual 3D model by exploring and developing these qualities into an intelligible, aesthetical perception by building a 3D model on screen. Our research question is: How may CAD constitute a catalyst for mental scaling, by turning a documentation process into an extended design process through added iterations during the exploration of SolidWorks software? Our hypothesis is that even a parametric 3D software like SolidWorks - which often is considered as a rigid construction tool – can provide a relevant stimulus and thereby become a catalyst for mental scaling - or mental elasticity - during the design process.

1.3 The theory of mental scaling

From a pedagogical perspective, our strategy was to enable the students to understand how design evolves during successive phases of a design process. This was facilitated by encouraging the students to take a free-minded approach during the design exploration in part 1, in order to develop a conscious attitude and focus on aesthetical considerations as a foundation for further exploration and in part 2.
Parallel to this strategy Lawson [1] refers to the Markus / Maver map of the design process by suggesting that each step of the process from outline proposals via scheme design to detail design demands a separate internal loop of analysis, synthesis, approval and decision. In many ways, this model matches our philosophy for this design case, as Lawson's model seems to reflect our idea of a holistic and generative approach that enables a structured product design process by integrating an internal loop of evaluation within each step of the design process. Following this line of thinking, mental elasticity -or mental scaling- describes the ability to actively fluctuate between divergent and convergent thinking, enabling mental iterations during a design process. The theory of mental scaling accords somehow with De Bonos [2] theory that discusses the power of lateral thinking in developing new ideas. According to Skulberg [3], mental scaling describes the ability to consciously navigate between abstraction through a holistic view and concretization through a fragmented view while exploring potential solutions during the solution search process. This holistic approach seems to be an essential capability for designers in order to attack a given problem from different angles through added iterations in order to explore and produce optimal solutions to a defined problem. When examining student capability parameters in this framework A-navigators tend to move towards abstraction (A) while C-navigators tend to move towards concretization (C). The theory of mental scaling has been a pedagogical and theoretical framework and inspiration for our study.

1.4 3D CAD

Two different modes of CAD modelling are dominant today; surface and solid modelling, of which Solid Works (i.e. SW) represents the latter, Stroud and Nagy [4]. In contrast to free-form surface modelling software like Alias, parametric CAD software is often considered as a tool basically for construction purposes, while free-form software is considered as a much more versatile tool enabling a more artistic and designerly approach. SolidWorks is a 3D mechanical CAD program that runs on a Microsoft Windows platform. It is a parasolid-based modeller, and utilizes a parametric feature-based approach to create models and assemblies. This software represents a sequential and generic approach where the operator must comply with specific pre-defined sequences of commands in order to build a three-dimensional body simulating physical mass and surface. Building a model in SolidWorks usually starts with a 2D sketch using geometry as a guideline for building the final three dimensional model. Three levels are important in order to understand the software structure: *Parameters* refer to constraints whose values determine the shape or geometry of the model or assembly, *Design intent* refers to how the creator of the part wants it to respond to changes and updates, while *Features* refer to the building blocks of the part.
On the general principles of building 3D form, Akner-Koler [5] argues that the 3D spacial matrix constitutes the fundamental context in which all visual components interact, using vertical, horizontal

and depth as basic dimensions. This is the reference of orientation for all positive and negative visual elements, and SW substantiates this principle for simulating mass and surface in 3D volumes.

1.5 Research methodology

Three different research tools were used in this study; Observations of the CAD sessions with tutoring in the computer lab, photo- and screen documentation, and a written questionnaire. Procedural steps through the process as well as the final results were accumulated, and the student's reflections were evaluated. It seems important to explain the relevance of choosing these tools. Firstly, personal observations when sitting close to the students at their computer produce an immediate impression on how the students proceed during the CAD assignment, and this knowledge has been fruitful for evaluating the individual on-going learning process as well as the final course evaluation. Secondly, photo documentation has been considered as the most effective medium in order to document each student's individual strategy to transfer the intrinsic properties and formal qualities of the physical model into the CAD medium. In this manner both the physical and the virtual model can be documented in one visual image. Thirdly, a written medium as the personal questionnaire was chosen in order to accumulate quantitative feedback on the student's use of CAD software. Answering the questionnaire was voluntary, and of the total group of 32 students, 23 students answered giving a response rate of 72, which seems satisfactorily representative sample. With 11 questions in the form, a total of 253 answers were given by the students. The questionnaire was specifically designed to define a set of individual student capability parameters as well as explaining how the students experience both advantages and disadvantages of using SW. The appearance of the physical and virtual models was compared, and the student's reflections after using the SW software were evaluated. One interesting aspect of investigating how the CAD software may constitute a catalyst for iterations is why there often is a visual difference between the appearance of the physical model and the virtual model, and why and how this difference builds. Our experience indicates that these differences appear to be an indicator of the fact that mental scaling actually has happened, and this has been the motivation for comparing the appearance of the physical and the virtual model.

2 VISUALIZATION TOOLS

Similar to a typical ideation process starting with two-dimensional sketches, SW also has the 2D sketch as a starting point for building the final three-dimensional model on screen. Olofsson [6] distinguishes between investigative, exploratory, explanatory and persuasive sketches. All these different four media are comparable to the equivalent levels of 3D physical models, represented by mock-ups, shape and form models, functional models, show models and final prototypes, according to Saeter, Solberg, Sigurjónson, Boks [7]. In the same way, these different media represent comparable levels on the mental scale -or clarity scale- as they all relate to a final completion representing an optimal solution and they are accordingly observed both in physical models and in 3D CAD. In practice, the student's final CAD model could either be foundation for a new iteration going back to a round of making a new refined physical model, or directly to rapid prototyping printed from a CAD-file, Filippi [8], which then would be useful to tangibly evaluate various physical solution concepts.

3 THE STUDY

The observations of students and teaching assistants at work in the computer lab together with photo documentation and a written questionnaire produced an interesting body of insights and reflections. During CAD sessions (Figure 1) the exploration of software functionality is carried out, processing and organizing visual information from the artefact -seen on the tables- into a virtual CAD model.

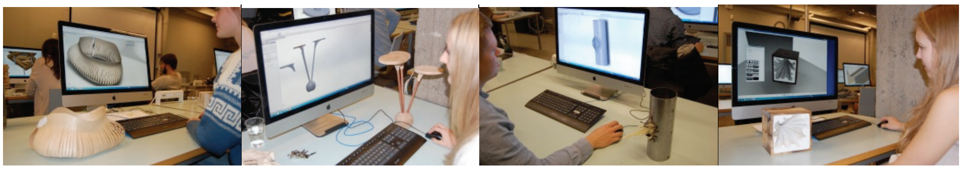

Figure 1. CAD sessions utilizing SolidWorks software in the computer lab, based on artefacts seen on the tables

When observing students during SolidWorks sessions, the act of switching between component level and assembly level, as well as zooming between render and extreme detail level, seems to initiate the student's mental elasticity, commuting from one mental level to another. In order to document the process of transforming a physical model into a virtual model, one particular student case (see Figure 2) exemplifies this process through a screenshot displaying the appearance of the new virtual object.

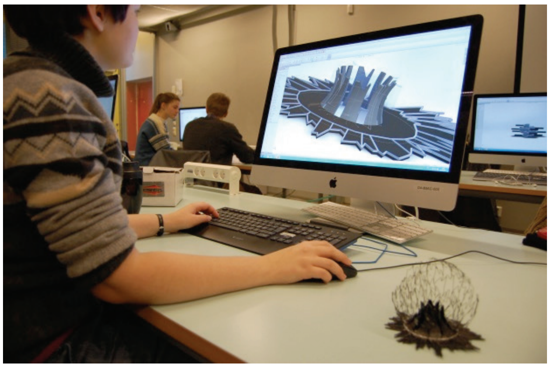

Figure 2. Exploration of software functionality using SolidWorks Motion

In the process of freely rotating the model on the screen, functionality in SolidWorks Motion is utilized. This is a virtual prototyping tool that provides motion simulation capabilities to ensure that the design actually works properly. However, we see that many of the students face challenges when translating the spatial information observed in the physical model, through parametric conversion in SW without losing the object's distinctiveness or subtle aesthetical character during the transformation process. The use of *Surface*, *Body* and *Coordinate* functions in SW enable quick manipulation of the object's structure, and these functions generate highly effective form modification abilities. Our observations also indicate that moving the point of view through rotation, zooming and equivalent modes seem to stimulate the student's imagination in terms of discovering a multitude of new form possibilities not previously revealed.

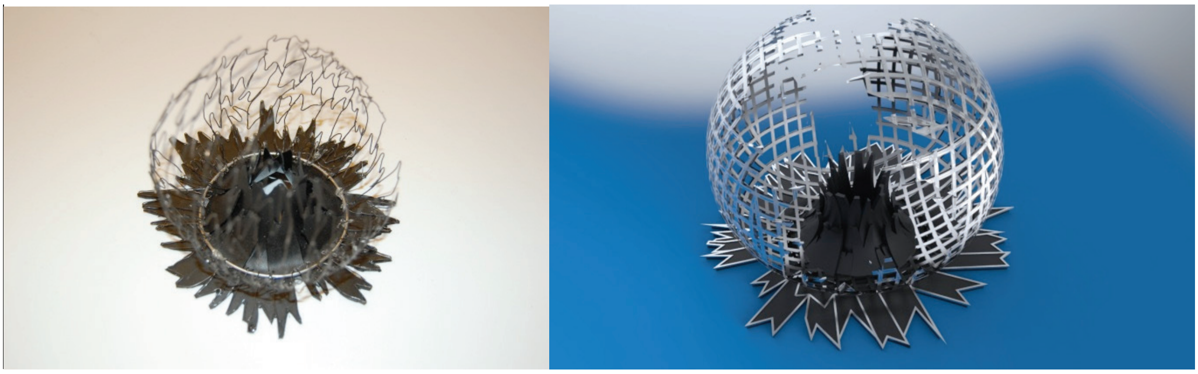

Figure 3. A comparison between a physical model and a final CAD model

Figure 3 shows how the irregular and unclear structure of a physical model (left) has been transformed into a new and much more precise geometrical structure (right) where the vertical rotation axis has been an important starting point for the form generation. As the pictured student expressed, the absence of formal clarity was a major problem with the physical model. The final result demonstrates the intention of making a precise, intelligible and easily recognizable form, however the formal translation has required distinctive alterations in component and material appearance.

While being a parametric CAD software, SW typically contributes towards a visual order and formal clarity in the 3D model, and this process often results in an aesthetical clarity by redefining the model's aesthetical expression, as the operator is forced to comply with the parametric rigidity of the software. As an example, several of the handmade models consist of complex, irregular hand-made body structures, and imperfections like joints consisting of glue or screws are present. These irregularities are erased in the virtual model, enabling a simpler and cleaner geometry which contributes to a stronger visual comprehension.

Table 1. The questionnaire

Questionnaire: 3D CAD and mental scaling	Do not agree	Partly agree	Quit agree	Totally agree
1. As a person I like best to work conceptually, I like working visionary with big visions, thoughts and issues, not details.	5	8	8	1
2. As a person I like best to work concretely with specific things like drawings or physical models, often on a detailed level.	0	4	7	12
3. When I work with hand drawings I like best to create rough, quick sketches.	3	6	7	7
4. When I work with hand drawings I like best to work with precise lines.	3	8	8	4
5. I feel that SolidWorks gives me many new solution possibilities because I discover new features or solution variants that I was not previously aware of.	2	9	11	1
6. When I work with SolidWorks, I discover new design possibilities that I put into the solution along the way, and that makes the solution better.	3	14	5	1
7. I find that working with SolidWorks limits my solution possibilities.	6	7	10	0
8. Working with a tool like SolidWorks has a stimulating effect on me.	0	5	15	2
9. I feel that I have discovered so many new design opportunities after after working with SW, it had been helpful with another round of hand drawn sketches and sketch models before any final solution drawn in SW.	5	8	7	2
10. The following functions or features in SolidWorks help strengthen my design process (summarized): • More insight into the component structure • Good navigation • Precision & realism • Testing surfaces and textures • One can easily go back and change parameters • Opportunity to test many solutions quickly • Something unexpected happens which can be utilized in the design solution				
11. The following functions or features in SolidWorks weaken my design process (summarized): • It seems to be a complicated program to learn • Basically the functional aspects comes into focus • Hard to learn without a geometric affinity				

3.1 Focus areas and findings

The questionnaire constitutes three main focus areas: Q1-Q4 determines the distribution of personal student capabilities between A- and C-navigators in the group. Q5-Q9 assesses how SW stimulates towards added iterations and mental scaling. Q10-Q11 gives a qualitative feedback on how the students subjectively experience strengths and weaknesses of functions and features in the software. When assessed holistically as a group, the answers 1-4 indicate a tendency towards C-navigation among the majority of students. The highest individual score in the questionnaire is found in question 8, where 15 of the total of 23 students confirmed that Solid Works has a stimulating effect. Question 5 supports this attitude. Conversely, question 7 indicates that a significant number of students find that SW limits their solutions. The summarization of Q10 indicates that SW stimulates cross-level navigation, and the freedom to change parameters in an opportunistic manner is highly appreciated.

3.2 Mental fluctuation scale

In order to convey the complexity of mental scaling, we found it fruitful to develop a chart to describe the relation between mental iterations, solution space and software- or form generative limitations. Figure 4 describes a principal and simplified picture of how a typical mental scaling process is observed during the SW sessions, producing mental fluctuations between level A – holistic structure, and level C – detailed component design. As an example, the shaded area at point A3 will typically represent the point where the student recognizes how a search for solution on too abstract or holistic level exceeds software limitations or the form generative framework, and the consequence will then be that an iteration starts to build by commuting back towards a more convergent search. On the opposite end of the mental fluctuation scale, point C3 will typically represent the point where the student explores too complex details on a fragmented level, by testing and challenging software functions through commands that are invalid and which the software is unable to process. The fluctuation between A- and C-level finally culminates with a detailed component design constituting the final assembly structure comprising all individual parts of the virtual object within the given solution space.

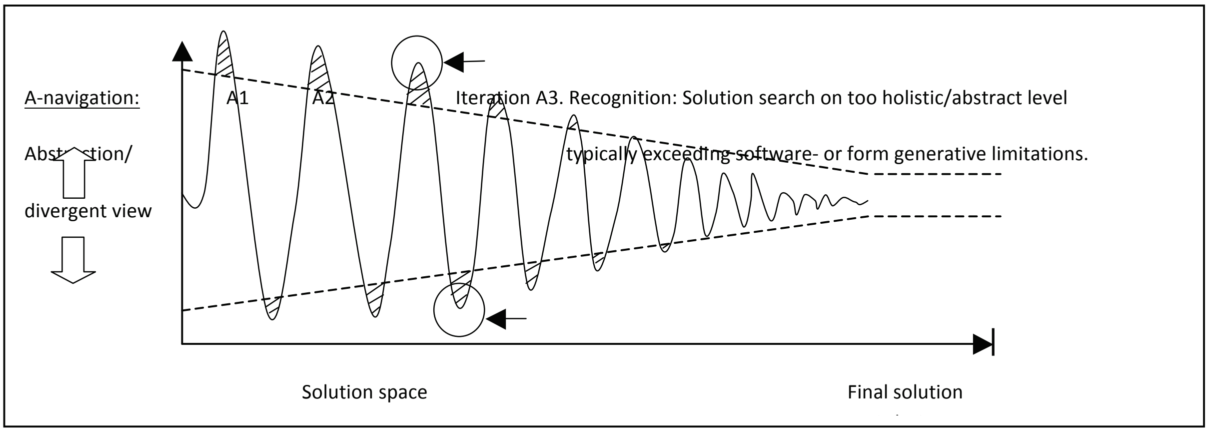

Figure 4. Mental scaling during 3D CAD simulation in Solid Works

4 CONCLUSION AND REFLECTIONS

Our hypothesis of SolidWorks constituting a catalyst for mental scaling is to some extent verified by our study. Given this particular scope, our study indicates that even a parametric 3D CAD software like Solid Works may stimulate an active fluctuation between abstraction through a divergent view and concretization through a convergent view. The mental fluctuation between a divergent exploration and convergent search for optimal solution is evidenced in the act of frequent switching between component level and assembly level, as well as zooming between render and extreme detail level. These mental fluctuations are driven by the need of a structural overview and a form generative insight, together with the intended exploration of components on a detailed level.

However, feedback from the students indicates that some of the students are challenge by what they describe as s software rigidity which limits their solution possibilities. It would be fruitful to study a larger number of design assignments in order to produce a more solid body of evidence, and this could be the next step for investigating this topic further. Furthermore, it would be advantageous to investigate the student's development in a long term.

The importance of rich media environment seems crucial for design teaching, as relevant tools are essential to the student's ability to investigate, explain and persuade effectively. The process of mental scaling initiates an active and explorative mindset, and the student cases indicate that CAD contributes as a creative tool for building formal imagination, not only as a construction tool. In general, the whole body of information produced by observation, photo documentation and answers given in the questionnaire has demonstrated the importance of evaluating learning outcomes from using powerful CAD tools like SW. This study has produced new and valuable insights on the utilization of relevant design tools, and how technology can contribute as a creative tool during the learning journey.

REFERENCES

[1] Lawson, Bryan. How Designers Think: The Design Process Demystified. *1980 (London: Architectural).*

[2] De Bono, E. Serious creativity, using the power of lateral thinking to create new ideas. *The Bono Thinking Systems, 2006.*

[3] Skulberg, H, *Proceeding of The 13th International Conference on Engineering and Product Design Education; Design education for creativity and business innovation, 2011.*

[4] Stroud I, Nagy H. Solid modelling and CAD systems: How to survive a CAD system. *London: Springer-Verlag; 2011.*

[5] Akner-Koler, C. Three Dimensional Visual Analysis. *Department of Industrial Design, University College of Arts, Crafts and Design, 1984. ISBN 91-87176-16-5.*

[6] Olofsson E, Sjölen K, Design sketching. 3rd ed. *Klippa: Ljungbergs Trykkeri AB; 2007.*

[7] Sæter, E., Solberg, M. H., Sigurdjónsson, J., Boks, C. A Holistic View on Ideation and Visualisation Tools. *Proceeding of The 14th International Conference on Engineering and Product Design Education; Design education for future Wellbeing, 2012, 217.*

[8] Filippi. CAD and the rapid construction of physical objects. I: *Bordegoni M, Rizzi C, red.* Innovation in Product Design; From CAD to Virtual Prototyping. *London: Springer, 2011.*