UNIVERSIDAD EAFIT

Escuela de Ingeniería

Departamento de Ingeniería de Diseño de Producto

DIAGNOSTIC STUDY ON SHAPE PERCEPTION ERRORS WITHIN 3D-MODELING COURSES

Sebastián Ochoa Gutiérrez

Ingeniero de Diseño de Producto

Trabajo de grado presentado como requisito parcial para optar al título de
Maestría en Profundización en Ingeniería

Tutor

Juan Diego Ramos Betancur

Jurados

Juan Alejandro García Flórez

Juan Carlos Arbeláez Estrada

Medellín, Colombia

Octubre del 2015

UNIVERSIDAD EAFIT

Escuela de Ingeniería

Departamento de Ingeniería de Diseño de Producto

DIAGNOSTIC STUDY ON SHAPE PERCEPTION ERRORS WITHIN 3D-MODELING COURSES

Trabajo de grado presentado como requisito parcial para optar al título de

Maestría en Profundización en Ingeniería

AUTOR

(Sebastián Ochoa Gutiérrez)

TUTOR

(Juan Diego Ramos Betancur)

Foreword

The purpose of this document is to serve as a comprehensive report of a Master's Project, on specific issues in the field of 3D-modeling. Its objectives are mainly pedagogical, in order to expand the understanding of the field and improve existing educational strategies at the undergraduate programm of Product Design Engineering, at EAFIT University.

Abstract

Form has always been a central concern for design. Several tools and strategies have been developed aiming to support form generation from different perspectives. And these issues are also a matter of study for design education. Under this view, it is relevant to explore how technology and new interactions can aid design students to better understand form generation. The present study, therefore, is centered on the 3D-modeling courses (ID0245-Modelación 3D1 and ID0267- Modelación 3D2) and tools (PTC® Creo 3.0™) provided inside the Product Design Engineering syllabus at EAFIT University.

In the ever changing academic world, new generations of students will be always in need of new methodological approaches from educators, in order to better understand the knowledge they are being given. Curriculum adaptations will be always necessary to achieve this goal. Therefore, the scope of the present study aims to set the ground for new teaching strategies around the 3D-modeling courses, based on the most commonly identified errors and difficulties found in 3D-modeling students.

These errors or difficulties might not be isolated factors, only present in the named courses. They can be intrinsically connected with the acquired skills from other form generation-related courses, such as Drawing and Projects (where physical model are built and techniques are introduced by guidance). However, since the project is framed by the mentioned 3D-modeling tools and courses, it is necessary to understand how form is being generated inside 3D digital environments as a starting point for future work.

Nowadays, individual software provide increasing capabilities to help achieving specific modeling tasks. This segmentation and specialization demands high expertize from users to become accustomed and keep up with the ever demanding industry standards. Nonetheless, speed and quality cannot be compromised. Hence, the main target around the study will be design students that take their first steps towards product embodiment.

The project, therefore, aims to understand how students approach styling activities and to report on their most common mistakes. It is based on how they perceive 2D representations of products and how accurate their 3D-models are, based on selected shape properties. This will serve as an essential input for new teaching strategies towards students' self-awareness when performing in 3D form-giving environments.

***Keywords**: Design education, Aesthetic Design, Form generation, Visual perception, Spatial thinking, Shape properties, Styling, Design features, 3D-modeling, Computer Aided Styling (CAS), Product embodiment and Product design process.*

Acknowledgements

First of all, I would like to thank my family, which continuously supports me in every new challenge I pursue. Thereupon, to Juan Diego, who motivated me and always kept an open mind to whatever approach I wanted to try. To Jorge Maya, whose knowledge I could always find when needed and who oriented me to achieve coherence. To Juan Alejandro, which provided me with all the resources and opportunities to learn and be updated within its field of expertise. To Juan Carlos, whose insights helped me to question myself and to not take anything for granted. Likewise, I would like to thank Camila and Laura, for helping me to keep track of our findings and make them look good. Finally, to Federico and Sebastián, for remaining patient and provide me with valuable feedback from their academic and professional experience as my colleagues. And to everyone who helped me with their laughs and cheers to keep my mood and goals aloft.

Table of contents

List of figures

List of tables

CHAPTER 1

Introduction

The present document aims to deepen in the understanding of the Computer Aided Styling (CAS)[1] field within *Design Education*. It does so throughout a review of the field and a case-study, where students' performance when using CAS tools towards form-giving is analyzed.

There is a global interest in trying to individualize education (Hedrick, 2012), in order to heighten students' learning and skills. And EAFIT University is no stranger to this tendency. Thus, there is an effort to take actions towards this goal. Even more, it can be a crucial step within the undergraduate program of Product Design Engineering (SNIES code: 7446), where differentiation could lead to better performance within the design context (Bar-Eli, 2013).

The project, therefore, takes interest in how students approach form-giving within a CAS dedicated environment. How they understand 2D shapes and *translate* them to a 3D system is also a project milestone. A general assumption is that, if students' performance is evaluated through a set of shape properties, common mistakes could be identified. Furthermore, they could be clustered in order to establish differentiated 3D form-giving approaches, under some profiles' categorization.

---

[1] Computer Aided Styling (CAS): digitalization of a product's outer appearance through 3D modeling tools (Bae & Kijima, 2003).

All in all, those profiles will serve as a starting point towards an individualized CAS education, since specific teaching strategies could be designed from and for them. This, eventually, will lead to significant improvements in their spatial thinking skills and design-based professional performance (Dankwort, Weidlich, Guenther, & Blaurock, 2004; Youssef & Berry, 2012).

Accordingly, the general hypothesis leading the project are as follows:

- Shape features associated with visual perception, sketching and image matching and recognition technologies can also be identified in 3D-modeling environments.
- A diagnosis of 3D-modeling students' use of such shape features can provide valuable insights for curriculum improvements.
- Clustering of common 3D-modeling mistakes related to shape features can generate students' modeling profiles, helpful for student's self-awareness and individualized pedagogical strategies.

1.1. Background

Design is an activity essential to people, used to modify their reality (Simon, 1996). In its core, design seeks to improve people's life and experiences, through products and services. Muller (2001) assures that designers consider two essential aspects of a product: the *technical function* and the *sociocultural value*. The first one is a *given* and a *means*, whilst the second is an *end*.

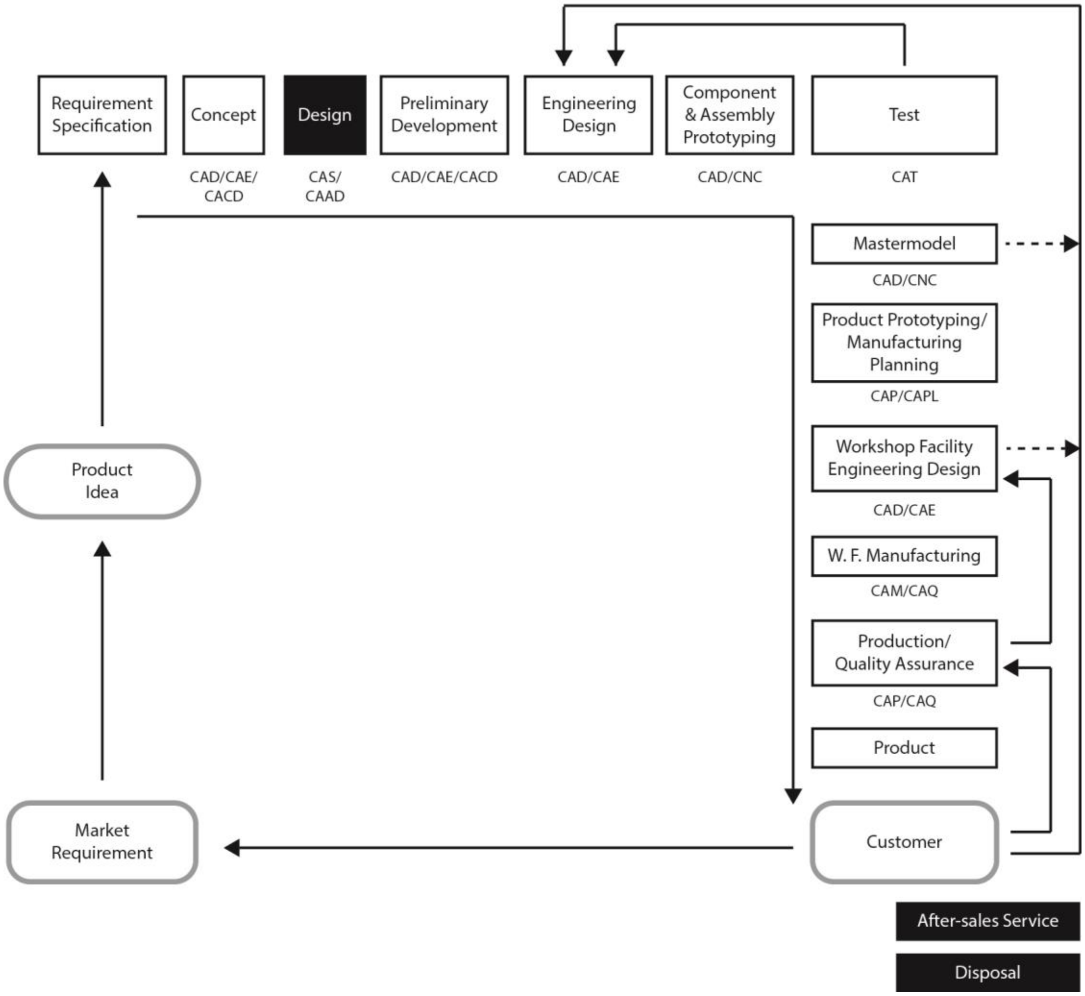
This ***end*** is usually perceived by users through product's shape. And this is achieved in a wide range of possible ways. Arnheim (1954) states that *"artistic activity, in particular, has its own 'reasoning' (...) but also architects and* ***product designers****, think with their senses during synthesis".* Therefore, not only research, but (life) experiences and intuition fuel the designer's thought process. And this influences form genesis and style to some extent.

And, regardless of the design objective at hand, *styling*[2] is always evolving to fulfill not only aesthetic requirements, going beyond the functional ones (technical function). It should help to understand product usability, be in tune with the available manufacturing processes and identify (the product) with the customer (Owen, 2013).

Accordingly, design methods are known to provide a guideline to assure an orderly workflow towards such objectives (Tomiyama et al., 2009). Usually, the general framework must be divided in several stages, which change their names according to the author. Among these stages, one who stands out when defining products' shape is the conceptualization phase. It becomes the first approximation to form and illustrates it in a general manner. This is where the styling activity starts to play a role. The designer and/or the team must dive into this stage to define the first formal solutions to the functional and aesthetic requirements. However, *"expectations for concepting are higher in terms of the creativity, freedom and obligation to innovate and explore"* (Takala, Keinonen, & Mantere, 2006). Thus, the challenges for guiding the concepting stage, which definitely influences de product´s shape, are numerous. The results of such stage will be the input for the design stage, where the CAS activity find its way into the process, as can be noticed in Figure 1 (Dankwort et al., 2004). It inherits the complexity due to variety and attempts to innovate in terms of shape from the mentioned conceptualization phase. And there is where some of the main CAS challenges are rooted: "*The knowledge about the previous process steps is to maintain the design intend, the knowledge about the following process steps is to guarantee their feasibility"* (Dankwort et al., 2004).

---

[2] Styling: activity intended to provide a product with a certain look (Person, 2011).



CAD	**C**omputer **A**ided **D**esign
CAM	**C**omputer **A**ided **M**anufacturing
CAE	**C**omputer **A**ided **E**ngineering /Simulation
CAP	**C**omputer **A**ided **P**rocess planning
CAT	**C**omputer **A**ided **T**esting
CIM	**C**omputer **I**ntegrated **M**anufacturing
CAGD	**C**omputer **A**ided **G**eometric **D**esign
CAS	**C**omputer **A**ided **S**tyling
CAAD	**C**omputer **A**ided **A**esthetic **D**esign
CAID	**C**omputer **A**ided **I**ndustrial **D**esign
CACD	**C**omputer **A**ided **C**onceptual **D**esign
CASE	**C**omputer **A**ided **S**oftware **E**ngineering
CAPL	**C**omputer **A**ided **P**lant **L**ayout
CNC	**C**omputer **N**umeric **C**ontrolled
FEA	**F**inite **E**lement **A**nalysis
PDM	**P**roduct **D**ata **M**anagement
PLM	**P**roduct **L**ifecycle **M**anagement

Figure 1. CAS within the product design process. Adapted from (Dankwort et al., 2004).

Generally, the first approach to shape is made using the initial ideas provided by any given brainstorming technique. Regardless of the technique, such as quick sketches or IDEO's[3] *"gadget boxes"*, ideas start to take shape in 2D or 3D, and some starting points are settled. In design methods, this is the idea generation (sub)stage. And throughout this process, those ideas are evolved and refined, acquiring detail levels. However, *"its fundamental characteristics should still be evident"* (Takala et al., 2006). That is why they should be taken into account when trying to understand shape generation in every design process. This is due to the fact that they provide the concept with some identity (design intent).

Andreasen (2011) comments about the different ways in which design activities could be supported through operations in computational environments. Therefore, this contrasts with sketching being the most popular representation mean for designers when trying to externalize their thoughts. With digital technologies in their peak, this activity has passed to be ruled by tablets or any other technological means, complemented by the 3D-modeling software available. However, in Anderson & Lilly (2004), the fact that these technologies have *"affected the confidence"* of new designers and their creative ability is exposed. It is interesting to have this in mind when analyzing the CAS dedicated software with the purpose of understanding how could they overcome those issues, while integrally supporting the styling activity.

Within the Colombian context, several (if not all) of the previously mentioned issues are still prevailing. Re-design[4] activities usually end up becoming traditional *re-engineering* efforts and academic environments do not change this tendency, rather than engaging in creative acts of discover (Hara, 2007). Design education, therefore, should undertake a fundamental role in trying to change our understanding of re-design under a holistic perspective. The attempt of this project is to set the grounds in order to understand some of the main difficulties presented during the CAS activities. These will be the starting point

---

[3] IDEO: award-winning global design firm that takes a human-centered, design-based approach to helping organizations in the public and private sectors innovate and grow. Source: About IDEO. (n.d.). Retrieved September 27, 2015, from http://www.ideo.com/about/

[4] Re-design: to re-evaluate the design of existing objects (Hara, 2007).

to improve current curriculums and to generate a more comprehensive design culture around products' shape.

Thus, the assumptions held by the case-study to support the general hypothesis are as follows:

- Performing a review of the CAS field will help to clarify essential issues to tackle within the current syllabus.
- Better understanding of designers approach towards products' form-giving are needed to generate actions for improvement.
- Identification of shape representation errors and their clustering will reveal cognitive trends.

Thus, it is expected that the contribution of the project within the program of Product Design Engineering at EAFIT University will reflect as follows:

- Knowing students' perception of the styling activity will be crucial for designing new academic approaches.
- Under an academic environment, students' self-awareness will encourage them to explore their own design and creative potential and stylistic profiles.
- Better understanding and control over the product's shape will boost creativity and better product designs and interactions (Product Experience (UX))[5].

1.2. Justification

Within the academic domain, the ever changing technologies are shifting classroom dynamics and student behaviors; and design education is in need to cope with this trend (Oxman, 1999). EAFIT University is not exempt from these changes. The implementation of new technologies and syllabus modifications are just some of the internal attempts to

---

[5] Product Experience (UX): self-awareness about the psychological effects felt when interacting with a product (Hekkert & Leder, 2008).

provide students with a better academic experience, matching international initiatives (Berry, 2008).

The need for the mentioned changes within the CAS field can be summarized by the following statement:

> *Product design as a term covers many forms of designing including the fuzzy area of styling. "In the context of aesthetic design, the difficulties to formalize knowledge are mainly related to the knowledge characterizing the styling process itself"* (Cheutet et al., 2008)[6]*. Styling, being easy to define as a process, however difficult to quantify, produces pedagogic challenges (…). Tangible feedback for students about their learning is essential, not only for studio tutor critique, but for self-reflective evaluation* (Berry, 2008).

Accordingly, in the area of form generation, 3D-modelers are also trying to cope with the new standards imposed by industry and designers expectations (Dankwort et al., 2004). Therefore, the focus of the project is to improve students' performance within the mentioned field of Computer Aided Styling (CAS).

This will be done throughout the analysis of a body of students deliverables were the more recurrent perceptual mistakes will be identified. These outputs are assumed to reveal subjacent students' cognitive approaches towards form generation. Therefore, some patterns are expected to be found in order to better understand academic dynamics within the 3D-modeling domain. These findings will be used to establish some modeling profiles and to improve course syllabus and professor's methodological strategies by segmentation of students' characteristics.

---

[6] Cheutet, V. et al., 2008. Preserving car stylists' design intent through an ontology. International Journal on Interactive Design and Manufacturing (IJIDeM), 2(1), pp.9–16.

1.3. Objectives

1.3.1. General objective

To identify students' shape perceptual errors and to establish a relationship with 3D-modeling profiles framed inside the CAS field boundaries.

1.3.2. Specific objectives

- To perform a review of the field on the main issues related to Computer Aided Styling (CAS).
- To select a form generation model in which the CAS field can be feasibly framed to better guide the project.
- To comprehend designers' approach towards form generation through literature examination.
- To carry out surveys in order to understand students' preferences and opinions towards their 3D-modeling approaches and abilities.
- To select essential shape properties needed to be considered when generating a 3D-model, suitable to be observed in students' performance.
- To design tests which allow the identification of the main perceptual errors committed by students when *translating* a 2D image into a 3D-model.
- Analyze the data in order to establish conclusions, identify patterns surrounding the perceptual errors found in students and generate clusters.
- To propose 3D-modeling profiles which can describe students' approach toward 3D form-generation related to the CAS activity, based on perceptual errors.

1.4. Scope

The main goal of the project is to better understand students' performance when executing Computer Aided Styling (CAS) related activities. This will be done through the identification of their most common mistakes around some essential shape properties. A statistical report will summarize those findings. Patterns will be sought in order to establish some common practices among students. This patters will be translated into 3D-modeling profiles, which are expected to help both students and professors to find improvement opportunities. Altogether, the findings of the project will nourish the 3D-modeling courses' syllabus at EAFIT University, specifically at the undergraduate program of Product Design Engineering.

1.5. Structure

This introductory chapter depicts the general aspects of the current *Master Project*. It includes the motivation behind it, the expected goals and the possibilities that lie ahead.

Chapter 2 establishes reference points in strategic domains. They involve the main ingredients required for a better understanding on how designers deal with 3D form generation in their daily tasks; and this is intended from a formal (related to shape and aesthetics) perspective, focusing on ideas generation and product embodiment. Thus, the reader will find specific topics that were subject of analysis for establishing the foundations of the project and the selection of the mentioned shape properties.

Chapter 3 presents the methodology followed during the project. It starts with a general reference model used to frame the project. Then, it establishes the context, the test subjects involved to understand the problem at hand and the expected limitations in terms of resources, time and accuracy. It ends with the selection of the properties to be evaluated during the case-study and the structure of the tests.

Chapter 4 presents the implementation of the case-study and reflects on the feedback gained from the users, as the information required to establish the results. A complementary work proposes a categorization of students' profiles, which could serve as a starting point towards improvements in a more individualized education. It also exposes what could follow from the current study.

CHAPTER 2

Theoretical framework

This chapter aims to outline the fields and concepts from which the project takes references. It presents different perspectives that have been taken in order to analyze the issues at hand, such as design cognition (Cross, 2001). That is, how previous theories and studies tackle the essential aspects of product form-giving, from traditional to contemporary means (Jonson, 2005).

Thus, the chapter first goes from the general concepts of aesthetics that will frame the project and their importance within product design; it will serve as an introduction for the subsequent sections. Then, it follows with the different approaches designers use to adopt towards form generation. Afterwards, it focuses on the 3D-modeling and CAS fields and the technicality of interest to the project. Finally, it deepens in the particular elements that will be used during the project case-study. The mentioned chapter structure has been assumed to help the report's narrative. However, concepts might be intertwined across sections.

2.1. Aesthetics and form-giving

When trying to understand aesthetics within the field of product design, one must arrive to the question: Why is it important to have a product with certain shape conditions? And, where are those conditions allocated? Among others, Muller (2001) disputes the famous assumption that *form follows function*[7]. As previously mentioned (see Background) he prefers to refer to the *technical function* and the *sociocultural value* conveyed by products' shape. This duality is certainly complex, reason why it is needed to set some grounds for the current work.

First of all, the focus of the project is framed within the CAS activity. As it will be explained in subsequent chapters (see Section 2.3), the CAS field develops around the outer *appearance* of the product. In Muller's subject-matter, this means that the main concern is being given to the sociocultural value of shape. Therefore, products' aesthetics will be understood as the pleasure induced over the senses (Goldman, 2001). Even if aesthetics are not limited to the *visual aspects* of a product, it is the intention of this work to narrow the study to this perceptual domain within the *Product Experience* (UX) (Hekkert & Leder, 2008).

Thus, when it comes to the issue of visual aesthetics, the means throughout which they are conveyed within a product is its outer *surface*[8]. And following on this visual domain, those product surfaces are the main interest of the *styling* activity (Hekkert & Leder, 2008).

---

[7] Form follows function: statement of the American architect Louis Sullivan (1896), in his article "The tall office building artistically considered".

[8] Surface: virtual entities used to visually support the design of industrial products (Fontana et al., 1999).

2.1.1. Aesthetic product design

Given the issue of understanding students' performance during CAS form-giving, it is important to set the ground rules that will serve as a starting point to evaluate such performance. First, it is necessary to introduce how the Aesthetic Product Design (DESPRO)[9] takes place.

In the big picture, visual aesthetic preference towards design objects can be categorized under three groups: psychophysical, organizational and meaningful properties (Berlyne, 1971). For the current work, the so-called psychophysical properties are the main focus, such as shape, size or color, given their quality of being *measurable* (Hekkert & Leder, 2008).

These properties and their elements, of course, are only a fragment of the body of work dedicated to the study of aesthetics. Project UMA[10], which seeks to define a Unified Model of Aesthetics, is just one example of the international initiatives that have tried to tackle and formalized a common language and concepts within the aesthetics domain. Some of the issues dealt by those initiatives search for answers to questions such as: Which are the differences among the aesthetic feeling, emotions and other affective feelings? How is the aesthetic product design (DESPRO) achieved?

However, it is not the purpose of this work to enter on such philosophical domains. Within the framework of the current study, it is sufficient to establish the general conditions the properties to be evaluated have to fulfill. That is, they have to pertain to the visual domain of aesthetics; able to be classified under the psychophysical properties previously mentioned; and have a technical relation with the features or commands supported by existing CAS solutions (in this case, PTC® Creo 3.0™).

---

[9] Diseño Estético del Producto (DESPRO), by its Spanish acronym.

[10] For more information refer to THE UMA MODEL. Source: THE UMA MODEL. (n.d.). Retrieved September 27, 2015, from http://www.project-uma.com/uma-model/

2.1.2. Positive aesthetic evaluation

As it could be expected, a brand or designer might seek that its products catch the attention of consumers and generate a positive reaction towards them. This is where the Positive Aesthetic Evaluation (EVESPRO)[11] enters to play a role.

About 50 variables related to such experience and evaluation have been established under 4 different classes (Hekkert & Leder, 2008). Several of those variables are also part of the previously mentioned organizational and meaningful properties by Berlyne (1971). Some are intended to assure a visual harmony, such as symmetry or balance; others seek to attract people's attention, such as complexity or novelty variables (Nadal Roberts, 2007). Taking into account the set-up of the students' deliverables within this project (see Section 3.4) and the CAS fundamentals (see Section 2.3), attention will be paid to those variables measurable from 2D images.

Again, apart from which variables influence the aesthetic experience, the EVESPRO looks for an answer to a general question: How are design aesthetics evaluated? Since this is an utterly complex task, the scope of this study centers on the matching between the given reference product and the 3D-model generated by the student. It is in the search towards such equivalence or fidelity where the selected shape properties are to be allocated.

2.1.3. What is styling?

Since CAS is essentially defined by the concept of styling, it is important to provide some insights on this notion. At some point, styling has dealt with the creation, appropriation and application of a certain style within the design of products (Person, 2011). As Owen (2013) states: "styling produced visual paradigms such as streamline design and other

---

[11] Evaluación Estética Positiva (EVESPRO), by its Spanish acronym.

excesses of form for its own sake”. The concept had its peak with the massification movement referred as Modernism in design (Lees-Maffei & Houze, 2010; Raizman, 2003).

However, in order to provide a framework for this paper, it is necessary to review the different definitions referring to styling. For that purpose, Table 1 summarizes the most relevant ones concerning the scope of this document. Thus, taking into consideration the different definitions presented in Table 1, an integral new definition within the boundaries of this project is proposed, oriented towards the fulfillment of the previously mentioned emotional experience (Hekkert & Leder, 2008; Hekkert & Schifferstein, 2008):

> ***Styling:*** product design bounded activity which through formal elements (geometric shape, color, material, textures) generates in the users an intended product experience or UX (self-consciousness of the psychological effects we feel when interacting with a product (Hekkert & Schifferstein, 2008). This UX includes tree main components: an aesthetic one (sensorial impression of pleasantness or unpleasantness caused by the product), a semantic component (values, symbols, expressive elements, metaphors) conveyed by the product, and an emotional component (emotion, feeling, mood) generated by the product (Smyth & Wallace, 2000).

Table 1. Styling definitions across authors and fields.

Source	**Styling-related fragments**	**Conceptual principles**	**Description**	**Retained “variables”**
Wang (1995)	“Imparting a particular type for products concerning form, appearance, or character”. “As styling encompasses a multiplicity of styles, fashions, design changes, redesigns and design variations within a product range aimed at different market segments, it becomes a strategic tool”. “Styling is a major strategy for product	Appearance Character Variations Product Differentiation	It focusses on how to support market growth through trends.	Appearance Character Differentiation

	differentiation when an industry moves into its mature phase".			
Catalano (2002)	"Creative activity to define a product that evokes a certain emotion, while satisfying the imposed constraints".	Creative activity Emotion Constraints	Emotional aspects of the products within the PDS.	Emotion
Owen (2013)	*"Functionalist styling*: The form of the product should be functional, help to convey how to be used, be easy to produce, fit into the user's environment and should contribute symbolically to the user's self-image".	Communication Usage Symbolism Self-image (relatedness)	Form has integral communication usages.	Symbolism
Norman Bel Geddes in book: *Horizons* (1932)	"Styling addresses the 'psychological' dimension of design to 'appeal to the consumer's vanity and play upon his imagination' (…) It was also used to appeal to irrational desires and thereby seduces potential customers (Lees-Maffei & Houze, 2010)".	Psychology Vanity Desires Seduction	Manipulation of consumers through their subconscious desires.	Psychology Desires
Elmo Calkin in book: *Consumer Engineering* (1932)	"Styling is used to raise goods from the commonplace to the distinctive. Stresses the need to manipulate psychologically consumers' latent and unsuspected demands and desires (Lees-Maffei & Houze, 2010)".	Distinction Manipulation Psychology Latent Demands Desires	Marketing strategy based on consumer manipulation.	Psychology Desires
Monti (2011)	"We consider as styling features both derived and constructive elements as long as they are connected with the aesthetic impression of the object (in contrast to engineering features, which modify the shape for functional or technical reasons). Styling features may also provide information about the technical quality (e.g. surface continuity) but mainly about the aesthetic and the emotional character of the product".	Aesthetics Emotion Product's character Impression	Shape as a means to produce aesthetic and emotional impression and to convey product information.	Aesthetics Emotion Character
Fung, Chong, & Wang (2004)	"Styling (the process used to enhance visual aesthetics of a product)".	Enhancement Visual Aesthetics	Aesthetic improvement.	Aesthetics
Podehl (2002)	"Styling concentrates on modelling the outer appearance of a product. It uses emotional and aesthetic values and does not serve any technical or functional purpose".	Outer appearance Emotion Aesthetics Non-technical/functional	Purely aesthetic function. Disregard of technical functionality.	Appearance Aesthetics Emotion
Person (2011)	"Styling - roughly defined as providing products with a particular look and feel".	Particularization Looks	Product's character.	Looks Feelings

		Feelings		
Eggink & Reinders (2013)	"Basis for these three styling principles is the communication function of design, where the messages that are transferred can be functional (where to hold your hands when manipulating a product) or mental. The last category can be rather straightforward, for instance when a product is perceived as "new" or "masculine" or "engaging", or more complex, when a product is perceived as "something that is going to cure me" or "something that is controlling me". These three principles are (1) level of complexity, (2) the combination of novelty and typicality, and (3) the framing of meanings with associations and metaphors".	Communication Message Function Perception Complexity Novelty Meanings Associations	Styling as a three-fold communication tool.	Communication Meanings Associations Functionality Perception
Chen (1988)	"Despite eternal arguments over the place of style and styling in design, a designer's duty includes shaping the forms of products to satisfy consumers' tastes". "The 'custom' design (…) is not only at the functional level but also at the level of style".	Consumers' tastes Custom design	It focuses on personalization of products.	Tastes Customization

However, the mentioned UX has found several obstacles as an affective construct: in everyday use, the concepts used to express affective states around the UX are used interchangeably or entangled. Furthermore, the dynamics of its components is still not well understood: i.e. the emotional character is mistaken with the aesthetic or semantic one. The differentiation between the aesthetic UX and the elements of the aesthetic appreciation are not clearly distinguished (Peng, 2008; Person, 2011).

2.2. Approaches towards form generation

After introducing some general notions about how aesthetics, user experience (UX) and styling play an important role for both design education and CAS activities, it is of relevance to explore how form generation usually takes place within these fields. Usually, it is assumed that such process takes place through *"cycles of analysis-synthesis-evaluation"* (Cross, 2001).

Furthermore, traditionally, form generation has been studied mainly from the drawing activity, due to its close relation with the concept of emergence (Menezes & Lawson, 2006; Oxman, 2002); this is to say, the generation of new (design) ideas. However, approaches to these new designs can be accomplished or motivated by different fields, perspectives or goals (Kavakli & Gero, 2001; Pittalis & Christou, 2010; Youssef & Berry, 2012). The following sections add some depth into some of those approaches.

2.2.1. The Problem-Solving Process and Form Generation Model

In order to set some study boundaries, this project will use the Problem-Solving Process and Form Generation Model of Wallschlaeger, Busic-Snyder, & Morgan (1992) as a general layout to provide a review framework. It also serves to guide the reader through the relevant stages onto which the project is focused. The fragments of the general model relevant for the current work are depicted in Figure 2. Appendix A provides a full detailed picture of the model (in Spanish).

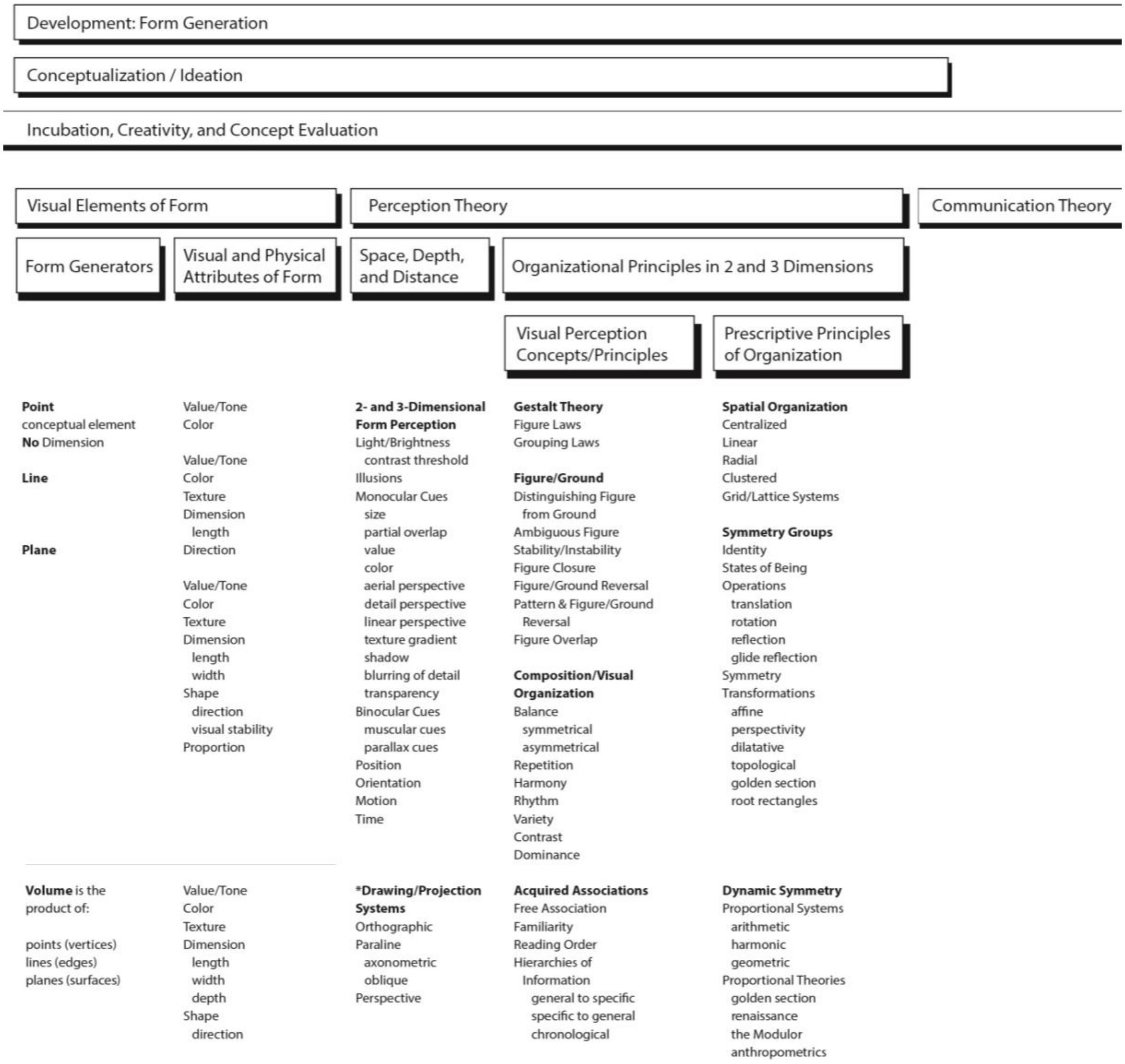
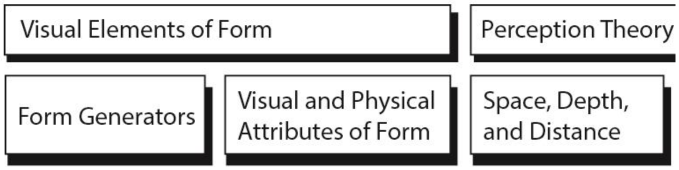


Figure 2. Problem-Solving Process and Form Generation Model. Adapted from (Wallschlaeger et al., 1992).

Generally speaking, the model presents a hierarchical structure, where the design process is decomposed in several stages. Each stage is further segmented into new phases or theoretical domains and their elements. Something interesting to be noticed about this model is the dual conception of the design process, as a problem-solving activity deeply intertwined with a form-generation activity. This is important within the project's context given its pedagogical nature, where knowledge is oriented towards a problem-solving design learning. Therefore, the elements of study from the Form Generation model will intrinsically support such learning.

Among these stages, the current study encompasses the stages of *Visual Elements of Form* and *Perception Theory*, as seen in Figure 3. Amid these domains, every sub-stage of the *Visual Elements of Form* stage are considered. From the *Perception Theory* stage, however, only the first sub-stage, namely *Space, Depth and Distance* is to be included. Thus, the sub- stage dealing with *Organizational Principles* is not considered; the reason behind this decision is that most of its elements rely on relational properties, which considerably increases the number of variables to be accounted and constitute a higher perceptual domain. The study, therefore, accounts for the most basic entities within the issue at hand, in order to set the ground for subsequent studies.



Point
conceptual element
No Dimension

Line

Plane

Value/Tone
Color

Value/Tone
Color
Texture
Dimension
  length
Direction

Value/Tone
Color
Texture
Dimension
  length
  width
Shape
  direction
  visual stability
Proportion

2- and 3-Dimensional Form Perception
Light/Brightness
  contrast threshold
Illusions
Monocular Cues
  size
  partial overlap
  value
  color
  aerial perspective
  detail perspective
  linear perspective
  texture gradient
  shadow
  blurring of detail
  transparency
Binocular Cues
  muscular cues
  parallax cues
Position
Orientation
Motion
Time

Volume is the product of:

points (vertices)
lines (edges)
planes (surfaces)

Value/Tone
Color
Texture
Dimension
  length
  width
  depth
Shape
  direction

***Drawing/Projection Systems**
Orthographic
Paraline
  axonometric
  oblique
Perspective

Figure 3. "Visual Elements of Form" and "Perception Theory" stages within the Form Generation model. Adapted from (Wallschlaeger et al., 1992).

The model, thereby, provides the first elements from which the project takes reference. However, deeper understanding of these and more elements involved with the form-giving process is also necessary. Next sections delve on more specific theoretical domains and approaches.

2.2.2. Spatial thinking and visualization

Before entering on a more specific segmentation of how form generation can take place, it is useful to have a first glance on the general abilities we use to rely on. Among all different postures on spatial thinking, most seem to agree on some general concepts and steps. With regard to spatial thinking and shape understanding, perception and visual imagery are two key concepts (Ganji et al., 2006; Les & Les, 2003), regardless of the differences that may exist between individuals when perceiving geometrical properties in an object's shape (Hoffman & Prakash, 2014). Perception deals with the stimulus from the real world, while visual imagery consists in the mental associations related to the given stimulus. This imagery includes a meaning and a visual representation of the object (Les & Les, 2003). This study is only concerned with the visual representations used during the CAS activity.

When referring to a 3D-oriented reasoning (Pittalis & Christou, 2010), 3D manipulations support *inference, prediction and creativity* (Youssef & Berry, 2012), activities taken in high regard within the design field. Accordingly, substantial efforts have been made in order to establish a common ground in terms of how we perceive our world and the main ingredients for such understanding. Recognition of shapes, therefore, are expected to rely on common elements like points, lines, planes (Kandinsky & Rebay, 1947); linearity, circularity, shadows and the concept of continuity (Piaget, 2013); and so forth. Product designers, therefore, are expected to have considerable abilities in terms of manipulating those shape elements and their relations, performing actions like rotation or transformation (Pittalis & Christou, 2010; Sorby, 2009; Youssef & Berry, 2012).

For instance, such spatial abilities have been classified by Piaget (2013) in three groups, namely *Topological, Projective* and *Euclidean*; this was based on his pioneering works on human intelligence and cognition. Youssef & Berry (2012) provides a review on this abilities. The project is mainly concerned with the last two. Projective skills deal with understanding of an object from different viewpoints. Euclidean skills deepen in further control of concepts such as distance, direction, etc.

These categorization supports the hierarchization and incremental acquisition of designedly abilities, in line with the scope of the current project. Similarly, Computer Aided education usually follows an incremental learning workflow, moving from 2D skills to 3D manipulations (Dankwort et al., 2004); most of these skills nourish from sketching activities (Menezes & Lawson, 2006; Prats, Lim, Jowers, Garner, & Chase, 2009). Thus, subsequent sections aim to depict how these abilities and manipulations are used to fulfill design intent from different domains.

2.2.3. Perceptual approach

When trying to tackle the issue of emergence from a perceptual and cognitive approach, the first question that comes to mind is: *How can a mental representation of the shape be externalized?* This, hence, constitutes the foremost approach towards form-giving.

In the process of going from a mental representation of the shape to an external one, it is essential to have a *mental catalog* of shapes that needs time to be acquired. That means it is determined by our past (Les & Les, 2008). The acquisition of such information is related to the *knowledge*, while the ability to make connections from that information is related to the *understanding* (Les & Les, 2008).

Such knowledge about shapes comes from a group of shape classes. Primitives, platonic solids or *geons* (Hummel & Stankiewicz, 1998) are some of the names that have been assigned to them. The so-called *visual thinking* consists of generating *mental images* (Marr, 1982), from *visual concepts*, which are built based on those shapes. The creative capacity or the ability to generate novel shapes is related to the *visual understanding*. This is the process in which the mental transformations of the visual imagination take place. And these transformations are the ones that lead to form generation, by a mental representation (Les & Les, 2008; Les, 2001).

Appearance or the external figure is what we commonly refer as form. It is necessary to use abstraction and generalization to generate those forms in our *mental images* and, thus, solve visual problems. Such abstraction is associated to more extent with the general or structural characteristics of the *mental images*; not that much with the details it could have. Oxman (2002) presents its notion called "The thinking eye", where externalization of mental imagery is categorized. As such, visual cognition of an object is divided in its *functional type, cognitive type, mental image, verbal concept* and *configurative schema*. Each category is filled with a description, which constitutes the general layout of the object being analyzed.

Several authors defend the role of sketching as a means to have an *internal* conversation with one-self. (Dörner, 1999) refers to this as a *self-reflective thinking*. Schön (1983) describes it by the well-known expression "seeing-moving-seeing", as effectively depicted in Oxman (2002) (see Figure 4).

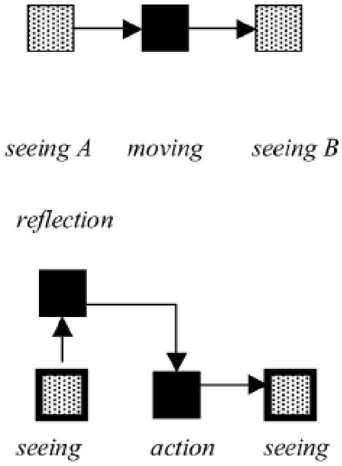


Figure 4. "Reflection in action" as a complement of "seeing-moving-seeing". Adapted from (Oxman, 2002).

All this has to do with the well-known term *visual thinking* (McKim, 1972). And sketching or drawing usually takes a crucial role in supporting that *kind* of thinking (Wim Muller, 2001). However, according to Verstijnen (1997) a sketch is a complement of that *mental* *image*, and presents implicit information we cannot directly deduce in our minds. This is a step in an ever refinement cycle Figure 5.

This is why our *imagination* is only capable of *solving* shape issues partially and there is a need to engage them by parts; for instance, Les & Les (2003) states that we can only understand 3D objects by means of 2D mental representations. This is similar to a process of *seeing* the different views or details as we imagine them. Figure 6 depicts a model able to summarize this notion.

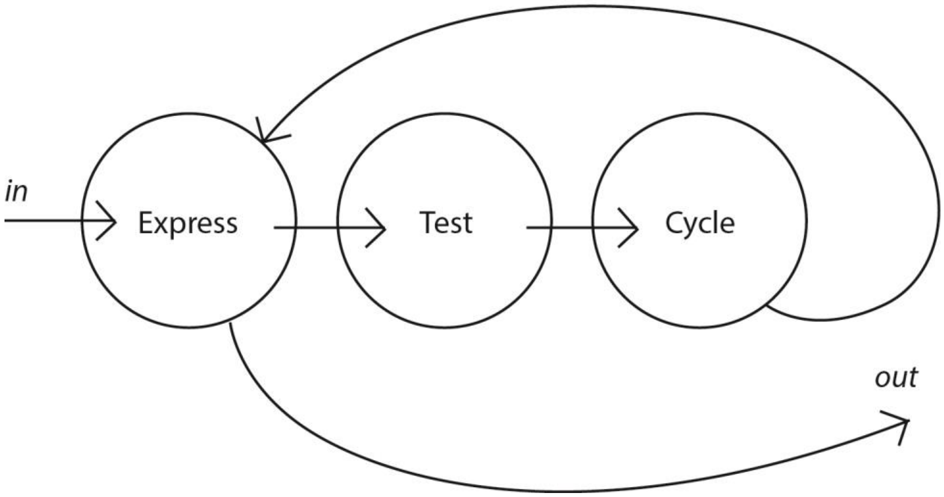


Figure 5. Design process summarized as Express, Test and Cycle. Adopted from (McKim, 1972).

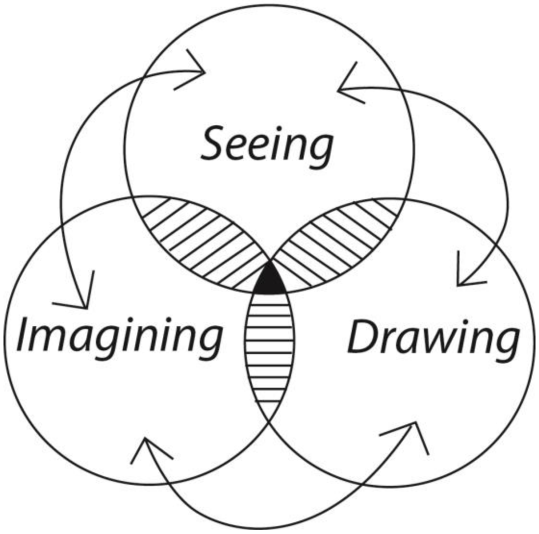


Figure 6. McKim's model of visual thinking. Adopted from (McKim, 1972).

In his models, McKim (1972) (Figures 5 & 6) depicts how iteration is fundamental for achieving the desired results, especially when different stakeholders have influence on the process (Takala et al., 2006).

Because of its intrinsic versatility, sketching is used to be the first shape externalization means for designers and thus helps in understanding designers' cognitive processes. Muller (2001) argues that *"designers feel the urge to visually support the ideation process"*. And this happens, most of the times, through sketching.

In accordance to this, Dillon (2010) explores the different ingredients that constitute the designers' process at the moment of giving shape to their ideas through sketching. Thus, she proposes to understand the cognitive process behind the sketching, in order to break it down throughout a general taxonomy. Moreover, recognizes that the basic skills for sketching can be taught, but the true novel creations use to rely on an implicit reorganization of a verbal or spatial learning. And that is part of each designer.

In fact, Purcell & Gero (1998) reckon the difficulty designers usually have when trying to explain their thought processes. Thus, generally speaking, the dynamics of the cognitive process answer to two overlapping principles: *unexpected discoveries* or *re-interpretations* (Dillon, 2010). However, other schemes are also analyzed as possible decoders of the designing activity.

Having in mind the previous ideas, form generation depends, greatly, on a *visual literacy*. Those people that can draw as well as build possess greater potential for understanding form generation. Due to the low costs they represent, sketches have surpassed building as a method for shape externalization. And, inside the drawing world, perspective is the closest technique to reality (Anderson & Lilly, 2004). For instance, Bar-Eli (2013) analyses the different types of representations and complements used by designers (specifically, interior designers), like axonometric, perspective, cross-sections, hatching, color, planes, etc., also supported by diagrams, narrative texts and descriptions.

In general, visual depiction is taken as crucial for supporting design activities, since it not only contains graphic elements, but implicit meaning. This boosts sketching as a highly powerful means. That is why Suwa & Tversky (1997) proposes a categorization to divide the design processes, based on visual and non-visual information. More importantly, such classification makes easier to find relationships among types of information and where the reinterpretations (novel designs) appear in the process:

> *An architect recognizes that the shape and size of one of the depicted features (a visual element) in a sketch would create a functional response in the movement of crowds through the space (a non-visual element)* (Dillon, 2010).

All in all, an interesting proposal made by Purcell & Gero (1998) assumes that there is a hierarchy in cognition processes through sketching, from lower to higher levels, namely: *physical, perceptual, functional* and *conceptual*. They follow a time line from creation to refinement of the design.

This opens an interesting approach to understand designers' cognition through sketching. However, further refinement may be necessary, since specific high level goals (from the conceptual category) might influence on lower level decisions in more complex ways (Hawkins & Blakeslee, 2007). Furthermore, a bottom-up or top-down influence between levels needs to be explored in more detail. But the schema certainly provides cues for identifying particular actions crucial for sketching and shape perception, which future analysis could try to measure (Dillon, 2010).

Similarly to the shape categories previously mentioned, Andreasen (2011) comments about the different ways in which design activities could be supported through operations in computational environments. One alternative he proposes is the so-called "*masters*". The idea is that models with pre-defined shapes help as a starting point for arriving to design solutions. The similarity with the shape categories relies in the necessity to use abstractions or formal simplifications as a starting point to comprehend or transform formal entities. And this is a stepping stone for eventually arriving to new designs. In the software scenario, they constitute the first stage for the mental image exteriorization.

Therefore, this contrasts with sketching being the most popular representation mean for designers when trying to externalize their thoughts. Whit the digital technologies in their peak, this activity has passed to be ruled by tablets or any other technological means, complemented by the 3D-modeling software available. However, in Anderson & Lilly (2004) the fact that these technologies have affected the confidence of new designers and their creative ability is exposed. It is interesting to have this in mind when analyzing the CAS dedicated software with the purpose of understanding how could they overcome those issues, while integrally supporting the styling activity.

As mentioned in the previously cited article, *"Knopp et al[12] agree that computer support of* the latter stages of design is easier to achieve since the product description is already well *known"* (McGown, Green, & Rodgers, 1998). The challenge, therefore, underlies in how CAS systems can help in the conceptual stage, in the same measure as they do in subsequent stages.

---

[12] Knoop, Breemen, Vergeest, & Wiegers (1996). Towards more effective capturing of empirical data from design processes. In Proceedings of 1st Conference in Descrptive Design, Istanbul.

In general, two relevant types of sketching has been identified: *idea-sketches* and *presentation sketches* (I. M. Verstijnen, 1997). The first ones, however, are more *intuitive* or personal, and have not been understood as well as the latter ones. In fact, while presentation sketches can find support in CAD software, idea-sketches do not have the same luck (I. M. Verstijnen, 1997; I. Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998).

All in all, this section dealt with the issues of perception and cognition, mainly through sketching, towards an understanding of how we perceive and generate shape, for design purposes. The root notions where presented and will serve as a basis for introducing new concepts and approaches along the following sections.

2.2.4. Methodological approach

Similarly to the previous section, within the methodological domain of form generation, one might want to answer the question: *How does shape answer to design requirements?*

It is important to reckon that a product can take its shape by different means of every day design task; that is to say, by drawing, building, modeling, etc. However, for this section, more emphasis will be given to those supported by design dedicated 3D-software.

In order to hold the *big picture* of the design process in mind and how form generation is supported by different 3D software (Dankwort et al., 2004), refer to Figure 1 (see Section 1.1). This is useful to understand the workflow throughout which shape is modified towards a fully detailed product. In terms of Computer Aided activities, a great deal of alternatives have appeared since the first “Loft Curves”[13] used by airplanes and ships

---

[13] Loft Curves: “Another mechanical tool, called a spline was also used. This was a flexible strip of wood that was held in place and shape by metal weights, known as ducks. When drawings had to be produced to scale, the attics (or lofts) of buildings were used to accommodate the large size drawings – the word lofting has its origins here. A spline “tries” to bend as little as possible, resulting in shapes which are both aesthetically

manufacturers. Here is where the first attempts to technify and standardize the design process from manual styling techniques took place. For a more recent history on this evolution, see Monti (2011).

However, the industry that really took the lead role towards the evolution of the field is the automotive industry (Bae & Kijima, 2003, 2003; Berry, 2008; Dankwort & Podehl, 2000; Hummels, Paalder, Overbeeke, Stappers, & Smets, 1997; Kara & Shimada, 2008; Kókai, Finger, Smith, Pawlicki, & Vetter, 2007; Monti, 2011; Santos, Stork, Filipe, & Jorge, n.d.; Singh, 2006; M Tovey, 1994; Michael Tovey & Owen, 2000; Michael Tovey, Porter, & Newman, 2003; Michael Tovey, 2002; Vignesh, Suganthan, & Prakasan, 2007; Z. Wang, Yang, Le, & Zhao, 2013; Warell & Young, 2011; Zimmermann, 2008). Consequently, it has tried to establish methodologies and guidelines that shine some light over the underlying designers' form-giving process. This works under the idea that form-giving abilities can be learnt and some standards applied for the styling profession. Therefore, two aspects are of relevance: which elements are part of the styling workflow? And what kind of requirements set the boundaries for the styling field? Both questions are assumed to be susceptible of generalization for other major design fields, and may help to understand shape properties or components.

Among the mentioned elements, one that outstands is the so-called *Character Lines* (Catalano, Falcidieno, Giannini, & Monti, 2002). These are abstract and essential curves that determine product's identity. More complex than canonical shapes, they rely mostly on continuity and influence surface characteristics (Bennett, 2011). However, the level of sophistication of this kind of curves are far from reach within the scope of this project. They demand highly specialized software and quality control as can be noticed in the car industry workflow (Catalano et al., 2002) illustrated by Figure 7.

---

pleasing and physically optimal. The mathematical counterpart to a mechanical spline is a spline curve, one of the most fundamental parametric curve forms" (Farin, 2002).

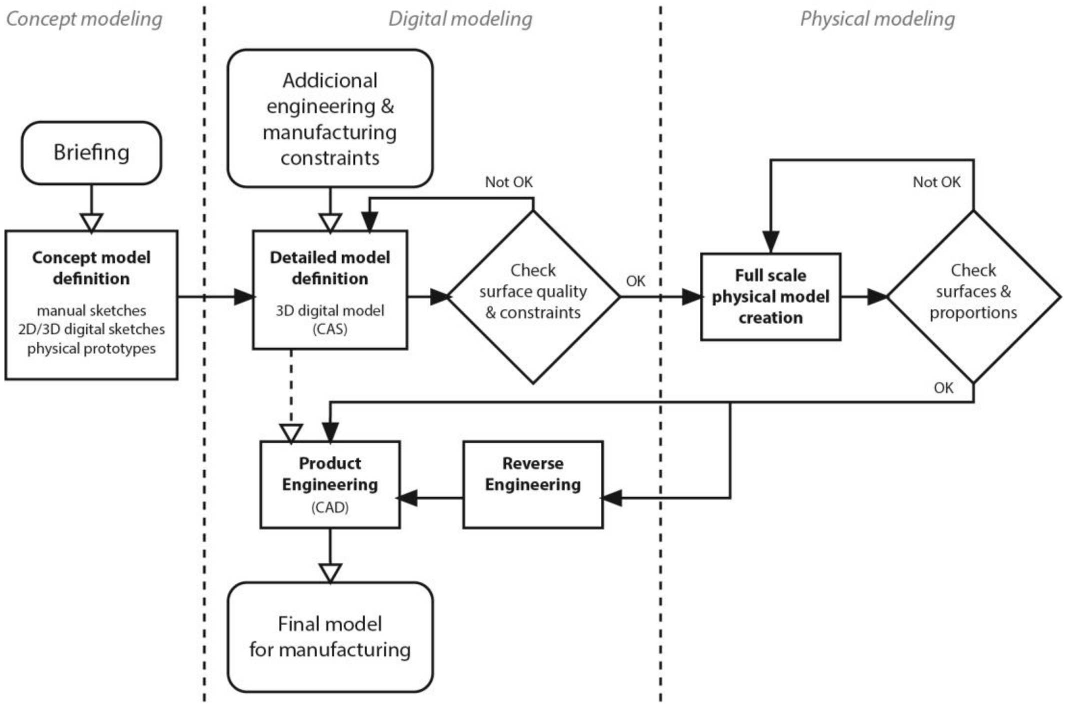


Figure 7. Automotive industry styling workflow. Adapted from (Catalano et al., 2002).

Something important to acknowledge is that CAS attempts to support creativity. That is, by means of letting designers to create complex shapes and maintain design intent along the product design cycle. As mentioned at the beginning of this document (see Section 1.1), conceptualization is the first approximation to the product's final shape. It then follows to the design or embodiment phase. This is why design education must strive to understand students' needs during the form-giving learning process. Additionally, cross-disciplinary teams are becoming more relevant every day. This implies a need for organizational techniques and technological support. And products evaluation will be done through some company's criteria, based on strategy and user needs (Smyth & Wallace, 2000).

In that sense, the ideal designer's *tool* will be one that enables creativity and, at the same time, helps to visualize and convey ideas to different stakeholders; always fulfilling the *design drivers* (Takala et al., 2006). This is why, inside the Computer Aided Design (CAD) field, the relevance of styling for communication is being held in high regard, through the so-called Computer Aided Styling (CAS).

Therefore, a fundamental starting point is to identify the sub-stages of the conceptualization phase. *Information acquisition, concept creation* and *concept evaluation* are the most general ones. Under this framework the designer must know the needs, the (business) environment and the technology surrounding the design challenge (Takala et al., 2006). Transversal to all three sub-stages should be the understanding of shape as a whole and its elements, as well. Thus, new technologies can also drive new designs, in terms of shape, since those technologies imply/drive new interactions; these interactions have potential for new forms.

Different kinds of concepts can also be identified: *"product development concepts, emerging concepts and vision concepts"* (Takala et al., 2006). The first ones deal with the definition of product specifications and require more detailed briefs, whilst the remaining two can have more fuzzy targets. The intention of this article is to focus on the concepts that obey to certain design requirements (*Product Development Concepts*). Ideas' input can stem from different brainstorming techniques, like sketches or the previously mentioned IDEO's *"gadget boxes"* (see Section 1.1), and an initial identity is conceived. From this sub-stage ideas evolved and get refined by detailing, while at the same time *"its fundamental characteristics should still be evident"* (Takala et al., 2006).

But this not only rests on the designers' expertise. Nowadays, customers are becoming a central part in the process of idea generation and, therefore, have influence in the original product shape to some degree (Bordegoni, 2011). Their direct involvement in the process is leading to a more accurate fulfillment of their emotional and aesthetic requirements and desires, among others.

Additionally, as mentioned by Smyth & Wallace (2000) brand identity or brand DNA is a decisive factor in shape decisions surrounding a product. Therefore, it could determine several design requirements related to form. Each brand establishes its own parameters to guaranty the coherence among product families or lines. And those parameters have to be clearly defined inside the design process. So, the brand designers or external consultants will support the process under those *limits*.

Finally, one of the most significant stages of any recognized design method is the *Detail Design*. Aspects such as production costs or manufacture tolerances have relevance in this stage. In Crilly, Moultrie, & Clarkson (2004) these issues are discussed, along with the way in which they could limit the skills of the designer; thus, leading to shape modifications in unexpected ways. Chan (2001) explains how a designer's style is influenced by the design process, given that this process usually follows a sequence, where *"tasks*" and *"goals"* impact the style of the outcome, when combined with the designer own approach.

However, in contrast to all attempts to guide design through *standardized* methods, W Muller (1989) emphasizes that they could have negative effects on an activity deeply influenced by intuition. He argues that *"designers feel the urge to **visually support the ideation process**"* (Wim Muller, 2001). In general, visual depiction (sketching) is taken as crucial for supporting design activities, since it not only contains graphic elements, but implicit meaning (sociocultural value).

Also in line with this, Wim Muller (2001) reflects on different functions associated with sketching within the design process. One of them talks about *"its incomplete definiteness"*, where *"the sketch can be interpreted in more than one way (...) or it can even lead to serendipity"*. This is an important aspect that supports creativity, and encourages some questions around whether CAS can provide designers with the same qualities.

All in all, brand and users' requirements, boundaries, technology, among others, have been tried to be taken into account within methodological approaches towards form generation. This highlights the complexity designers have to face in order to fulfill the expectations for a good aesthetic experience through form-giving. However, when considering the entire workflow, two key stages for styling stand out: sketching and design intent evaluation (after 3D-modeling). These activities will be further analyzed (see Section 2.4) for extracting essential shape features towards CAS form-giving.

2.2.5. Stylistic approach

A general description of the kind of *problems* designers deal with and the ways in which they use to tackle them is presented in Michael Tovey (1997). He emphasizes the implementation of a markedly visual communication when modelling an idea. This is considered as their language, which provides them with their own style.

However, contrary to what one could expect, most of the efforts in the attempt to assist the stylist are focused on the automation of the process; for instance, the so-called generative design (Krish, 2011). There, the designer will be in charge of the decision making, rather than the *doing*.

Jean-Francois, Carole, Fabrice, & Améziane (2007) establishes some design rules that obey to semantic concepts and links them to formal attributes. These elements are part of the form generation process from a designer's point of view. For this, the chosen technique was the so-called *agglomerative clustering*, which they argue is close to designers' cognitive processes:

> *"We experimented agglomerative clustering in order to develop design rules between semantic concepts, semantic adjectives and the low level dimensions of design: colors, textures and shape descriptors"*(Jean-Francois et al., 2007).

Smyth & Wallace (2000) propose a new shape synthesis method coherent with a company's *"Brand DNA"*, which can also generate a style. This is an ever more relevant term used to refer to the identity of a given brand or company. And this identity must be reflected upon its designs. Evidently, the use of such a method will held some influence on the designer's style when approaching form generation. Summarizing, this method allows the designer to define the product skeleton[14], while the software proposes different

---

[14] Skeleton: "Internal" structure of the product's architecture.

"skins"[15] for the given structure. Throughout a selection process it is possible to arrive to the desired shape after the software proposes different product alternatives. This is a clear case of how a designer's style will depend upon the tool type used in his creative framework; the one presented by Andreasen (2011) includes the so-called *"masters"* for the same purpose.

Similarly, Ma, Huang, Sheffer, Kalogerakis, & Wang (2014) presents a solution for *"Style Transfer"*. It is based on *shape analogy queries* as used by IQ studies, in a process including a *source,* a *target* and an *exemplar*, to produce an *output*. Plainly speaking, an object can adopt the style of another (reference) object, while maintaining its structure. Chen & Owen (1998), on the other hand, argue that style transference relies mainly on manipulation of faces, edges and corners.

Therefore, the previously mentioned attempts focus on the automation or assistance of form generation. But, as quoted before (see Section 1.1) Arnheim (1954) states that *"artistic activity, in particular, has its own 'reasoning' (...) but also architects and product designers, think with their senses during synthesis".* This is why in Bar-Eli (2013) the stylistic difference among designers is acknowledged. Thus, an attempt to relate (interior design) students' sketching styles with their own *"behavior profile"* is made. Both sketching and behavior profiles where classified under three classes: *Realization Oriented, Learning Oriented* and *Designer Oriented.* The *Realization Profile* centers on an end solution; the *Learning Profile* is expected to generate multiple alternatives for solutions in order to test and improve them; the *Designer Profile* focuses on self-reflective activities rather than the *real world* problem. Each profile uses specific sketching techniques, tools or approaches to visualize their solutions or process. It is assumed that the understanding of personal trends within form generation will help to improve design education, and provided a wider comprehension of the design field (Bar-Eli, 2013).

This is in tune with Schön (1983) description of sketching as a personal activity where the designer understands the design problem for him/herself. Chan (2001) also supports this

---

[15] Skin: "Outer" surface or surfaces of the product.

notion by enumerating some *"forces that generate a style"*, such as owns *"cognitive mechanisms, (…) personal preference (…) and seasoned design knowledge"*. Accordingly, in the frame of this study, the position adopted by Bar-Eli (2013) is taken as a reference, for a complementary work on the evaluation of students' performance around selected shape properties. It is expected that their performance will provide valuable insights towards their classification in specific 3D-modeling profiles.

2.3. 3D modeling, CAD and CAS

The field of 3D-modeling has to do with virtual representations of three-dimensional objects. Those representations hold underlying mathematical processing for visualization, rendering, simulation or manufacture (Dankwort et al., 2004; Tomiyama et al., 2009). A key concept is the term Computer Assisted; so, what is it? A brief introduction to its relevance and generalities is to follow.

What is Computer Assisted?

Design processes, at some point, aim to generate multiple solutions in order to select those which better meet the requirements. In such a process, designers usually engage in some trial and error activities (Michael Tovey, 1989). With the emergence of new technologies, the need for such ambiguity has been tried to be reduced. H. Wang (1995) exposes some essential activities of the design process susceptible of being aided through specialized software. Thus, styling can be assisted by means of *morphology*, *geometric transformation* and *interpolation*, centered in the conceptualization phase of design. All in all, designers engage in these activities using their knowledge, experience and intuition. However, the utmost intend of Computer Assisted is to facilitate such processes by creating and listing a higher amount of possibilities from which the designer can select or be inspired from (van Dijk, 1995; H. Wang, 1995).

According to Chen & Owen (1998) there are three kinds of CAD software: *functional*, *manipulative* and *rule-based*; but only *rule-based* ones can be style-related. One of the first and best representatives of the *rule-base* group is the theory of Shape Grammars (Stiny & Gips, 1971; Stiny, 1980). However, there is not enough sophistication yet to support styling in real products. Chen & Owen (1998) also proposes a system towards this goal, under the notion of "C*ustom Design*"; Figure 8 represents their system workflow from shape primitives. Figure 9 shows some of the stylistic elements designers could manipulate in the search of the desired style.

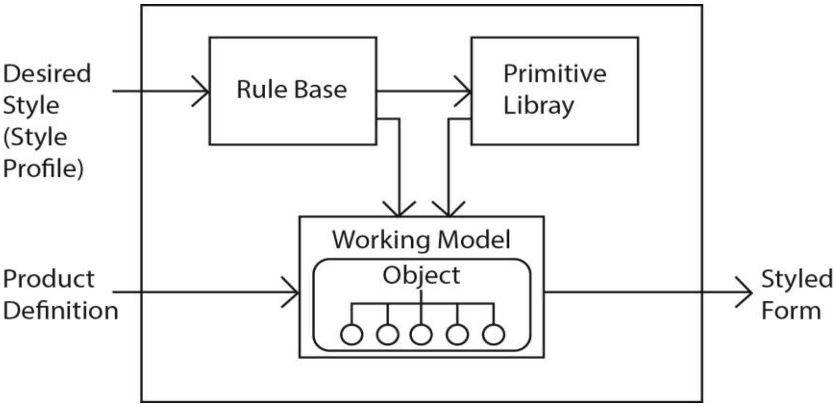
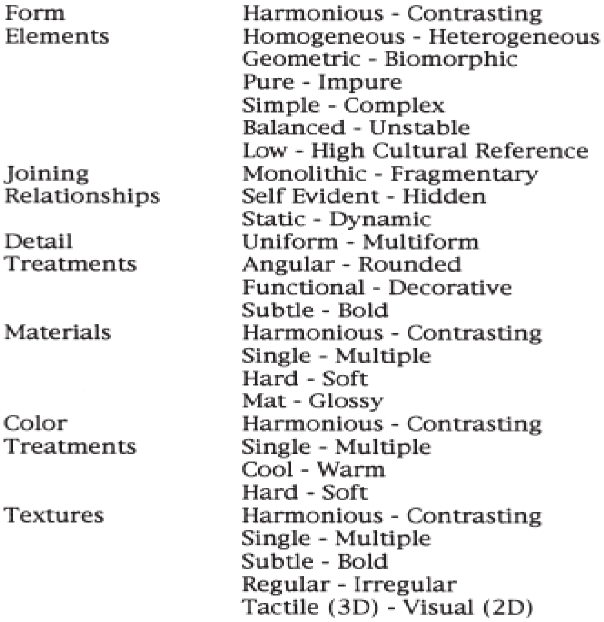


Figure 8. Rule-based system proposed by Chen & Owen (1998). Adapted from (Chen & Owen, 1998).



Form Elements	Harmonious - Contrasting
	Homogeneous - Heterogeneous
	Geometric - Biomorphic
	Pure - Impure
	Simple - Complex
	Balanced - Unstable
	Low - High Cultural Reference
Joining Relationships	Monolithic - Fragmentary
	Self Evident - Hidden
	Static - Dynamic
Detail Treatments	Uniform - Multiform
	Angular - Rounded
	Functional - Decorative
	Subtle - Bold
Materials	Harmonious - Contrasting
	Single - Multiple
	Hard - Soft
	Mat - Glossy
Color Treatments	Harmonious - Contrasting
	Single - Multiple
	Cool - Warm
	Hard - Soft
Textures	Harmonious - Contrasting
	Single - Multiple
	Subtle - Bold
	Regular - Irregular
	Tactile (3D) - Visual (2D)

Figure 9. Styling attributes for a rule-base system. Adapted from (Chen & Owen, 1998).

The next step would be to eliminate any sort of ambiguity by completely removing the need for trial and error. This will lead to analytical solutions which will match all the needed requirements (Andreasen, 2011; Smyth & Wallace, 2000; H. Wang, 1995).

2.3.1. What is CAS?

The field of Computer-Aided-Styling (CAS) has to do with the digitalization of a specific stage within the product development process (Bae & Kijima, 2003). It has evolved from Computer-Aided-Design (CAD) in order to deal with more complex shapes (Monti, 2011). Its origins date back to the first Knowledge Based Engineering (KBE) systems, such as iCAD (Bermell García & Ip-Shing, 2002).

Since some products cannot be decomposed into traditional canonical shapes, they need to be modeled from more ambiguous representations; thus, from initial free-hand sketches, some essential and meaningful curves need to be translated into digital entities. The so-called *Character Lines* (see Section 2.2.4) are an example of such entities (Monti, 2011).

From a designer's point of view, there are certain challenges that surround the CAS activity. Those complex shapes, along with the *Character Lines* and other elements of form, would convey all the elements that would fulfill the affective needs of the user. For instance, if the user wants a more *aggressive* shape, the designer would make his/her design providing acute angles, sharp points, etc. A crucial issue here is the need of a styling *taxonomy* and its automation; two European projects, named FIORES and FIORES-II have been pioneers for this enterprise (Dankwort & Podehl, 2000; Fontana, Giannini, & Meirana, 1999; Monti, 2011)

And from a users' perspective, he or she must be able to read, feel, interpret, infer, the shape elements conveyed by the designer. In an ideal case, these elements should arise an affective reaction coherent with the expectations of the designer, the company, and the product managers. However, a gap in this process is always acknowledged due to its subjective nature.

As Bae & Kijima (2003) summarizes, the CAS field has two general objectives:

- *"The conversion of a traditional styling method into a digitalized form".*
- *"2D/3D evaluation of designed shapes".*

As previously stated, CAS involves the digitalization of products' form. This implies a process in which an original image is to be translated to a *new* digital image, using specific software. Here is where some root concepts appear in order to describe such a process. One of these concepts is the already mentioned *Shape Grammars* (Stiny, 1980).

The purpose of such grammars is to reduce the implicit ambiguity of design, by means of computation. However, it is completely focused on the visual thinking involved in designing (Özkar & Stiny, 2009). Furthermore, it emphasizes the importance of decomposing a shape while at the same time considering its whole, when practical. This will lead to the necessity of having a shapes' vocabulary to be use in the creation of new designs as *sentences* (Stiny & Gips, 1971).

Within this theory, several concepts arise in order to explain the rules and procedures involved. As Stiny states:

> *"Design has reasoning within... Counting is at the root of computing and calculating. Visual calculation on the other hand, gives room for seeing as well as for counting"* (Özkar & Stiny, 2009).

Counting requires discrimination among parts. It all involves the ability to separate a shape into discrete parts, as well as an understanding of the whole. This is essential for CAS if we are to consider the need to *translate* shape attributes from an image to software.

> *“Shapes can be points, lines, planes, solids or combinations of these. Shapes also can have labels that indicate additional information about them and weights that indicate the magnitude of some formal properties. Labels are useful for adding more constraints necessary for tasks such as establishing the order in which rules are applied in computations”* (Özkar & Stiny, 2009).

Al-Kazzaz & Bridges (2012) present a practical application of these concepts in the field of architectural design. It relies on the manipulation of shape through *transformation*, *substitution* and *hybridization*. This is also based in the so-called *Euclidean transformations*. The method is summarized by means of two different approaches, named *Incremental* and *Morphing* (Figure 10).

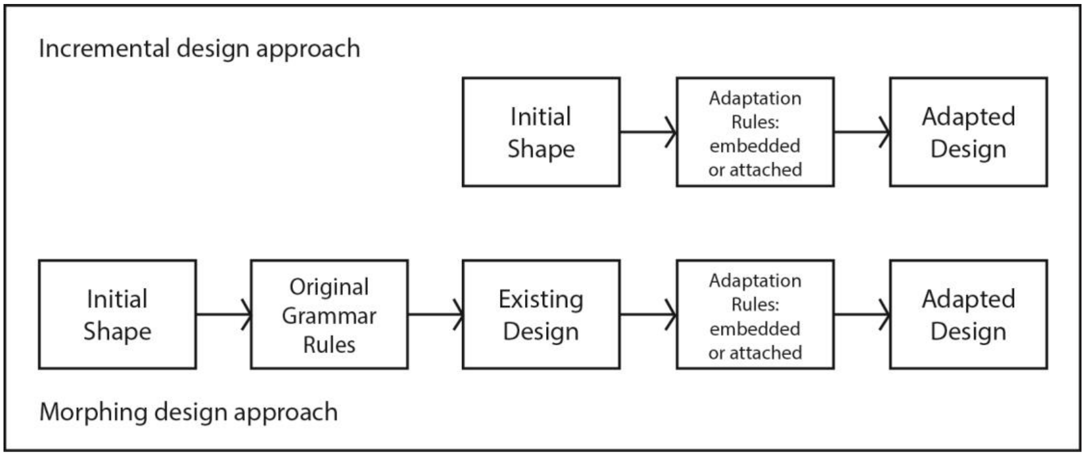


Figure 10. Incremental and Morphing shape grammars. Adapted from (Al-Kazzaz & Bridges, 2012)

Apart from this sophisticated researches within the CAS field, there is a common set of possibilities that every CAS system must provide to designers, regardless of its complexity. These will be the subject-matter for the next section.

2.3.2. CAS system characteristics

At this stage, it is important to reflect on how a general CAS system is made up. Among the different specialized software inside the Computer Aided Styling category, some are part of the CAD group as well (Dankwort et al., 2004). However, it is important to establish which characteristics are especially relevant for CAS, due to their high influence for shape generation. These elements can range from simple commands to highly specialized ones.

In Catalano et al. (2002), a general description of the modeling tools for aesthetic modeling is presented. Throughout the article, it is possible to identify some aspects that should be common to every CAS software. They aid designers to generate or preserve shape from the conceptualization stage up to the detail stage (when focusing on the stylistic design). The relevant elements identified for this study are:

- **Image importation**: the software allows images importation. This is useful for importing early concept sketches, so the designer or surfacer[16] can have a first grasp upon the desired appearance of the product.
- **3D curves:** allow the creation of 2D initial curves, which can be modified afterwards from every relevant plane/datum or view. They will generate the 3D contours of the product. However, *"this is often not an easy task, since some characteristic elements are exaggerated in the sketch to enforce the desired effect"* (Catalano et al., 2002).
- **Surfaces creation from boundaries:** Surfaces creation from 3D contours.
- **Surfaces analysis**: include reflection or curvature analysis tools (i.e. radius) in order to guarantee surface *fluency* and its connections (continuity). Nevertheless, *"even if in general a curve is considered good if its curvature is smoothly continuous, i.e. no rapid changes in the radius value and sign, there are not a priori criteria on the acceptability of the curve. It is up to the user experience to evaluate the*

---

[16] Surfacer: also known as modeler, is the person specialized in translating 2D sketches into 3D digital surfaces (Dankwort et al., 2004).

conformance of the curvature behavior with the desired results" (Catalano et al., 2002).

- **Reverse engineering data:** allow reverse engineering techniques (i.e. through 3D scanning of physical models: clay or sculpting). Hence, the software must allow the importation of this kind of data files for further refinement. Cycles of digital and physical modeling alternate until achieving the desired results.
- **Features:** include commands for adding details through the so-called *"Features",* such as fillets and blendings. This is a tendency generally proposed in the literature, who seeks to extend the concept of features beyond the mechanical design. The goal is to adapt it to stylistic design. However, the identification of such features in the design field is far more complex due to the intrinsic subjectivity of design.
- **Class-A surfaces:** commands that support *class-A*[17] surface modeling (i.e. Software such as Autodesk® Alias®, with its command *Align*). Its increasing relevance is transcending the automobile industry (which has traditionally held the biggest influence over the creation of CAS software).
- **Rendering:** rendering modules or environments that simulate the *street effects*. This will complement the reflection analysis tools in a realistic manner. Simulators of this kind must include the possibility of adding lights or selecting colors/textures to verify surface behaviors under different angles.
- **Functional "skeleton":** importation of CAD information relative to the functional components of the product, to be used as *skeletons or chassis* for styling activities. This reduces the time-to-market and avoids shape reformulation cycles for solving incoherencies. It depends somehow on the company workflow and schedules.
- **Touch technologies' inputs:** allow the *entry* of strokes or *inputs* from different 2D digitalization tools like Pen & Tablets (*touch* technologies).

---

[17] Class-A surfaces: *"good quality surfaces"* (under industrial standards) (Catalano et al., 2002).

These characteristics, somehow, provide insights on how to influence the designer workflow by means of a better understanding of styling or design features.

2.3.3. Design features and CAS field issues

Considerable efforts have been done in order to develop design features that support styling and shape attributes' evaluation (Cheutet et al., 2005, 2008; Fish, 2013; Hui & Li, 1998; Jean-Francois et al., 2007; Les, 2001; Ma et al., 2014; Peng, 2008; Michael Tovey & Owen, 2000; Van Elsas & Vergeest, 1998).

The main difference between this expected features and the existing ones is their *more-subjective* nature; basically, there is a contrast with traditional CAD mechanical design features (Fontana et al., 1999). *Mechanical features* usually relate to canonical shapes and correspond with direct Boolean operations. This generates CAD commands such as holes, rounds, protrusions, and so forth. One classification proposed by Fontana et al. (1999) is to divide *styling features* according to their way of assisting the aesthetic design. Thus, *Structural* features help in defining the general shape or frame, while the *Detail* features help in applying specific details in local regions.

Within the styling world, *semantics* and *knowledge-based* modeling systems are the fundamentals in which the *design features* are sustained (Cheutet et al., 2008). Concepts like sharp, convex, acceleration, tension, etc., are the ones such features seek to represent. Giannini, Monti, & Podehl (2004) also presents features in the same line; Figure 11 summarizes them. This is why the current project aims to improve students' skill in terms of shape control and fidelity; without such skills, students would not be able to arrive to high-level concepts and convey formal, brand or other attributes expected by the industry standards (D'Ippolito, 2014; Doblin, 1987).

- Radius/Blending
- Straight/Flat
- Soft/Sharp
- Hard/Crude
- Convex/Concave
- Hollow
- S-Shaped
- Acceleration
- Tension
- Lead in
- Crown

Figure 11. Some design features. Adapted from (Giannini et al., 2004)

In Monti (2011) the importance of formal aspects inside a sketch is mentioned, beyond the structural ones. Within this objective, the designer traces *Character Lines*, conveying a given style. As a complement for these lines, it is said that *features* could add emotional character to the product. The conservation of such entities in passing (transition) from a sketch to any modeling is essential to keep the design essence. The article provides a general vision of how *shape features* would help in achieving this objective.

However, this transition from 2D curves to 3D entities is not as *direct* as one might have thought. Masry & Lipson (2007) illustrates this issue very accurately (see Figure 12), where ambiguity from 2D to 3D transition is exemplified.

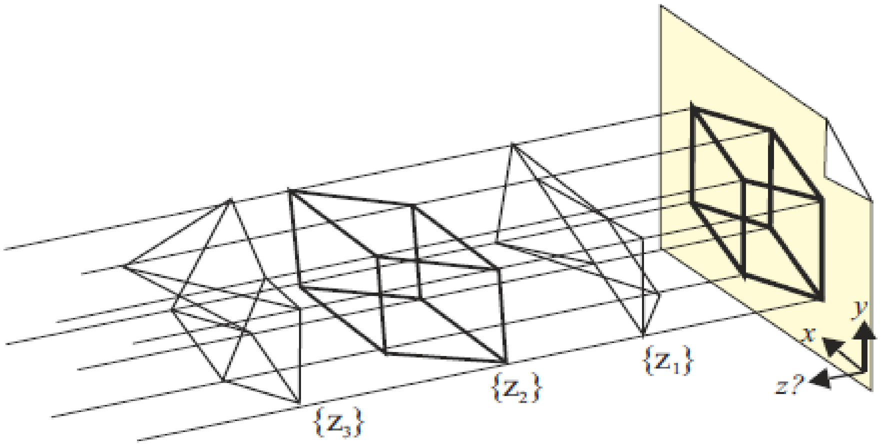


Figure 12. Issue of ambiguity from 2D to 3D transition. Adapted from (Masry & Lipson, 2007).

This is where one of the major difficulties for CAS dedicated software relies. The matter of how to assure aesthetic fidelity or equivalence is yet to be resolved. However, this not only depends on technical solutions. The need for a shape taxonomy for improving communication among designers, stylists, modelers or surfacers is recalled (Fontana et al., 1999; Olsen, Samavati, Sousa, & Jorge, 2008). Accordingly, system interfaces should be in line with this initiative, especially during concept to design stage, where only expressive sketches define products' shape (Olsen, Samavati, Sousa, & Jorge, 2009).

Features for the purpose of shape *blending* (Hui & Li, 1998), *displacement* (Van Elsas & Vergeest, 1998) or specific surface attributes such as *bumps* or *channels* (Cheutet et al., 2005) have been proposed, some *morphology-related* and others *topology-related* (see Figure 13). Thus, on the one hand, *topology* is linked with the location, while preserving joints, intersections, etc. *Morphology*, on the other hand, is linked with the shape itself, independently from location.

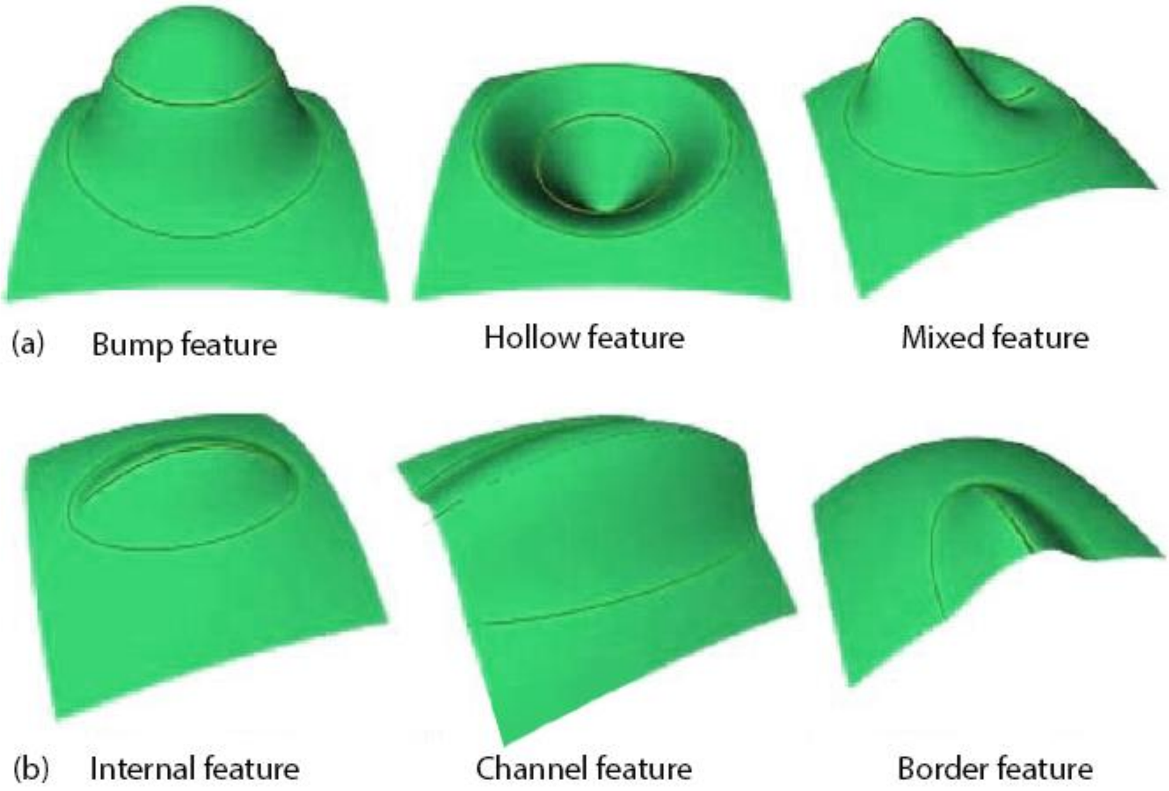


Figure 13. Morphology (a) and Topology (b) features. Adapted from (Cheutet et al., 2005).

Taking into consideration the previous figure, it is clearer why a shape taxonomy has been linked with such design features. If a designer is to convey aesthetic attributes to the design team and decisions are to be made, a common ground must exist, given the level of specificity that language can achieve; Fontana et al. (1999) provides some examples of how this taxonomy can be built (Figure 14).

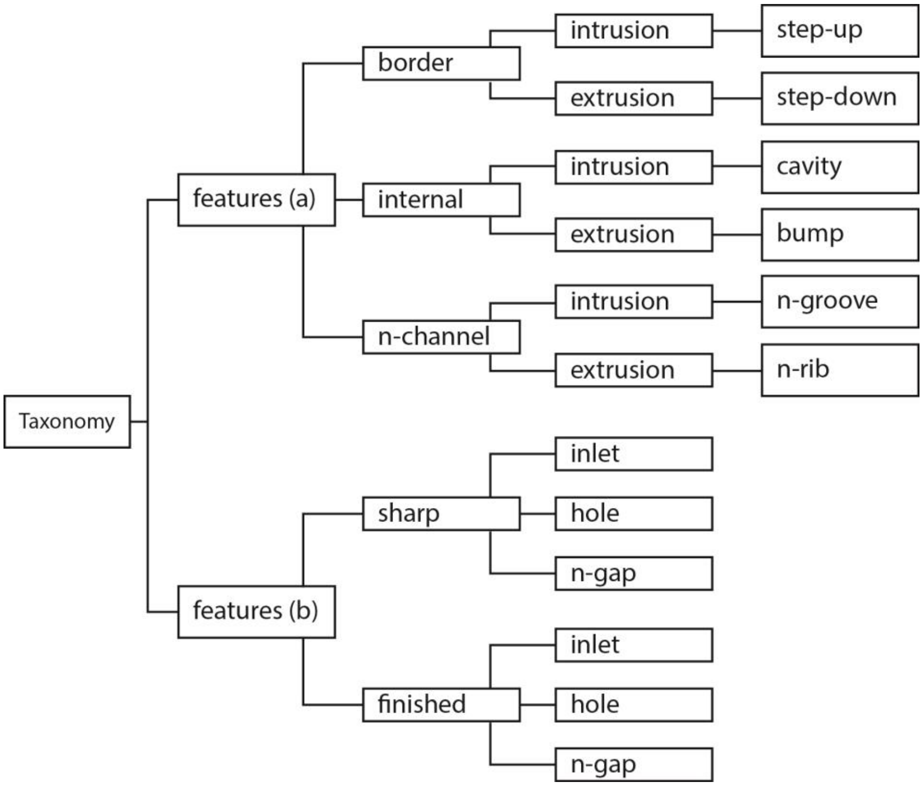


Figure 14. Brief example of shape taxonomy for design feature definition. Adapted from (Fontana et al., 1999).

Another special issue of styling, already mentioned, has been around the degree of fluency perceived through a surface. It is, however, more technically sophisticated and outside the boundaries of the current project. Nevertheless, it takes high importance within the development of the field, and somehow linked to design features. Usually, it is referred as Class-A surfacing (see Section 2.3.2) and includes levels of curvature refinement named by G-1, G0, G1, G2 (Catalano et al., 2002; Dankwort et al., 2004; Fontana et al., 1999; Podehl, 2002).

Again, design features rely on shape control. And such control depends on the geometrical properties in which a shape can be decompose. Students must be skillful enough in order to achieve such control. This depends on two essential steps in shape and attribute translation from 2D to 3D: *observation and execution*. The next section will briefly review how these steps have been tackle from traditional to contemporary means.

2.4. Visual perception and shape components

"Shape is one of those concepts that seem intuitively obvious, but prove to be surprisingly difficult to define" (Li, Sawada, Shi, Steinman, & Pizlo, 2013).

Throughout the former sections, concepts around aesthetics, visual thinking and 3D-modeling were exposed. Hopefully, they summarize the complexity of the styling activity within the design field. This section, on the other hand, seeks to present the evolution of design solutions, rather than theories or researches. Its purpose is to reflect on how products' shape has been decomposed towards higher accuracy in objects' visual representation.

For such purpose, human performance is evaluated around some cues which excel among others. Such cues have been long taken as a matter of study since some paramount work like Berlyne's (1971) psychophysics properties[18] (Hekkert & Leder, 2008). This includes features such as size, shape, color, etc. Some other design-related features have been classified under the well-known groups of *Elements* and *Principles* of design; Adams (2013) provides a schema for this grouping, as depicted in Figure 15. The findings of this chapter will constitute the input for the case-study properties selection. It is under the previous

---

[18] Psychophysics properties: objects' formal qualities.

considerations that the present project will be undertaken. The following sections will dive deeper on some of these notions.

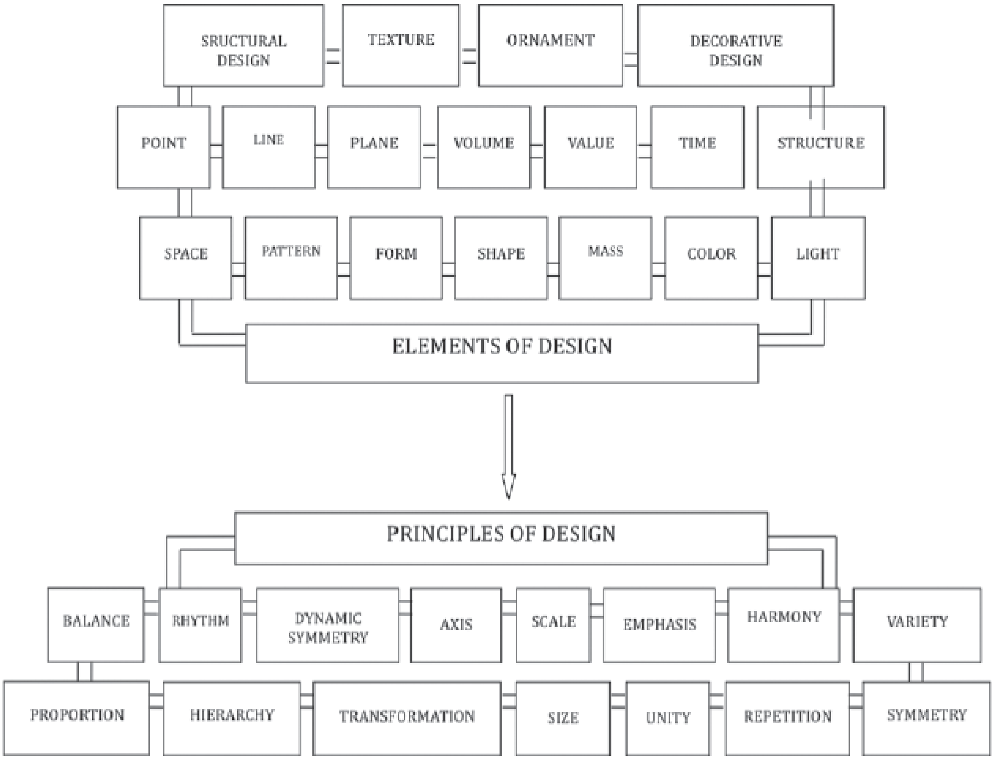


Figure 15. Some design features under the categories of Elements and Principles of design. Adapted from (Adams, 2013).

2.4.1. Sketching and observation

Sketching has been part of the design activity foundations (Bilda, Gero, & Purcell, 2006). It has had a transversal influence throughout the history of the profession, from early to sophisticated solutions (Anderson & Lilly, 2004; Bar-Eli, 2013; Cheutet et al., 2005; Company, Contero, Varley, Aleixos, & Naya, 2009; Dillon, 2010; Ibrahim & Pour Rahimian, 2010; Jonson, 2005; Kavakli & Gero, 2001; Levet, Granier, & Schlick, 2006; Masry & Lipson, 2007; Menezes & Lawson, 2006; Olsen et al., 2009; Purcell & Gero, 1998; Suwa & Tversky, 1997; Michael Tovey & Owen, 2000; I. Verstijnen et al., 1998).

Similarly, the field of visual perception and representation is utterly vast and has attracted the attention of researchers from long ago. For instance, Marr (1982) provides a comprehensive review on this issues from a computational approach. It can also be studied from different point of views, such as psychology and biology (Attneave, 1954; Won, Yeo, Ban, & Lee, 2007), medicine (Hassanpour, 2015), linguistics and semantics (Boutonnet, Dering, Viñas-Guasch, & Thierry, 2013; Cheung & Gauthier, 2014), art (Stiny & Gips, 1971), architecture (Menezes & Lawson, 2006) and even philosophy (Fish, 2013; Hill & Bennett, 2008).

To give an example, Fish (2013) presents such complexity by comparing Lewis (1929) and Peacocke (1983) notions on visual experience; each new element added to the experience will imply new variables (Figure 16).

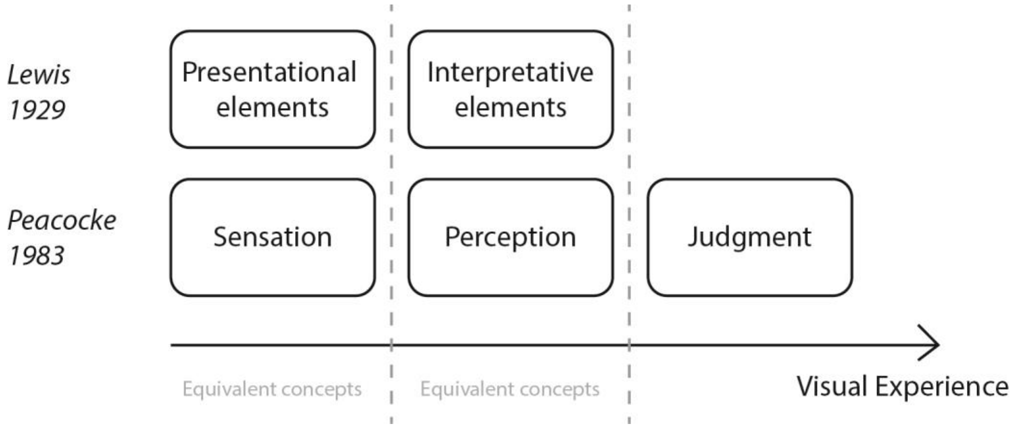
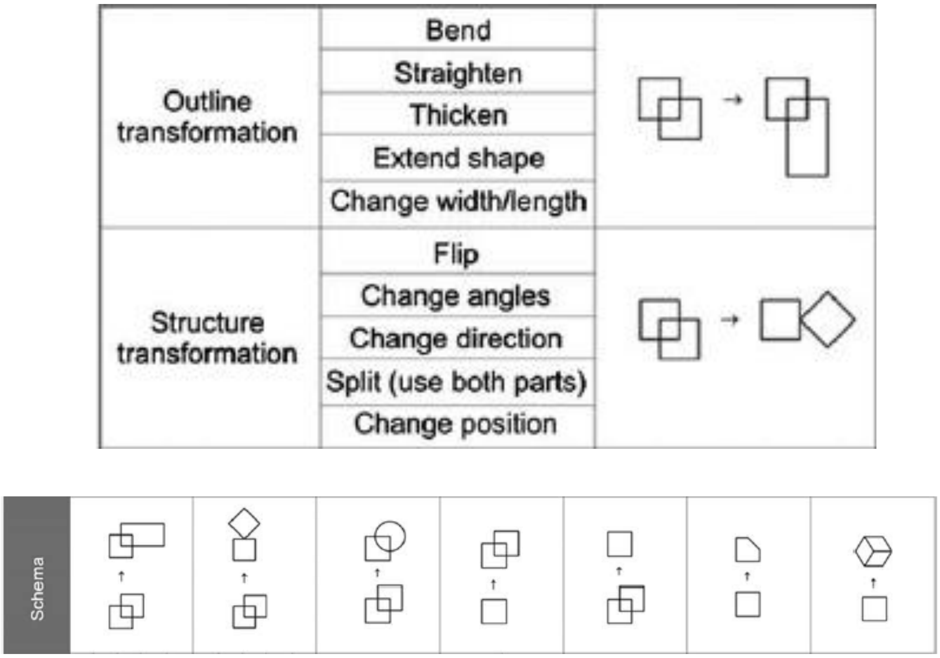


Figure 16. Lewis and Peacocke's views on Visual Experience. Adapted from (Fish, 2013).

Hence, regardless of the approach, technique, technological mean or style, sketching strongly depends on observation and the underlying visual thinking (see Section 2.2.2). This thinking domain has multiple theories and some might defend its subjectivity (Hill & Bennett, 2008; Hoffman & Prakash, 2014). However, it is a common posture to assume that our reasoning decomposes shape into parts by means of its boundaries, for instance, as stated by Hoffman & Richards (1984); this process relies on an inductive process of shape categorization.

Thus, it is of interest for the current study to explore theoretical proposals where objective understanding of shape and its elements is at hand. It is important to notice that among cues such as luminance, color, texture and shape, the last two usually outscore the others, being shape the most influential one (Elder, 2013). However, shape is complex in itself, since it not only includes object's contour, but also underlying details. Furthermore, it can be taken as a whole or by parts or sub-shapes (Biederman, 1987; Erhan et al., 2011; Pittalis & Christou, 2010; Stiny, 1980).

Prats et al. (2009) integrally explores sketching form-giving and depicts the concept of sub-shapes in relation to software assistance and *shape-rules*. The article is oriented towards shape transformation for design alternatives. However, it implicitly proposes shape properties to achieve the mentioned goal. In doing so, the authors segregate a shape into sub-shapes, by identifying entities or *shape-rules'* changes such as angles, positions, widths vs. lengths (Figure 17).



Outline transformation	Bend Straighten Thicken Extend shape Change width/length	
Structure transformation	Flip Change angles Change direction Split (use both parts) Change position	

Figure 17. Sub-shapes generation through shape-rules, their transformation alternatives and visual schemas. Adapted from (Prats et al., 2009).

Hsu, Chang, & Chuang (2005) presents a study where subjects were asked to compare objects' similarity. It does so by testing how individuals compare images and results indicate strong dependence on shape features. Some of the most relevant ones were ratio (proportion) and radius.

Similarly, Baylis & Driver IV (2001) have focused primarily on the importance of symmetry and repetition. An interesting finding to be mentioned is the fact that symmetry is easily recognized regardless of the contour complexity. Other shape features, such as repetition exhibited higher perceptual difficulties.

Hummel & Stankiewicz (1998), on the other hand, explored features in relation to design primitives or geons; object and shape classes were identified based on aspect ratio, curvature, parallelism, in working with simplifications of desk lamps, teapots, cars, among others.

Chen & Owen (1998), somehow more generally speaking, states that faces, edges, corners and joints are the details in which a shape relies to compel a certain style. This are essential features for determining specific attributes. If two objects are to have the same style, they would necessary have the same *values* for details and joints.

Fish (2013) recalls the feature-integration theory proposed by Treisman & Gelade (1980). It states that orientation, spatial frequency, color, brightness, etc., are basic features that people can notice even before object category classification. The latter process is expected to be a higher-level perception domain.

2.4.2. Image matching and object recognition

Object recognition systems appeared around the 1950s (Ommer (2013) in Dickinson & Pizlo (2013)). From there, a common approach towards the understanding of shapes' nature is to formalize the possibility of its segmentation. It can be done by classification of different shapes (Les, 2001), shape-rules (Stiny & Gips, 1971), components (Biederman, 1987), connectedness (Bhattacharjeea & Mittalb, 2015), regions (Guerrero, Auzinger, Wimmer, & Jeschke, 2015), visual Gestalts (Wagemans, 2013) and so forth. Some of these and more state-of-the-art approaches within the fields of object recognition and image matching are thoroughly exposed in Dickinson & Pizlo (2013); it deals with both artificial (objects), natural (people, animals, plants) and scene digital recognitions and reconstructions.

Thereby, most software solutions have achieve object recognition or image matching using points' clouds amid the subject of photogrammetry[19] (Gruen, 2012). Some focus on *relational* properties and others on *local* properties; some recognize global contour shapes and some specific geometries; in any case, all of them attempt to guaranty recognition in spite of data noise, occlusion, object orientation or viewpoints, etc.; they

---

[19] Photogrammetry: image measurement technique mainly based on surfaces' point clouds location.

can also be based on *stochastic* or *deterministic* frameworks. All in all, a brief review of this concepts can be found in González, Adán, & Feliú (2012) and Gruen (2012).

But, in order to achieve these types of segmentations, essential shape properties must be detected or proposed. For every mentioned segmentation theories, different shape properties or entities are more suitable.

Gruen (2012) classifies image matching into three categories: *intensity-based*, *feature based* and *relational*. Evidently, *feature-based* techniques are more related with the present work. However, this specific technique relies on patches, corners, junctions, edges and so on. These are not the kind of features the project aims to deal with, but exemplifies the relevance of sub-shape segmentation across the field.

According to Biederman (1987), the manner of segmentation and analysis into components does not appear to depend on our familiarity with the particular object being identified. Among others, properties such as symmetry, collinearity, curvilinearity, parallelism and cotermination are reviewed; Figure 18 shows a proposed workflow for object recognition (Biederman, 1987).

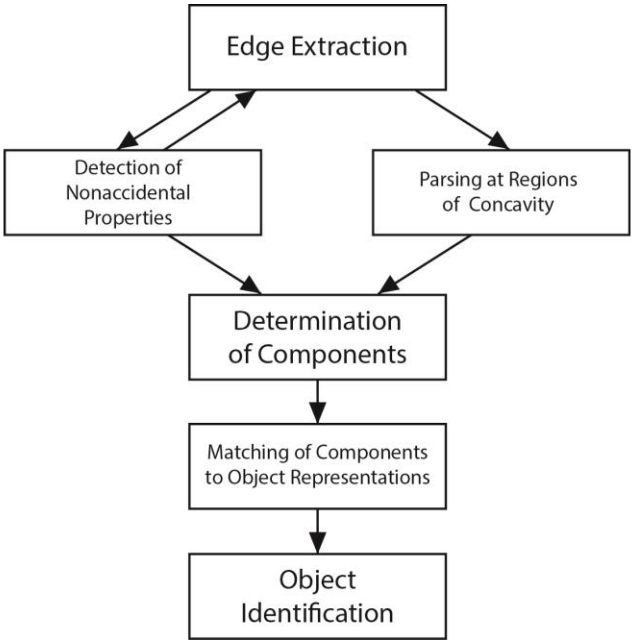


Figure 18. Object recognition workflow. Adapted from (Biederman, 1987).

Zhang & Wang (2014) proposes a method for recognizing both local and global object characteristics towards object categorization. Features like shape, location and size are used locally. Somehow alike, Anvaripour & Ebrahimnezhad (2013) recognition method centers on extraction of boundaries positions. (Les, 2001) proposes different classes of shapes based on *convex* and *concave* polygons; this mostly accentuate the importance of curvature or radius in shape recognition.

Hassanpour (2015) image matching depends on orientation, scaling and size relations (ratio). For higher accuracy, the method uses angles, circularity and eccentricity. For multi components within the same image, it uses location relative to selected origins. Equally, relation of shape regions and the whole are also frequently displayed in the literature; for instance (Guerrero et al., 2015) superficially shows an example of such relations (see Figure 19).

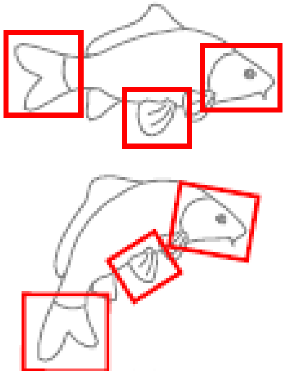


Figure 19. Shape regions within the whole. Adapted from (Guerrero et al., 2015).

Marr (1982) presents a classical framework for *"deriving shape information for images"*, based on shape primitives. A thorough review on the different representation methods and classifications can be found in González et al. (2012).

Many of these mentioned features are common to different researches and methods. These are the ones of relevance for the current study. All in all, it can be notice that sophisticated systems articulate similar approaches to those more empirically used in observation of designers' sketches or theoretical approaches of visual perception. A cross-matching procedure from the most relevant theoretical studies is performed in order to select the most distinctive features for the case-study (see Section 3.3).

However, it is also interesting to mention some other approaches used in the field of computer vision, object recognition and the like. Some studies, for instance, emphasize and measure the influence of context in such recognition process (Poltoratski & Tong, 2014).

Some other, on the other hand, discriminate recognition by levels of judgment (Cheung & Gauthier, 2014), separating object class from its individual attributes. In line with this, some stress that language and terminology deeply affect perception (Boutonnet et al., 2013).

A different domain centers on perception of novel objects, where categories and judgment levels are somehow obsolete or might bias such recognition (H. Zhang, Liu, & Zhang, 2013). Other approaches accentuate recognition by means of shape constancy and the perspectival properties of shape (Bennett, 2011); this is a relational approach among shape boundaries. Fontana et al. (1999) takes on the notion of transition among boundaries as another relevant condition for recognition.

All of these, of course, are interesting approaches. Nevertheless, these are somehow more elevated concepts towards recognition. This study, therefore, will try to stay within the boundaries of low-level perceptual recognition domains. As it will be notice, students hardly detect shape elements, relations and changes when translating 2D images to 3D models. The next chapter will depict the procedures carried out in order to revel such shortcomings.

CHAPTER 3

Methodology

This chapter is concerned with the presentation of the project's case-study. Therefore, it frames the study in terms of context, subjects of study and procedures.

Bassey (1998) reflects on the importance of understanding, evaluating and making changes on educational practice. This project attempts to do so by means of performing a diagnostic case-study (Creswell, 2012; Yin, 2013). Firstly, a model which contemplates the general aspects of form generation was selected as the project's framework (see Section 2.2.1). It summarizes, somehow, the elements mentioned throughout the theories and approaches from the previous chapter. Then, the conditions under which the project took place are exposed; that is to say, the project context description. A survey on students' opinions and approaches towards form-giving is also depicted, in order to expand our comprehension on students' needs. It is followed by the selection of the properties to be evaluated across the students' deliverables and the explanation of how the tests were implemented.

3.1. Project context

As mentioned, there is a clear tendency in CAD systems towards assisting the styling process in an increasingly manner, which eventually will end in the automation of several parts of such process.

Therefore, it is important to understand the general layout of the form generation process, in order to determine its limits and phases. For such purpose, this project used the Problem-Solving Process and Form Generation Model presented by Wallschlaeger et al. (1992) as a reference framework. It will guide the reader throughout the different aspects involving perceptual and organizational elements of design (see Figure 2, Section 2.2.1). It will help to keep in mind the *big picture* of the form-giving (design) process, as well as CAS sensitive aspects.

From the previously mentioned model, this report reflects on underlying aspects which tackle specific approaches towards form generation. The selection of the properties, hence, is to be in tune with the elements related by the model.

Generally speaking, all the technological approaches explored throughout the report aim to achieve object recognition or matching by means of image digitalization, as automated as possible (Dickinson & Pizlo, 2013). The difference with this specific project is that it *looks* at how accurate is students' *observation* for executing and evaluating such matching. The importance of improving students' visuospatial self-awareness and skills within the local context (Antioquia, Colombia) can be noticed in the findings of Rios (2012), where usage of CAD tools to support design is related. Students are expected, therefore, to perform correctly under professional conditions around this tools.

The project described in this report is allocated within the context of the undergraduate program of Product Design Engineering, at EAFIT University. It is framed in an 8-weeks course named ID0267- Modelación 3D2 (3D-modeling II).

In order for students to be able to participate, they have to already have passed the previous course, namely ID0245-Modelación 3D1 (3D-modeling I). As such, students are expected to already have a minimum literacy in how to interact with a 3D-modeling software (Creo™ Parametric 3.0) and how to model *geometrical* solid models (through extrusion, revolve and sweep commands/features). Usually, students from this course are allocated in the 2nd academic semester.

In contrast, ID0267- Modelación 3D2 includes, generally, students ranging from 3rd to 6th semester, given the possibility they have to customize some of the courses' offerings. The course is proposed to be taken in 4th semester and this is the usual condition. Students are introduced in how to model 3D surfaces for product design embodiment. This calls for more *Projective and Euclidean* spatial skills (see Section 2.2.1) from students, since models require previous 3D-wireframe *sketching* in order to create the appropriate 3D-surfaces.

The course focuses completely on digital tools and does not involve with any physical activities (sketching or physical modeling). Furthermore, every class activity is developed individually, and completely oriented towards the Product Design field. This conditions frame the selection of the objects selected in order to evaluate students' performance.

The pedagogical strategy is also in line with other international courses, such as the instructional framework describe by Youssef & Berry (2012). If follows sequential task-based activities, increasing in complexity. Also, constant assistance and feedback is provided on how to operate with the given software (PTC® Creo™ 3.0).

Even if the focus of the course is on CAS activities, specifically oriented towards the outer appearance of the objects/products, it is expected that students can understand how the *visual parts* relate to some basic functions. This means, for instance, that they can recognize if an object's zone corresponds to a button and if this button is visualized as a high or low relief in contrast to the product's body surface.

Accordingly, the 3D-models expected from students do not constitute explicit representations of the real life objects they depict. This means that no assemblies are required and a single part files include all the details of the object. Accordingly, the models do not include internal features either, as they are usually related to the functional elements of the products.

Task-based activities are carried out from existing modeled objects, expected to include the software commands already taught. They can be course-related own designs (Figure 20) or existing mass-produced products (Figure 21).

Figure 20. Example of novel reference product for task-based activities (ID0267- Modelación 3D2 course material).

Figure 21. Example of mass-produced reference product for task-based activities. Alessi (www.alessi.com/it)

For the mentioned task, images providing all relevant product's views are supplied in order to evaluate shape fidelity. Some other course activities do not include all views; it can be only a perspective image, with the purpose of challenging students' observation skills. However, these are not to be included in the current case-study given the complexity and new variables associated to the task. Examples of some reference views are depicted in Figures 22 and 23.

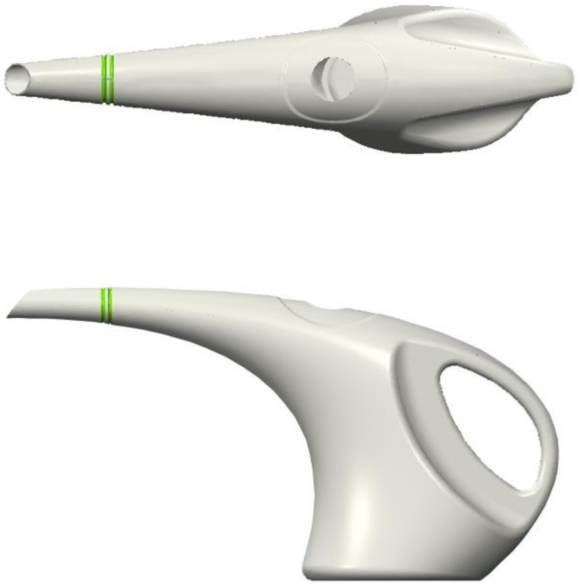


Figure 22. Example of novel product's views used by students as spatial reference (ID0267- Modelación 3D2 course material).

Figure 23. Example of mass-produced product´s' views used by students as spatial reference. Alessi (www.alessi.com/it)

The 3D-models were made using two different tools/modules within the PTC® Creo™ 3.0 suite, namely *Boundary Blend* and *Style* (Figures 24, 25 and 26). Both tools work under similar conditions; that is to say, a wireframe of the object is first modeled as a first condition for creating the final surface. This wireframe can have boundary lines as well as internal (control) lines (see Figure 24). This surface can be achieved by sections or with a single quilt. This influence the final surface continuity or fluency. However, for this specific study, students' performance was not evaluated on such aspects. In order to keep the product general measures and details as reference, images of the different product viewpoints can be imported into the 3D environment (see Figure 26).

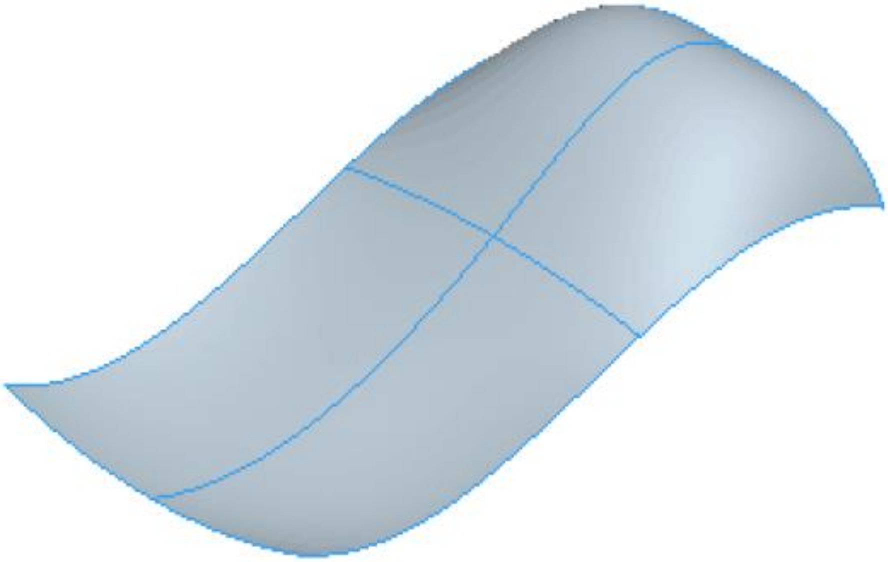


Figure 24. Example of wireframe lines used for both external and internal control of the surface, using Boundary Blend[20] *PTC®.*

---

[20] Source: TUTORIAL. (June, 2007). Retrieved September 27, 2015, from http://www.pdsol.com/tutorial-create-boundary-blend-surface-with-inner-boundaries-in-proe-wildfire/

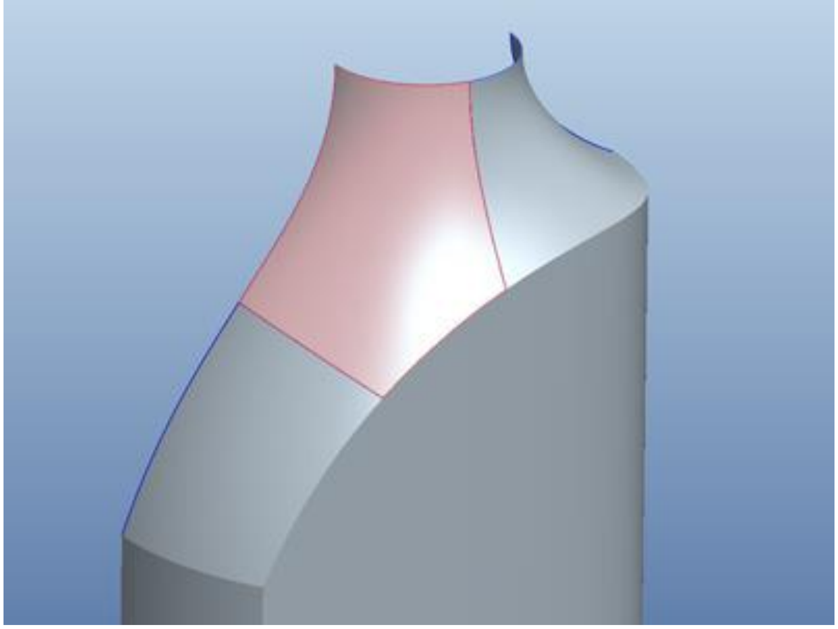


Figure 25. Example of Style[21] surface using object boundaries PTC®.

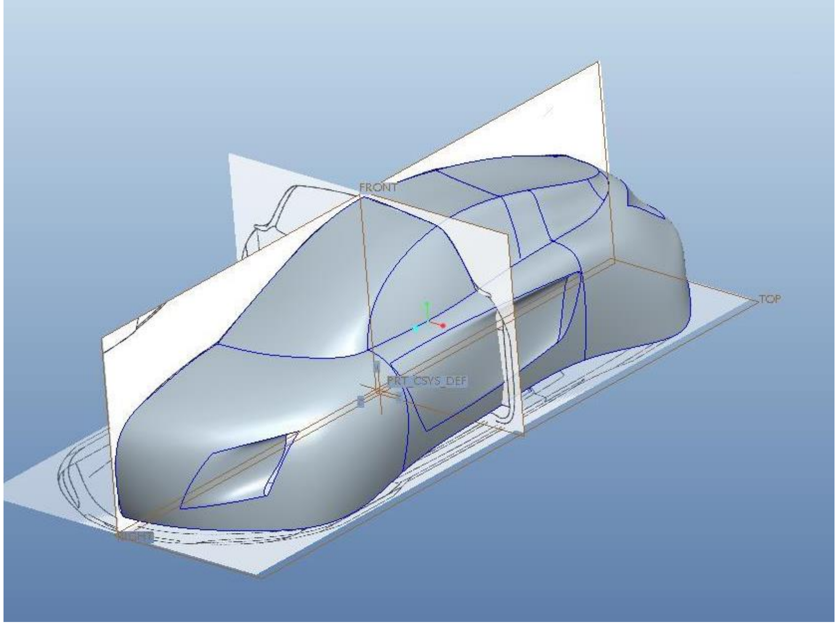


Figure 26. Example of imported images[22] for 3D spatial reference.

---

[21] Source: Superficies de N lados. (n.d.). Retrieved September 27, 2015, from http://support.ptc.com/appserver/wcms/relnotes/note.jsp?im_dbkey=77911

[22] Source: Car modeled in Pro/E. (November 29, 2010). Retrieved September 27, 2015, from http://modelacion3d.blogspot.com.co/2010/11/car-modeled-in-proe.html

All the aspects already referred are expected to provide a general layout on the project's context and conditions. Nevertheless, before performing any tests and diagnostics, a survey to validate the need of the study was performed. The following section reflects on its findings.

3.2. Surveys

With the purpose of further understanding the opinions, approaches and needs of students towards computer aided form-giving, specifically within a 3D environment, a survey was carried out in the mentioned ID0267-Modelación 3D2 course. Since the 3D-modeling activity is not an isolated one inside the undergraduate program syllabus, questions on their opinions and self-awareness on other domains were also asked.

Thus, questions alluded to their (students) self-perception on design skills, such as drawing, 3D-modeling and building. Questions also asked about 3D-modeling preferences, around specific techniques, modules, tools, etc. Finally, students were asked about their opinion of own flaws. Full detail on surveys' structure and results can be found in Appendix B. They were implemented in two different academic semesters, in order to reduce any biases on self-opinions by means of generational and academic differences.

Some of the findings show that students usually evaluate their own performance far above the reality. Figure 27, shows the final outcome of a student who scored him/herself as having almost perfect understanding of the software and full awareness of his/her mistakes. It is expected that a person who actually has such advanced skills will create a *perfect-matching* 3D-model, if compared to the reference product. However, that is not the case; this reflects on the need to improve both students' self-awareness and pedagogical strategies. The fact that students are able to use the software tools/modules and feel comfortable (mean score of 7.8 over 10) when using them (Figure 28), but outcomes are far from ideal, reveals that flaws are located in the perceptual and cognitive domains.

Figure 27. Example of divergence between student's own perception and his/her outcomes.

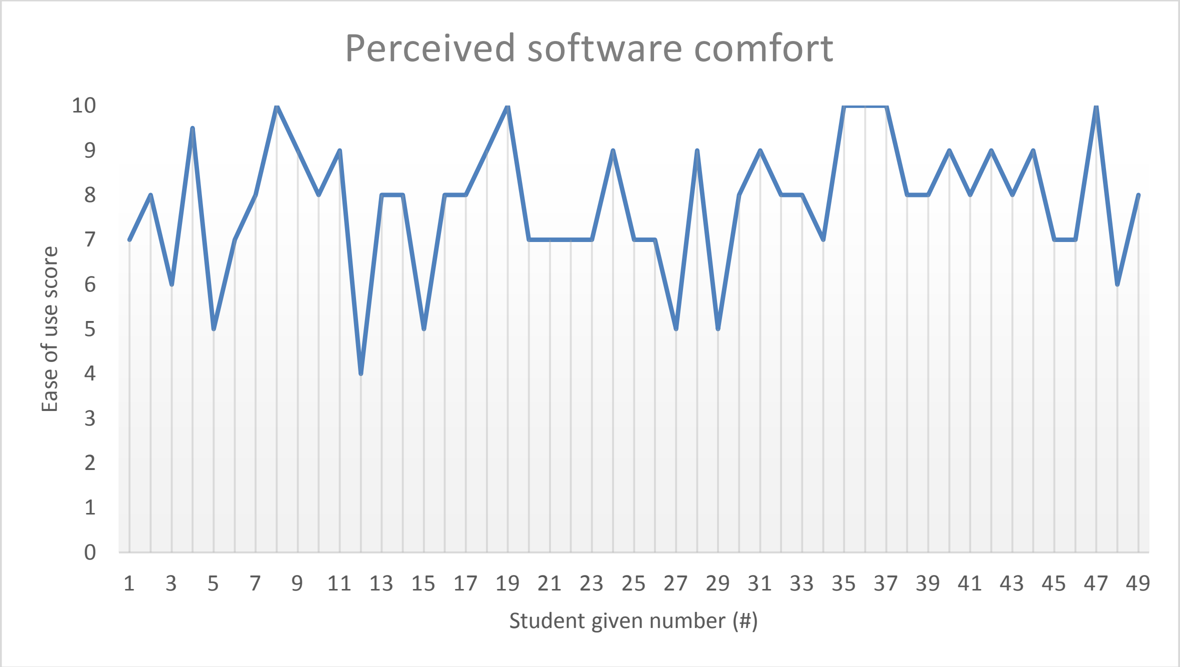


Figure 28. Students' opinion about perceived comfort when using the software PTC® Creo™ 3.0 for CAS dedicated activities.

In order to further understand students’ perception of the field and their own capacities, some other questions were asked. Following, the most relevant ones are presented, along with their results.

When asked about their self-perceived proficiency at some of the main form-giving activities, such as drawing, 3D-modeling and prototyping, the average results are as follows: 7.1 for sketching, 7.4 for 3D-modeling and 8.1 for prototyping. These values ranged from 0 (being no skill at all) to 10 (being full-developed skill). Within the chart depicted in Figure 29, it can be noticed that just a few students rated themselves with a low score, especially for sketching abilities. It can also be noticed that several students considered themselves as having perfectly developed skills, especially for sketching and prototyping. 3D-modeling self-perceived proficiency, on the other hand, shows a more balanced score-behavior. This is useful for the project case-study, since a more homogeneous sample helps when evaluating their performance.

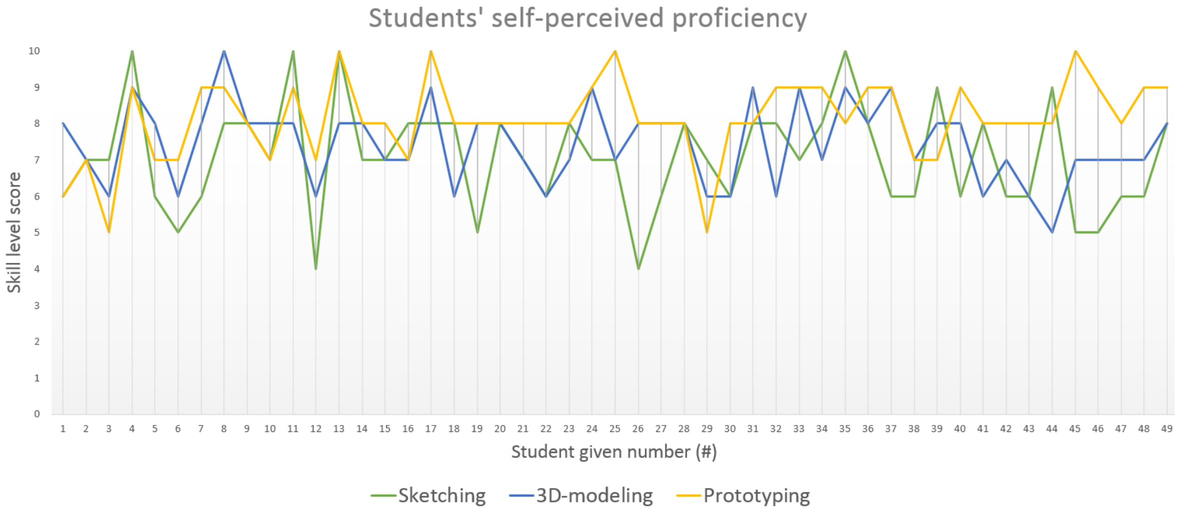


Figure 29. Students' self-perceived proficiency for sketching, 3D-modeling and prototyping activities.

Similarly, students were asked about how conscious they were of their own formal errors. Accordingly, they were also asked about how they perceived their 3D-modeling outcomes in terms of fidelity versus the reference image. Figure 30 summarizes and compares both results. As shown, several students think to have perfect awareness of the formal mistakes they might commit (8.1 out of 10). At the same time, they score their 3D-models highly with regard to product's fidelity (8 out of 10). If true, these results might correspond to students having outstanding control over their aesthetic-related capabilities.

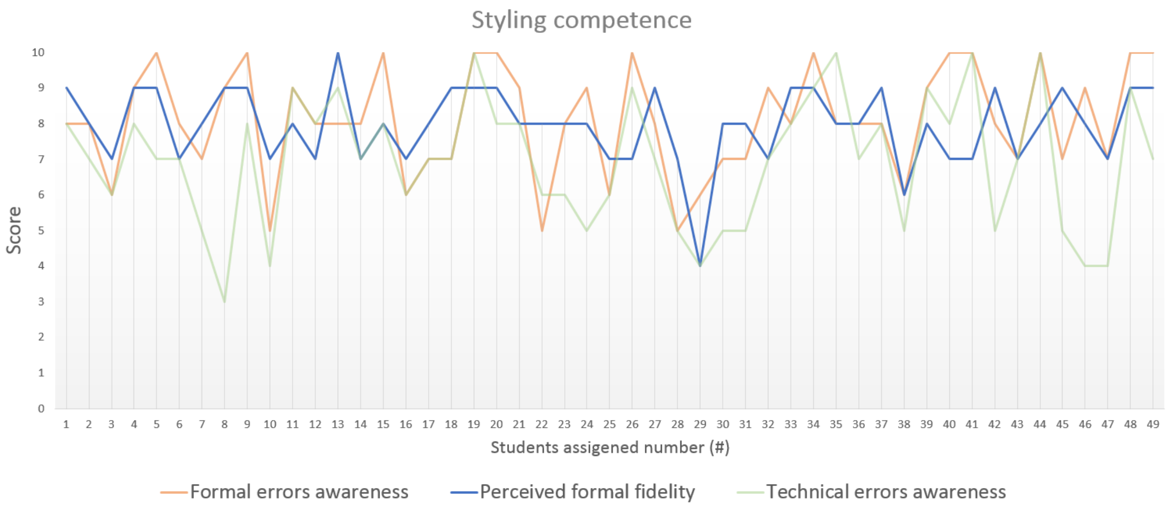


Figure 30. Styling competence in terms of aesthetic errors' awareness and image fidelity.

In order to contrast these findings with possible limitations from software usage, an additional question asked about the technical difficulties. Also shown in Figure 30, it illustrates how aware students think they are about the technical mistakes that could limit their form-giving task. In general, students' gave themselves a mean score of 6.9 out of 10, with just a few having a score below 5. This emphasis the fact that students do not consider the software as the main limitation to their form-giving process, and feel rather comfortable with it, as previously showed in Figure 28.

In line with this, another question asked about their preference for one of the two tools/modules used for the product's body form-giving, boundary blend and style (Figure 31).

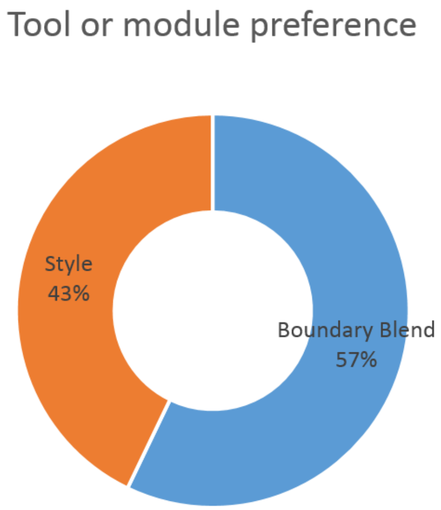


Figure 31. Students' preference for CAS dedicated tools/modules used inside the mentioned course.

In general, the main purpose of the survey was to provide an overview on how students reflect on the 3D-modeling activity for product's form-giving. In can be noticed that they do not consider the software as an obstacle for their performance. There is not a marked preference for one of the two main tool/module over the other. Furthermore, both tools/modules are base in a *contour-wise* modeling, as exposed in Figure 24 (see Section 3.1); and this modeling approach is the preferred one by most of the students (Figure 32).

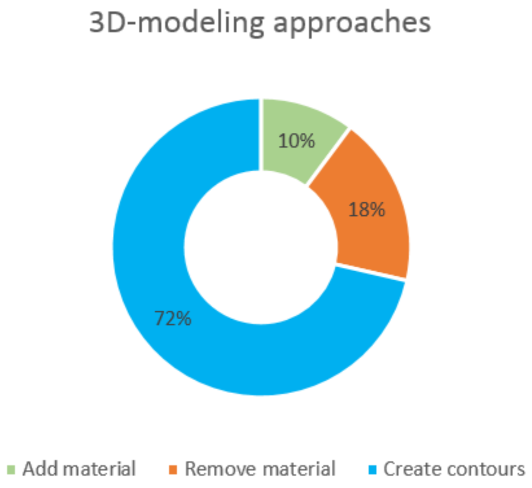


Figure 32. Students' preference for different 3D-modeling approaches.

All in all, students consider to have a good performance and appreciation for 3D-modeling as a form-giving design activity. Building on these insights, the next section aims to validate whether such opinions are accurate or not. In case of finding a negative answer, students’ CAS form-giving errors are most likely related with the perceptual and cognitive domains. This study expects to provide a valuable framework for reflecting on such mistakes based on the selected shape properties and improve students’ self-awareness as well as pedagogical strategies from educators.

3.3. Selection of visual perception errors types

After reviewing general and specific aspects around the main fields related to designers’ form-giving, this case-study attempts to select some essential shape properties susceptible to be measure in students’ CAS performance. Previous sections reflected on a variety of elements to be accounted for. However, given the scope of the project, a small set of features are to be selected in order to obtain practical results.

Being one of the main objectives for the current work, it is important to review the selected form elements throughout which students are to be evaluated. This selection is made under two conditions:

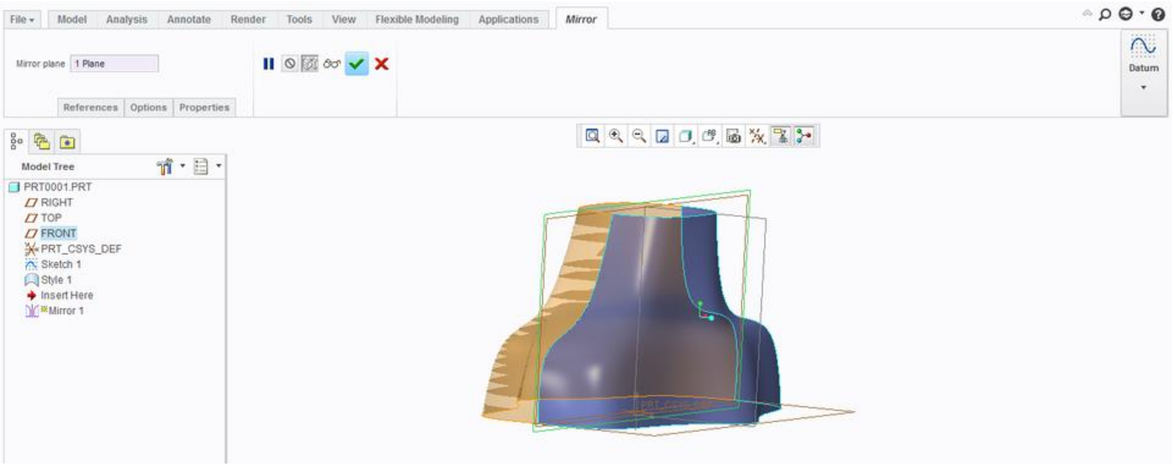
- The selected shape property has been consider of relevance through the literature review and across fields (spatial thinking, visual perception, sketching, image matching and object recognition).
- The selected shape element can be achieved using the referred 3D-modeling tools/modules (Boundary Blend and Style) or by solid-modeling features used as for details (extrude, revolve, sweep, etc.).

Additionally, the selected features comply with some extra condition for shape similarity. That is, they belong to the *"so-called separable dimensions (…) e.g., shape and color)"* (Wagemans, 2013). As such, performance in perceiving one property would be independent from the others.

By establishing such conditions, it is expected that student's evaluation is not based on their technical 3D-modeling skills. On the contrary, the valuable findings are set around their perceptual mistakes. That is to say, what valuable (shape) information are they missing?

Hopefully, the results will help to guide future pedagogical strategies towards the exploitation of the advantages a 3D environment can offer students, in order to improve their visuospatial skills (model rotation, zooming, dragging, etc.).

Some clarification, however, is suitable before such selection. For instance, even if symmetry is regarded as an important feature by the mentioned fields, as can be noticed in (Baylis & Driver IV, 2001; Biederman, 1987; Dickinson & Pizlo, 2013; Lamb & Bandopadhay, 1990; Li et al., 2013; Olsen et al., 2009), it was not considered for study. The reason behind such decision is that all the reference objects to be modeled are symmetrical, and the technical process (Boundary Blend or Style) for their creation is through *mirroring* one half of the object. Figure 33 exemplifies this process.



Mirror plane 1 Plane

Figure 33. Product's body modeling using "Mirror" [23] feature.

This avoids students' need of focusing on such shape feature. The one reason why reference products are symmetric is that most of them follow a case structure (two identical halves), from an external surface point of view. It also has a relation with their manufacturing associated process (blow molding, injection molding, etc.).

Other cross-field features on visual attention, such as color, intensity and texture (Hsu et al., 2005; Won et al., 2007), are not to be consider, even if their importance is acknowledged for identifying changes in materials and determine surface changes. Given that they are not modeling-related shape elements, they are considered outside the course boundaries and expectations.

---

[23] Source: Tutorial. (February 13, 2015). Retrieved September 27, 2015, from https://grabcad.com/questions/tutorial-how-to-use-style-command-in-ptc-creo-parametric

Thus, the final selection of shape properties includes:

- **Size-related properties:** proportion or ratio, length.
- **Orientation or rotation-related properties:** angle.
- **Relational properties:** location.
- **Curvature-related properties:** radius.
- **Pattern-related properties:** count or repetition.

Visually summarized, these properties are depicted in Figure 34.

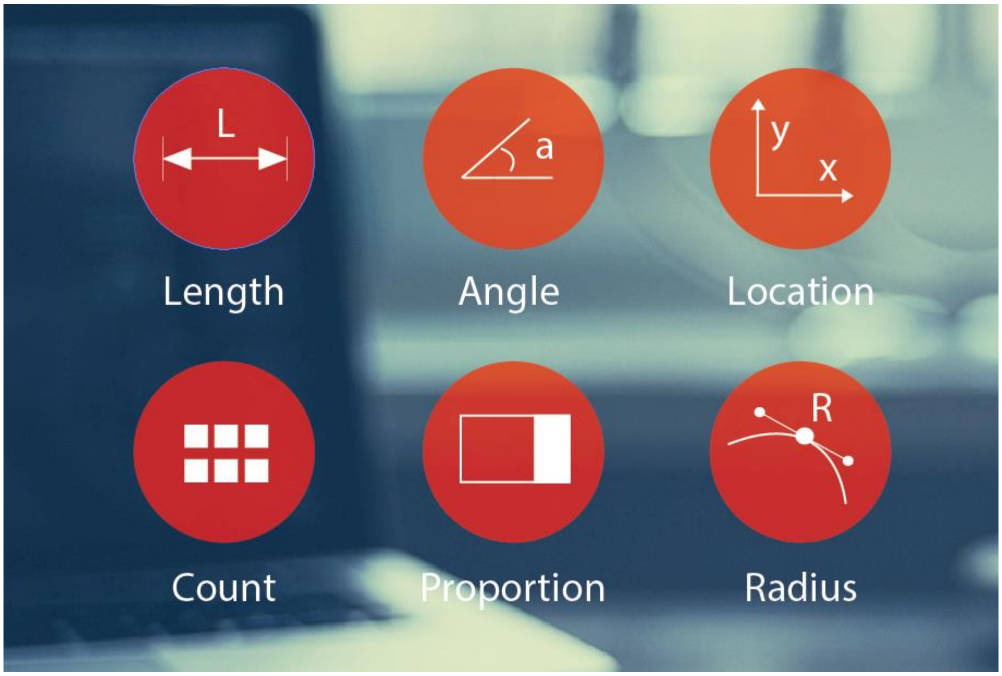


Figure 34. Selected shape properties for students' performance evaluation.

Following, for each shape element, relevant literature sources and the measurement techniques are presented.

Proportion or ratio

Considered to be one of the main shape features for object and parts identification, proportion is useful for supporting low to high-level processes, like recognition or categorization (Fish, 2013).

Some of the cross-field studies in which proportion or ratio are considered essential as a shape property or feature include: (Aslan & Arnas, 2007; Erhan et al., 2011; Hassanpour, 2015; Hsu et al., 2005; Hui & Li, 1998; Hummel & Stankiewicz, 1998; Prats et al., 2009; Purcell & Gero, 1998; Suwa & Tversky, 1997; Wagemans, 2013; Wallschlaeger et al., 1992; Youssef & Berry, 2012; W. Zhang & Wang, 2014).

Angle

This property is mainly concerned with the orientation or rotation of some shape elements. It is regarded as part of the third and *final* stage of spatial skills development by Piaget (2013), as mentioned in Piaget (2013; 2012). The ability to comprehend shape rotation in one’s own mental representations and imagery is essential to deal with multiple views’ representations of an object.

Supporting studies where angles or orientation are considered a necessity for the issue at hand are: (Anvaripour & Ebrahimnezhad, 2013; Aslan & Arnas, 2007; Guerrero et al., 2015; Hassanpour, 2015; Hui & Li, 1998; Kavakli & Gero, 2001; Pittalis & Christou, 2010, 2010; Prats et al., 2009; Purcell & Gero, 1998; Stiny, 1980; Suwa & Tversky, 1997; Wagemans, 2013; Wallschlaeger et al., 1992; Youssef & Berry, 2012)

Location

Within the literature, it refers to detail position, based on a reference coordinate system or representative boundary, point, joint, vertices, etc. Relevant literature studies where this feature is referred to include: (Al-Kazzaz & Bridges, 2012; Baylis & Driver IV, 2001; Bennett, 2011; Erhan et al., 2011; Hassanpour, 2015; Nadal Roberts, 2007; Pittalis & Christou, 2010; Prats et al., 2009; Stiny, 1980; Wallschlaeger et al., 1992; Youssef & Berry, 2012).

Length

It refers to the size of a fragment, edge, boundary, etc., of a given detail or section of the object. Particularly, for this study, length refers to a representative size of a detail. Some representative literature reference where this parameter can be found are: (Anvaripour & Ebrahimnezhad, 2013; Hassanpour, 2015; Hsu et al., 2005; Hui & Li, 1998; Kavakli & Gero, 2001; Masry & Lipson, 2007; Nadal Roberts, 2007; Wagemans, 2013; Wallschlaeger et al., 1992; Youssef & Berry, 2012).

Radius

Thoroughly mentioned throughout the literature, curvature is used to validate image or object correspondence, as well as style intended attributes; which in turn, can influence shape perception as sharp, smooth or accelerated, among other mentioned perceived traits. It is highly representative given its relation with the spline lines, a common component of CAS dedicated software. Within this study, it takes the name of radius, since it is used to measure significant product curves, rather than corner rounds. Reference studies include: (Bae & Kijima, 2003; Bhattacharjeea & Mittalb, 2015; Biederman, 1987; Cheutet et al., 2008; Giannini, Monti, Pelletier, & Pernot, 2013;

González et al., 2012; Hassanpour, 2015; Hsu et al., 2005; Hui & Li, 1998; Olsen et al., 2009; Podehl, 2002; Wagemans, 2013).

Count

Lastly, a concept commonly mentioned across studies is the usually named as patterns (or repetitions). These are features that readily help to determine product categorization or call for complexity and aesthetic preference (Nadal Roberts, 2007). Similarly, other studies that also refer to this feature, hereby referred as repetitions are: (Baylis & Driver IV, 2001; Chan, 2001; Dankwort & Podehl, 2000; Dickinson & Pizlo, 2013; Li et al., 2013; Nadal Roberts, 2007; Oxman, 2002).

3.4. Tests design

This section deepens in the main aspects related to the measurement of the mentioned shape properties and provides visual examples of the tests' designs. Within this case-study, *real world* measures are not taken into consideration. What this means is that evaluation of students' deliverables does not demand measure accuracy. In Figure 35, Alessi's Piripicchio[24] serves as an example: general dimensions framing the object are 8 x 6,5 x 14,3 cm^3. However, for students' performance evaluation, only proportions are considered. This is made by using one reference measure, usually a base bounding length (frontal width in Figure 36). Accordingly, the remaining measures should be proportional to the original ones.

---

[24] Alessi. General Catalog 2013. Piripicchio by Stefano Giovannoni (p. 199).

SG76 "Piripicchio" design Stefano Giovannoni, 2005

Levapelucchi in PC/Clothes shaver in PC/Rasoir à pulls en PC/
Flusenentferner aus PC/Quitapelusas en PC.
cm 8x6,5 - h cm 14,3 / 3¼"x2¾" - h 5¾"

SG76 R **SG76 AZ**

SG76 GR verde/green/vert/grün/verde
SG76 R rosso/red/rouge/rot/rojo
SG76 AZ blu/blue/bleu/blau/azul

Figure 35. Alessi's Piripicchio measures. (Alessi. General Catalog 2013).

Figure 36. Proportions accuracy through reference dimension.

In order to evaluate such properties within their whole spectrum, products used for testing where selected from a variety of sizes and contexts. They ranged from hand-sized home appliances to furniture. They also ranged from fully detailed to product's simplifications, all suited for being modeled throughout the instructed class tools or modules. A summary of all the products used during the case-study tests is depicted in Figure 37.

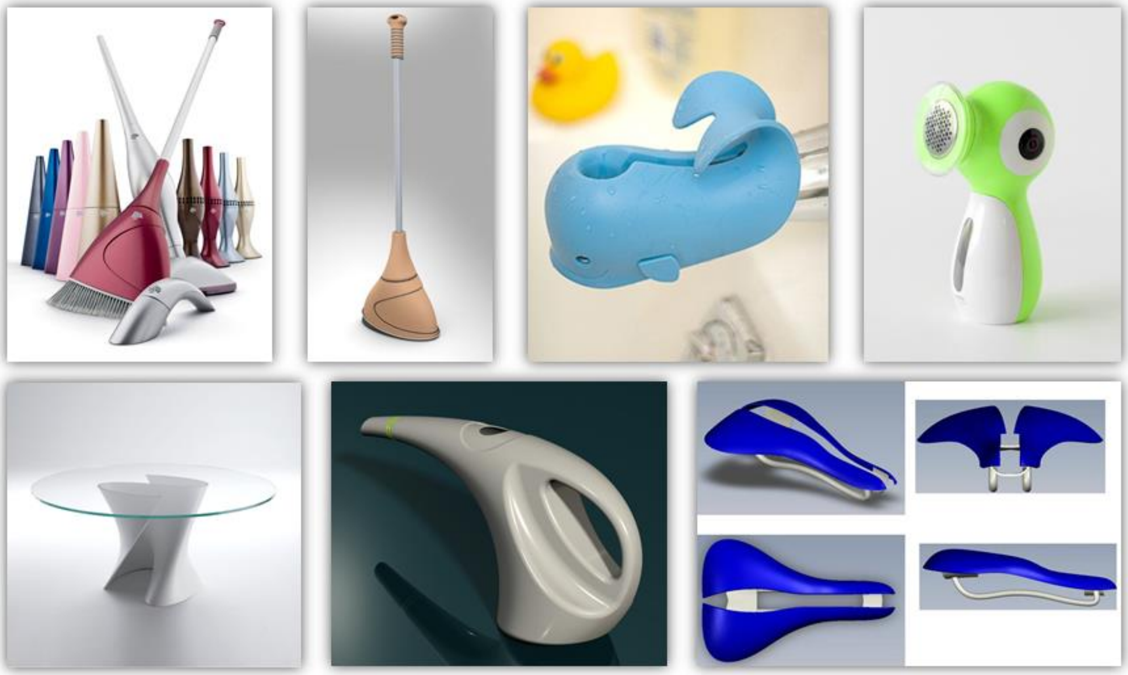


Figure 37. Summary of the products used to test students' performance.

Thus, a description of how each property is measured inside an object is now provided, summarized by a depiction of the properties (see Figure 38) within an object and their corresponding descriptions in a table (see Table 2).

- ***Proportions or ratio:*** Within the study evaluation, proportions depend on a reference value. They are mainly used for general bounding dimensions. For instance, given the product in Figure 38, the height parameter (B) is measured vs. the base length (Reference (R)).

- ***Angle:*** Angles are used to measure both the orientation of a detail with regard to a reference point or the characteristic angle of a detail in itself. In Figure 38, the second condition is fulfilled. Parameter (A) measures the shape of the water can's tip as perceived from a side view, determined by the angle generated with a cut or trimming feature, for example.

- ***Location:*** It refers to the distance from a reference point (edge or any representative element) to the detail being analyzed. In Figure 38, location parameter (G) is measured from the most external point of the water can's tip to the center of the hole, by means of the top view.

- ***Length:*** Corresponds to the size (measure) of a detail, in one fixed direction. In Figure 38, parameter (D) measures the length of the *protrusion* that generates the channel throughout which the liquid is poured, from the water can's tip to the most external point of the water can's base (to the left).

- ***Radius:*** It is used to measure a meaningful curvature within the object. In Figure 38, a visible *cut* in the grip area is characterized by a curve. Parameter (E) measures the radius of such feature.

- ***Patterns or repetitions:*** *This feature was thought to measure the amount of elements within a pattern (directional, radial, etc.). However, it was difficult to find relevant and meaningful patterns in every object to be modeled, without seeming like an add-on to the product's aesthetic. Therefore, from the originally selected features, this specific one was relegated for future works.*

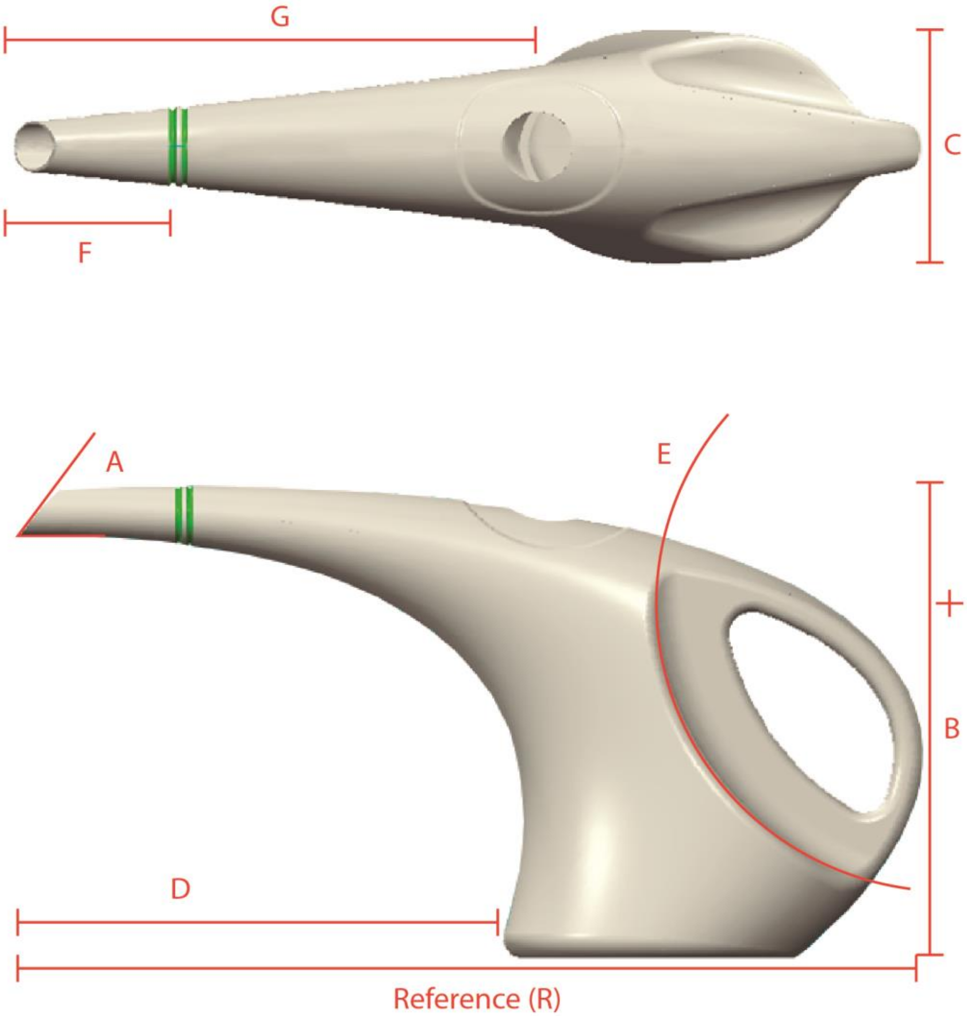


Figure 38. Shape properties used for evaluation within one of the test products.

Table 2. Description of shape properties and measurement references used in the example product.

Product	Item	Shape Property	Description
Water Can	A	Angle	Nozzle’s cut angle
	B	Proportion	Length vs. Height
	C	Proportion	Length vs. Width
	D	Length	Nozzle’s length (until base left extreme)
	E	Radius	Grip area detail (low-relief)
	F	Location	Nozzle’s start point to green low-relief detail
	G	Location	Nozzle’s start point to top hole

For each student, the preceding procedure was followed. Figure 39 shows a summary of a group of students evaluated through the mentioned Alessi's Piripicchio.

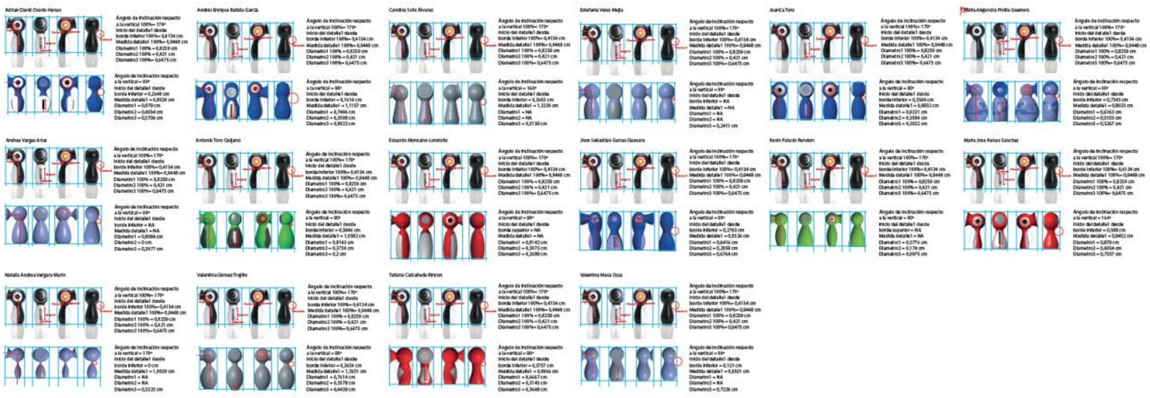


Figure 39. Summary layout of a group of students evaluated using the Piripicchio, by Alessi.

For each student, a table like the one depicted in Table 3 was generated. It included a number assigned to the student, the product being analyzed, the items' nomenclature, a description of how each item was measured, the original measure of the property, the measure inside the 3D model and the deviation error (%).

Table 3. Example of a student performance evaluation.

Number	Product	Item	Property	Description	Original measure	Student's measure	Error	Absolute V.
18	Dirt Devil® Broom	A	Angle	Inclination of broom's base to horizon	10	12	20,00%	20,00%
		B	Count	Number of helical turns	9	10	11,11%	11,11%
		C	Length	Grip's height	14,5	17	17,24%	17,24%
		D	Length	Broomstick's height	59	59	0,00%	0,00%
		E	Length	Broom's base height	37	38	2,70%	2,70%
		F	Proportion	Broom's total height vs. base length	105	114	8,57%	8,57%
		G	Proportion	Broom's total height vs. base width	13,8	13	-5,80%	5,80%
		H	Radius	Grip's curvature	6	9	50,00%	50,00%
		I	Location	Broom's low-relief detail height from base	21	20	-4,76%	4,76%

It can be noticed that error percentages had positive (+) or negative (-) values. Positive values imply a deviation bigger than the original measure. On the contrary, negative values imply a deviation below the original measure. For the same property (if several items where considered), there could be positive and negative values from different items (Figure 40). Therefore, the last part of the evaluation required to change all the percentages to Absolute Values before finding the average deviation for each product for a given student. The averages are displayed in charts as the one shown in Figure 41. These charts summarize the deviations for each student, regardless if they were bigger or smaller with regard to the original image. This allowed for a unique representation style and measures and also for comparisons among students.

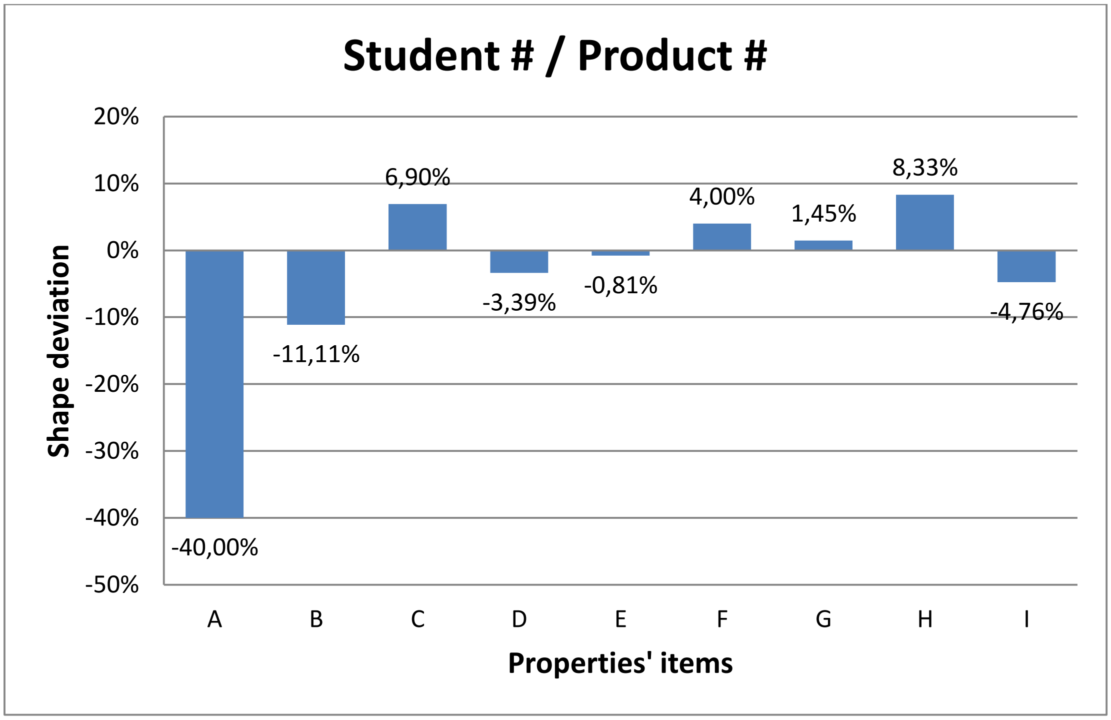


Figure 40. Example of positive and negative deviations for different items within the same product.

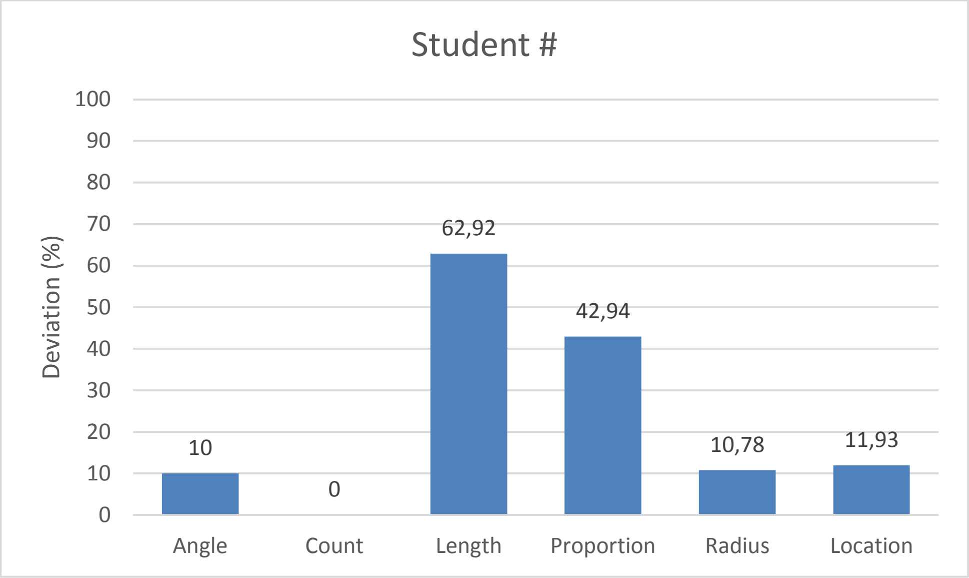


Figure 41. Example of student performance across different products.

The next section accounts for the specificities of each of the tests, following the mentioned lineaments.

CHAPTER 4

Implementation and results

Within this chapter, test measurements are accounted and results analyzed towards the understanding of students' performance. First, the task-oriented deliverables given to students are explained. Results for each of those deliverables are presented and evaluated. Following, the most common results are clustered in the search for common behaviors. Finally, an attempt to classify those clusters under 3D-modeling profiles is made through some profiles' proposal.

4.1. Observations on students' deliverables

Students were evaluated by means of 3D-modeling tasks, where few images of products from different viewpoints were available. These products ranged from hand-sized objects to furniture. Two stages of tests' implementations were carried out.

First, deliverables of three different objects were assigned. Students had different time spans according to the approximate number of software operations demanded by each product. In general, available modeling times ranged from 1 to 3 hours. The first test was use for assessing the original hypothesis, that is to say, that students perform poorly when *translating* 2D real representations of an object into a 3D matching model.

A sample group from the fall-semester of 2013 (2013-2) was selected as the test population. Students ranged from 3rd to 6th semester of the undergraduate program of Product Design Engineering. The average population was part of the 4th academic semester. Results indicate that, indeed, most of the students fail in trying to keep aesthetic fidelity.

This test, therefore, established a starting point. For this test, three different deliverables of the same students' group were analyzed. The conditions for the second test were the same as for the first one. A second test included students from three different semesters (2014-1, 2014-2 and 2015-1), in order to have a better description of the Product Design Engineers community, around the topic at hand. Thus, the full extent of the study compiles four academic semesters; that is two academic years.

Along the way, some hypothesis emerged, assuming that it was possible to find relevant trends among students. For this purpose, a third test was conducted. Its goal was to find patterns in students' 3D-modeling behaviors and to classify them under possible modeling profiles. For this tests, students from the first sample group were used, since the same students and products were used across the evaluations.

Following, there is a description for each test, including the objects and images provided and the items under analysis.

Sample Group 1

The first product for the first test group (Product #1) was the S Table, designed by Xavier Lust and manufactured by MDF Italia. Students were provided with two images were the general look of the product can be observed (Figure 42).

Figure 42. Product #1: S Table[25]*. Perspective and top views.*

Shape properties and descriptions for this products can be found in Figure 43 and Table 4.

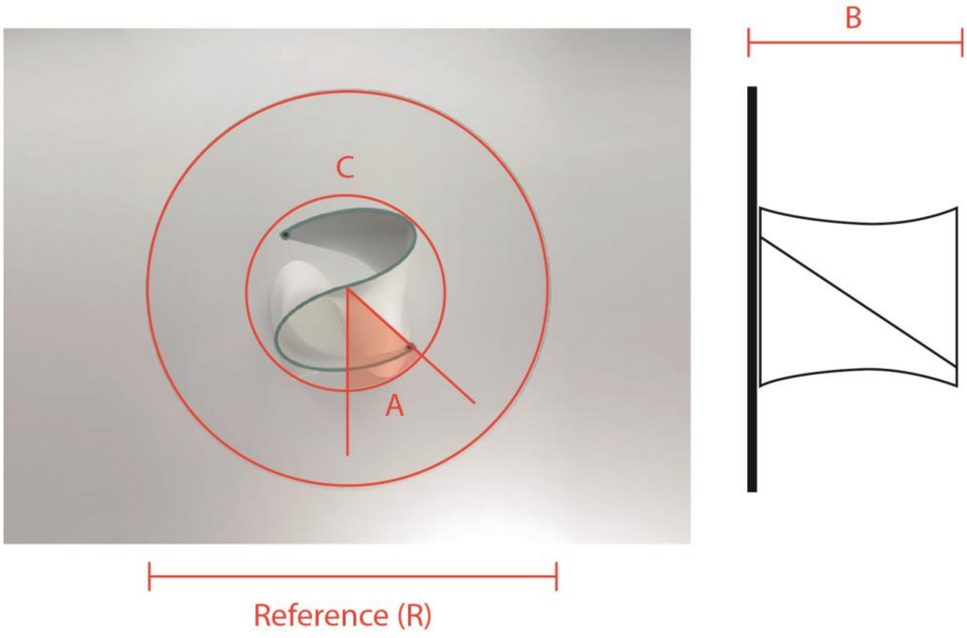


Figure 43. Evaluation features for Product #1.

---

[25] Source: Design Store. (n.d.). Retrieved September 27, 2015, from http://store.eckhart.nl/en/store/merken/70-mdf-italia/746-s-table/

Table 4. Description of shape features' relational measures for Product #1.

Product	Item	Shape Property	Description
S Table	A	Angle	"S" shape turn related to vertical axis
	B	Length	Height of table's base
	C	Proportion	Base framing circle (width) vs. circular glass

The second product (Product #2) selected for Test 1 was Moby, a bathtub cover designed by Scott Henderson for Skip*Hop®. A side view image for product fidelity was given to students (Figure 44), who were also allowed to search for additional images to fulfill detail purposes (Figure 45).

Figure 44. Product #2: Moby[26]. Side view.

---

[26] Source: Global Trends. (July 22, 2014). Retrieved September 27, 2015, from http://www.globallighting.com/scott-henderson-americas-designer-ambiente/

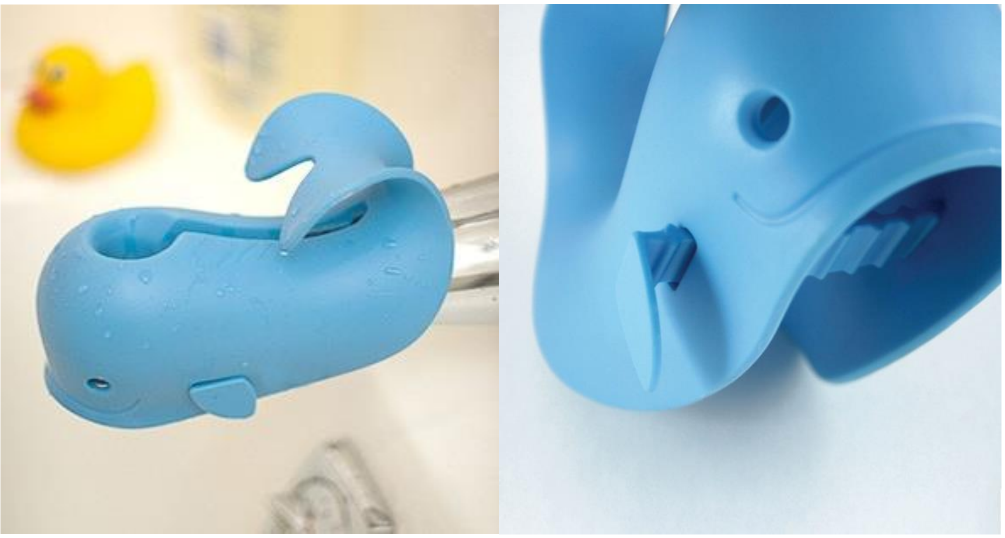


Figure 45. Examples of additional images for detailing Skip Hop® Moby[27] [28]*.*

Figure 46 and Table 5 illustrate selected shape properties and measure relations.

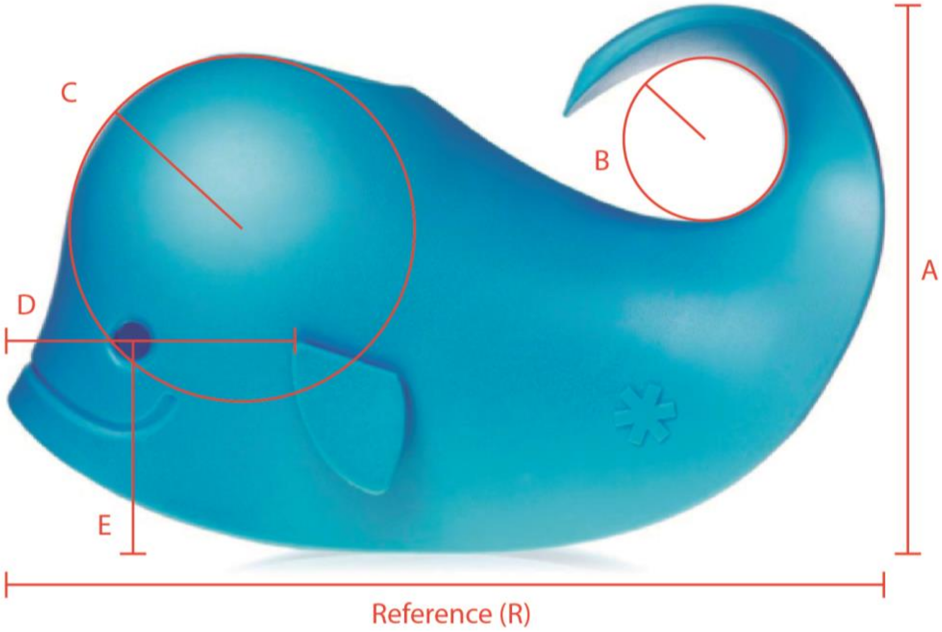


Figure 46. Evaluation features for Product #2.

---

[27] Source: Skip Hop Moby Bath Spout Cover. (n.d.). Retrieved September 27, 2015, from http://www.urbanbaby.com.au/SkipHop-Moby-Bath-Spout-Cover#.Vif6ZyuPwWs

[28] Source: Skip Hop Moby Protector Grifo. (n.d.). Retrieved September 27, 2015, from http://www.somospapas.com/1198-skip-hop-moby-protector-grifo-banera-ballena/

Table 5. Description of shape features' relational measures for Product #2.

Product	Item	Shape Property	Description
Whale	A	Proportion	Length vs. Height
	B	Radius	Tail's inner tangent circle
	C	Radius	Head's inner tangent circle
	D	Location	Flipper's left point location to whale's extreme left point
	E	Location	Eye's vertical center point location to base

The final product (Product #3) for Test 1 is part of the Dirt Devil® household cleaning brand, as part of the brand's redesign, carried out by international designer Karim Rashid. In Figure 47, the Dirt Devil® line can be appreciated (left), along with the 3D representation of the selected product (right).

Figure 47. Product #3: Dirt Devil® Broom[29]. Household cleaning line (left). 3D representation of the selected product (right).

---

[29] Source: EDGCHICAGO. (December 27, 2012). Retrieved September 27, 2015, from https://edgchicago.wordpress.com/page/2/

Likewise, properties and measurements were identified for the Dirt Devil® Broom. These are depicted in Figure 48 and Table 6.

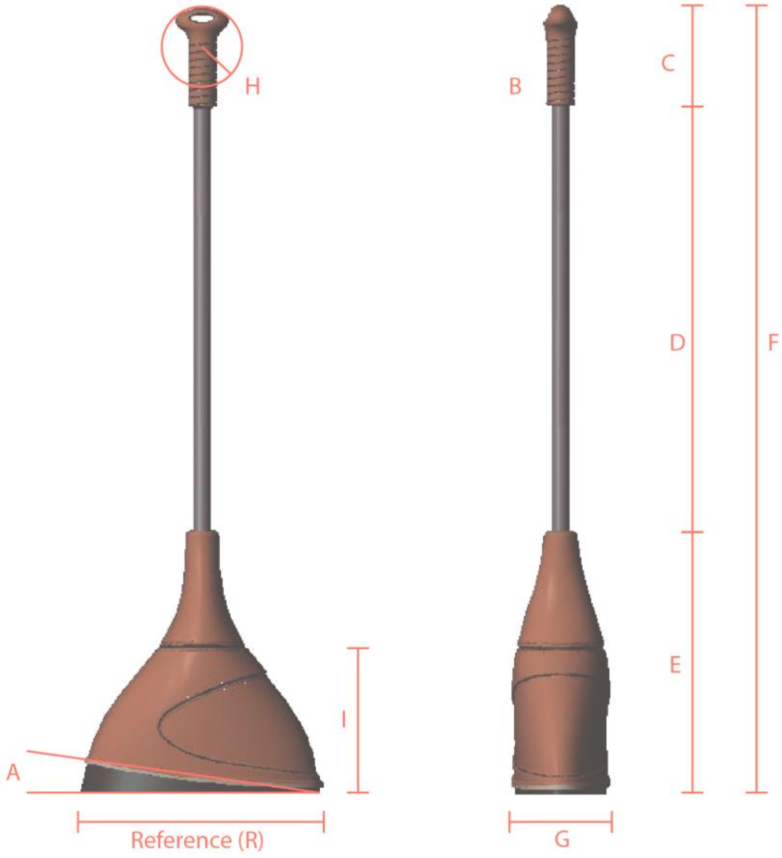


Figure 48. Evaluation features for Product #3.

Table 6. Description of shape features' relational measures for Product #3.

Product	Item	Shape Property	Description
Dirt Devil® Broom	A	Angle	Inclination of broom's base to horizon
	B	Count	Number of helical turns
	C	Length	Grip's height
	D	Length	Broomstick's height
	E	Length	Broom's base height
	F	Proportion	Broom's total height vs. base length
	G	Proportion	Broom's total height vs. base width
	H	Radius	Grip's curvature
	I	Location	Broom's low-relief detail height from base

Sample Group 2

The first product (Product #4) included in the test is the Alessi's Piripicchio. An image like the one depicted in Figure 49 showed the expected results from students. As it was previously noticed, the main body of this product is manufactured by halves, and the general appearance of the object follows a symmetrical configuration (as it can be seen by the dividing low-relief line). Students were free to search for complementary images were different viewpoints and details could deepen the product's shape comprehension. Some of those images can be seen in Figure 50.

Figure 49. Product #4: Alessi's Piripicchio[30]*.*

---

[30] Source: Trends. (n.d.). Retrieved September 27, 2015, from http://www.madeindesign.co.uk/prod-piripicchio-alessi-refsg76r.html

Figure 50. Alessi's Piripicchio available web reference images: side[31], front[32] and rear[33] views.

For the test purposes, characteristic shape elements were identified and classified under the properties selected in Section 3.3. A visual depiction of those elements and their descriptions are provided in Figure 51 and Table 7.

---

[31] Source: Piripicchio. (n.d.). Retrieved September 27, 2015, from http://item.rakuten.co.jp/rai-rai/ss-017/

[32] Source: ALESSI PIRIPICCHIO clothes shaver. (n.d.). Retrieved September 27, 2015, from http://item.rakuten.co.jp/androom/al-pir240/

[33] Source: Alessi "Piripicchio" Clothes/Fabric Shaver. (n.d.). Retrieved September 27, 2015, from http://www.lbcmodern.com/alessi-piripicchio.html

Figure 51. Evaluation features for Product #4.

Table 7. Description of shape features' relational measures for Product #4.

Product	Item	Shape Property	Description
Piripicchio	A	Angle	"Mouth" orientation to the vertical axis
	B	Length	Transparent low-relief detail
	C	Proportion	"Eyes" inner vs. outer circle
	D	Radius	Curvature between body and head
	E	Location	Height of transparent low-relief detail from base

The second product (Product #5) to be analyzed was a *water can*, included in the ID0267-Modelación 3D2 models' database. Again, it had the same symmetric configuration already mentioned for the selected products. Being a non-commercial design, a perspective rendered image of the design was provided to student as well as two orthogonal views for full understanding on the object's details (see Figure 52 and Figure 53).

Figure 52. Product #5: Water can. Rendered perspective representation.

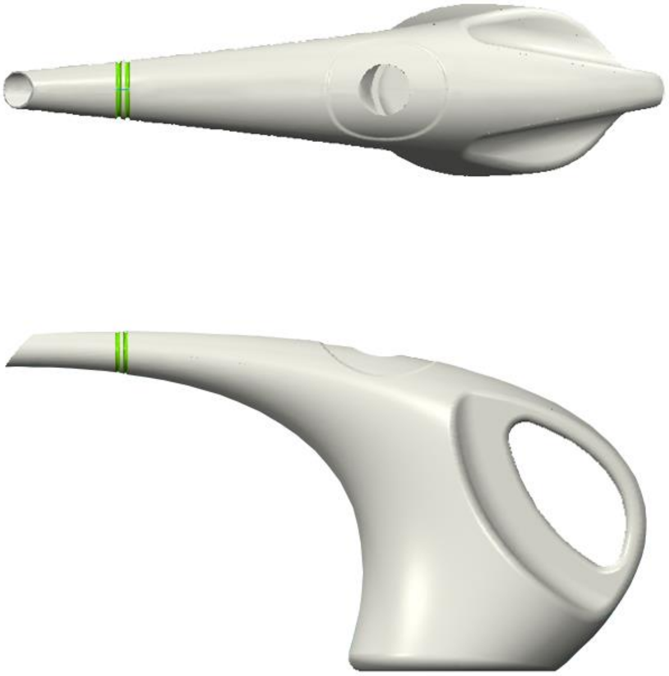


Figure 53. Side and top view of a water can.

Similarly, for test purposes, shape properties were identified and classified. Figure 54 and Table 8 further explain those elements and their measurement.

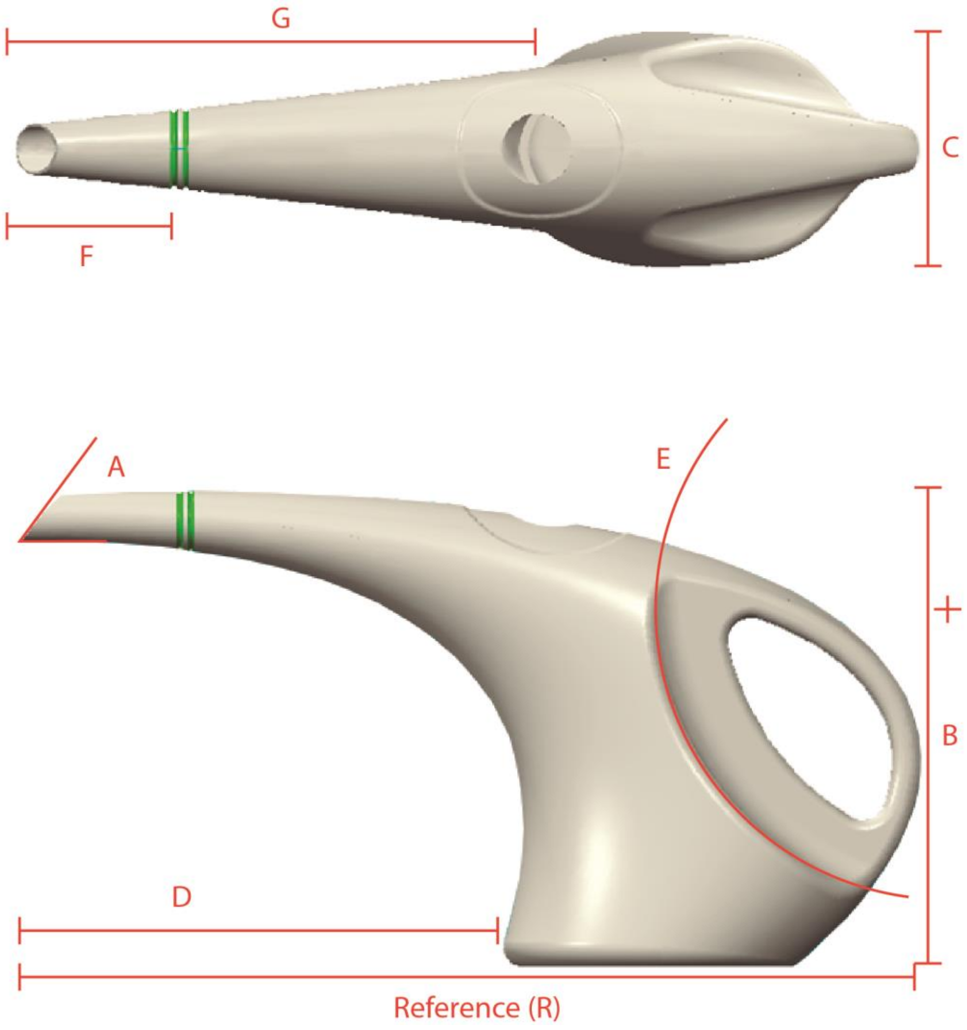


Figure 54. Evaluation features for Product #5.

Table 8. Description of shape features' relational measures for Product #5.

Product	Item	Shape Property	Description
Water Can	A	Angle	Nozzle’s cut angle
	B	Proportion	Length vs. Height
	C	Proportion	Length vs. Width
	D	Length	Nozzle’s length (until base left extreme)
	E	Radius	Grip area detail (low-relief)
	F	Location	Nozzle’s start point to green low-relief detail
	G	Location	Nozzle’s start point to top hole

The third and final product (Product #6) for the first test was a simplification of a bike seat. Also symmetrical, it challenged students in understanding curves intersection in the 3D space. An isometric view and three orthogonal views were provided for students' understanding of the product shape (see Figure 55).

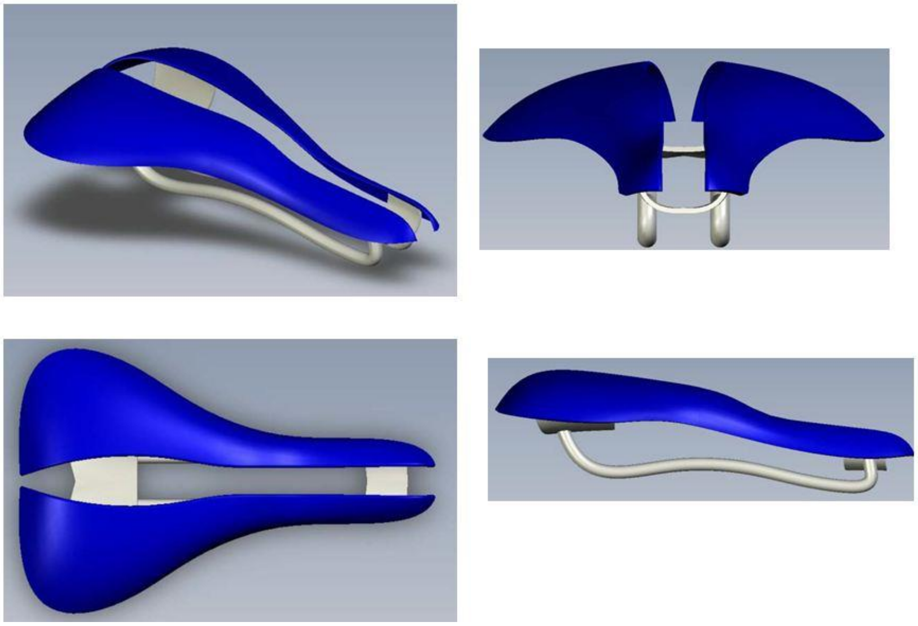


Figure 55. Product #6: Bike seat. Isometric and orthogonal views.

Finally, same shape properties and measurements were established for the bike seat. They can be observed in Figure 56 and Table 9.

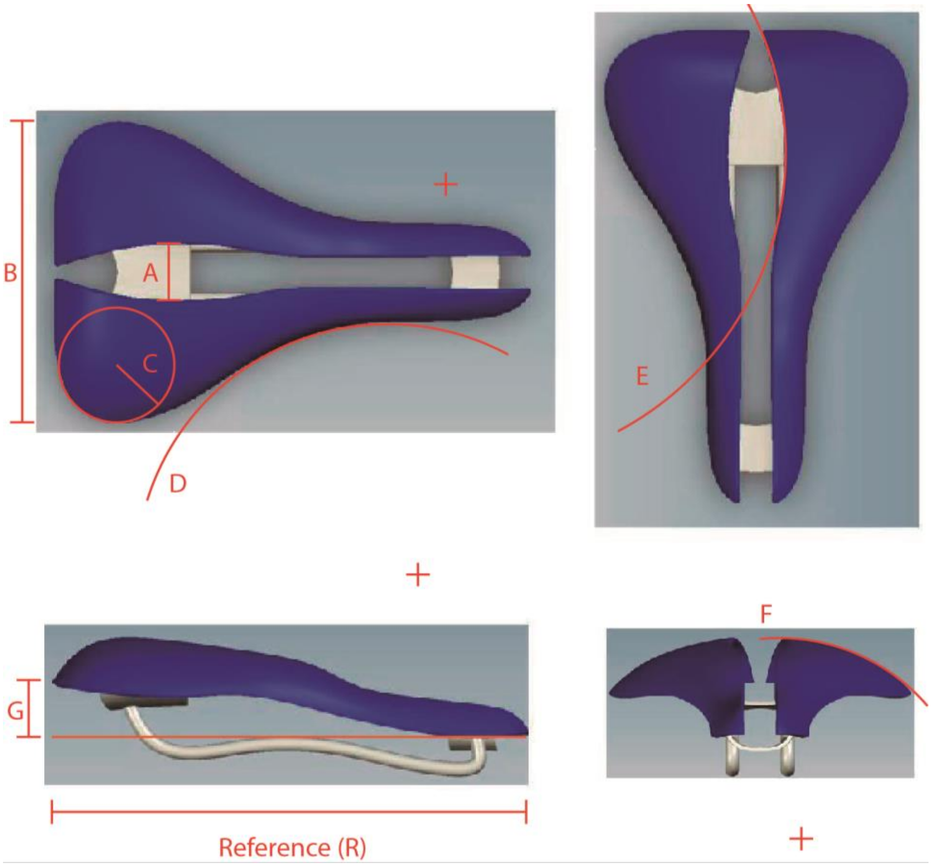


Figure 56. Evaluation features for Product #6.

Table 9. Description of shape features' relational measures for Product #6.

Product	Item	Shape Property	Description
Bike Seat	A	Length	Distance between seat halves
	B	Proportion	Length vs. Width
	C	Radius	Radius of seat’s inner wing
	D	Radius	Radius of seat’s outer wing
	E	Radius	Radius of inner hole detail
	F	Radius	Curvature of seat’s surface (from front viewpoint)
	G	Location	Location of upper extreme point to lower point

4.2. Results: Test 1

For Test 1, two stages were performed. Firstly, the mentioned S Table (Figure 42), labeled as Product #1, was used to rapidly confirm the hypothesis, since only three parameters were used (angle, length and proportion). The test confirmed that students perform poorly when translating 2D images into 3D models; image-model fidelity was very low. For instance, Parameter A, representing the angular deviation of the "S" shape, between the top and bottom sections, was incorrect in every single student. Only one student accurately established the height of the table (Parameter B) and only one student correctly set the proportions between the base framing circle and the circular glass surface (Parameter C). Figure 57 visually summarizes these findings. The sample for this stage of the test included twenty-four students (n = 24, 10 males, 14 females); all of them were part of the same academic semester (2013-2) and were coursing their 4th semester within the program of Product Design Engineering (SNIES code: 7446).

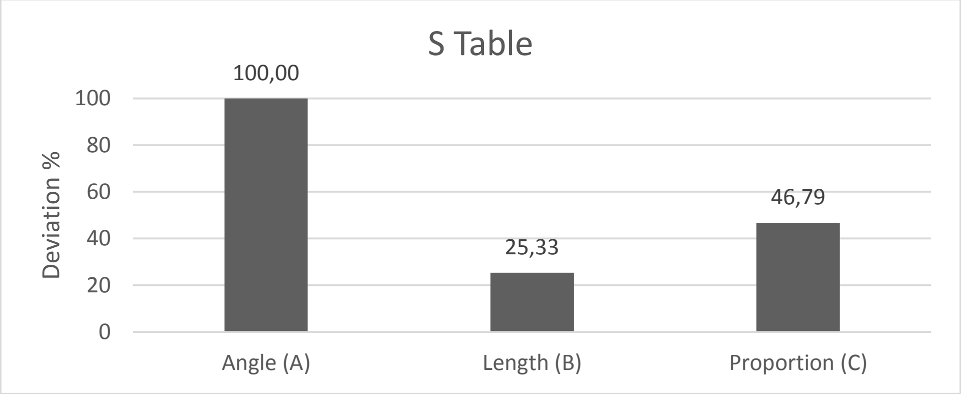


Figure 57. Students' performance for Product #1.

These findings justified the need for subsequent and more thorough analyses. Therefore, products #2 and #3 were used to broaden the results. The sample for this stage of the test included twenty-seven students (n = 27, 15 males, 12 females); again, all of them were part of the same academic semester (2013-2) and were coursing their 4th semester within the program of Product Design Engineering (SNIES code: 7446). This means that 54 products were analyzed according to the parameters exposed in Section 4.1. Figure 58 synthesizes the results.

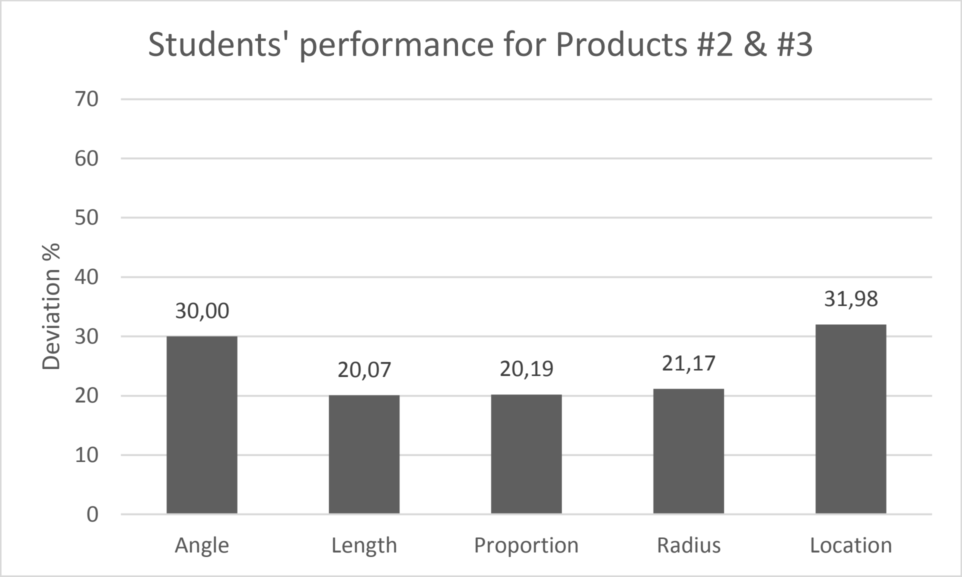


Figure 58. Summary of students' performance for Test 1.

After performing the second stage of the test, it can be observed that length and proportion are the parameters in which students perform the best, closely followed by the parameter related to curvature or radius; they had the most salient values, with similar results (around 20% of fidelity/correspondence gap in relation to the original object). On the contrary, angle and location are the parameters in which students perform more poorly (around 30%). The approximate difference is around 10%; this means that the performance for the former shape properties was 33% better when compared with the other two. The total deviation percentage of students across shape properties has a value of 24,68%.

The next section deepens further in how students perform throughout these properties.

4.3. Results: Test 2

Fort the second test, three different products were used across three different academic semesters (2014-1, 2014-2 and 2015-1). Products were selected to challenge students within the mentioned shape properties, but extending the spectrum in which such properties can be reflected upon a product. Accordingly, results for a given property might vary among products. Charts on performance for each product can be seen in Figures 59, 60 and 61.

The samples for each product varied; for Product #4, Allesi's Piripicchio (n = 15, 7 males, 8 females); for Product #5, Water Can (n = 23, 7 males, 16 females); and for Product #6, Bike Seat (n = 37, 17 males, 20 females). The average values for each property across products synthetizes the whole sample behavior (Figure 62).

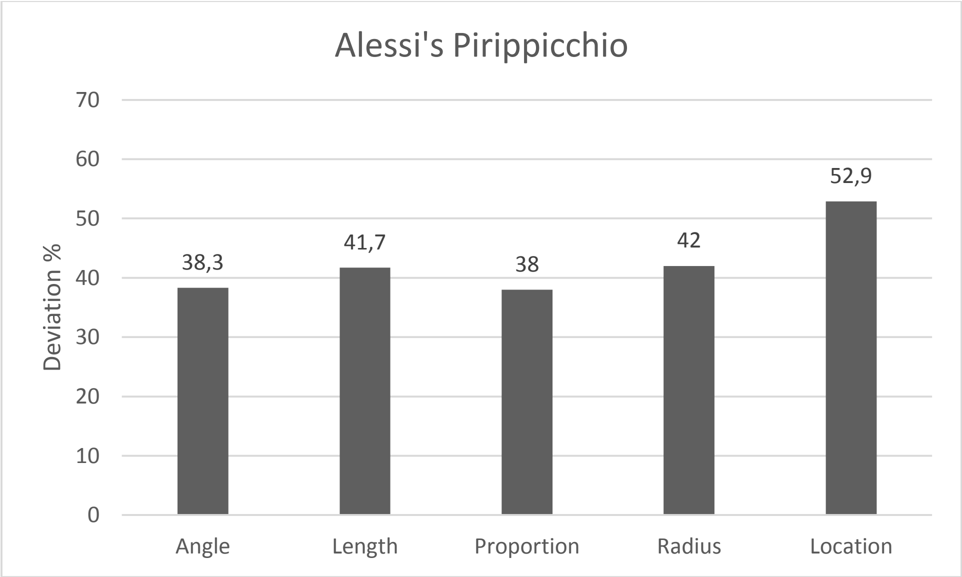


Figure 59. Students average deviation in Product #4.

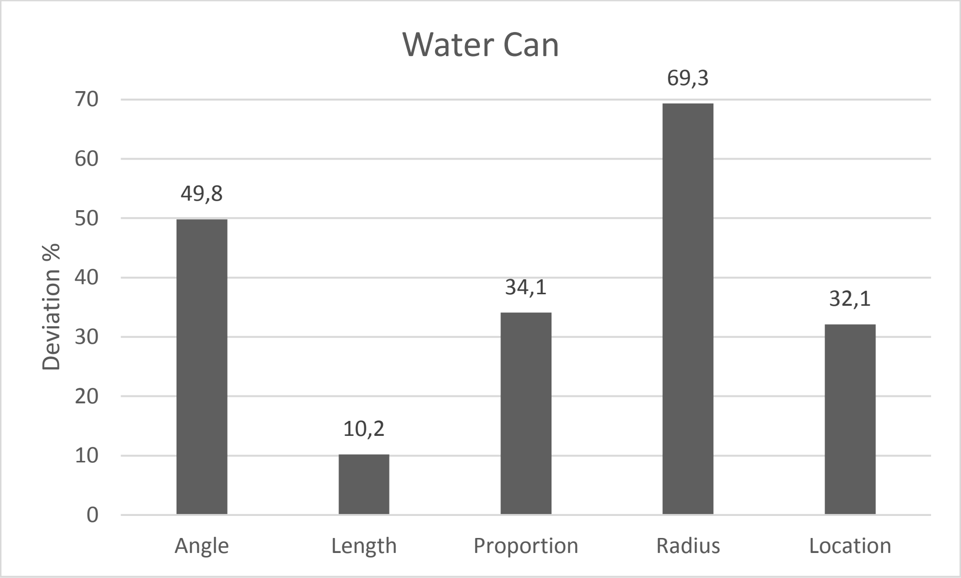


Figure 60. Students average deviation in Product #5.

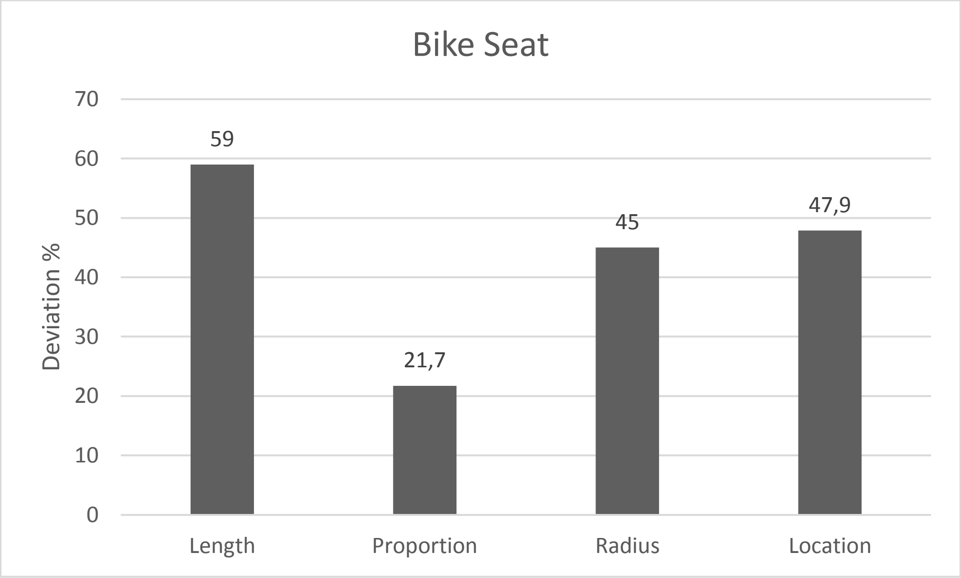


Figure 61. Students average deviation in Product #6.

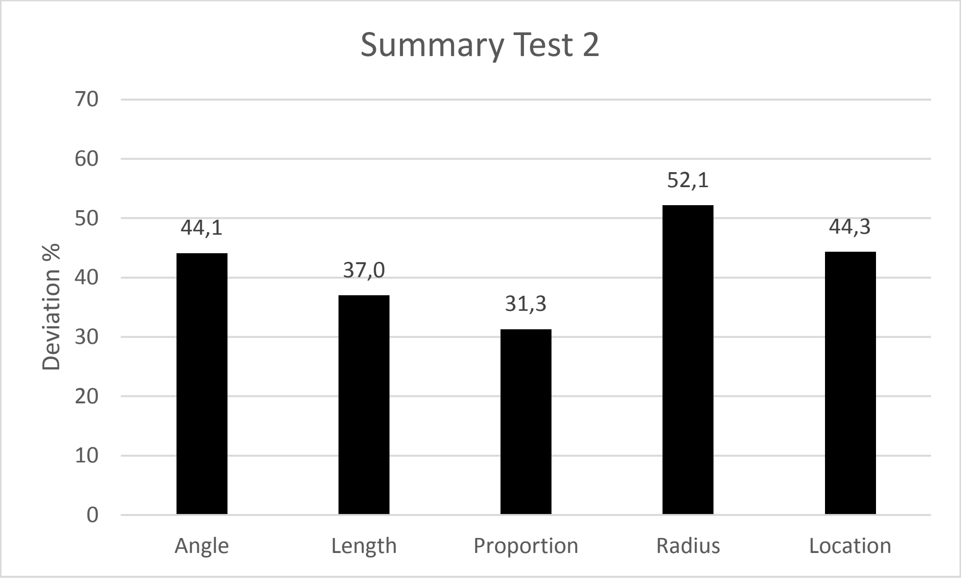


Figure 62. Students average deviation across products for Test 2.

When comparing the results from Test 1 against Test 2, all values increased (Figure 63). Most of the properties, except for radius, had a similar increase (ranging from 11% to 17%). Radius, on the other hand, had a significant increase of approximately 31%. This accounts for how students' attitude towards knowledge has changed since methodologies stayed basically the same; the cross-property average for Test 2 has a value of 41,76%. This implies a difference of 17,08% in comparison with Test 1 average.

If combined, results from Test 1 and Test 2 can be seen in Figure 64. Tendencies from test 1 stayed almost the same. This means that students perform better in proportion and length. They continued to perform poorly in angle and location; and in this case, also followed by radius. The combined cross-property average has a value of 33,23%.

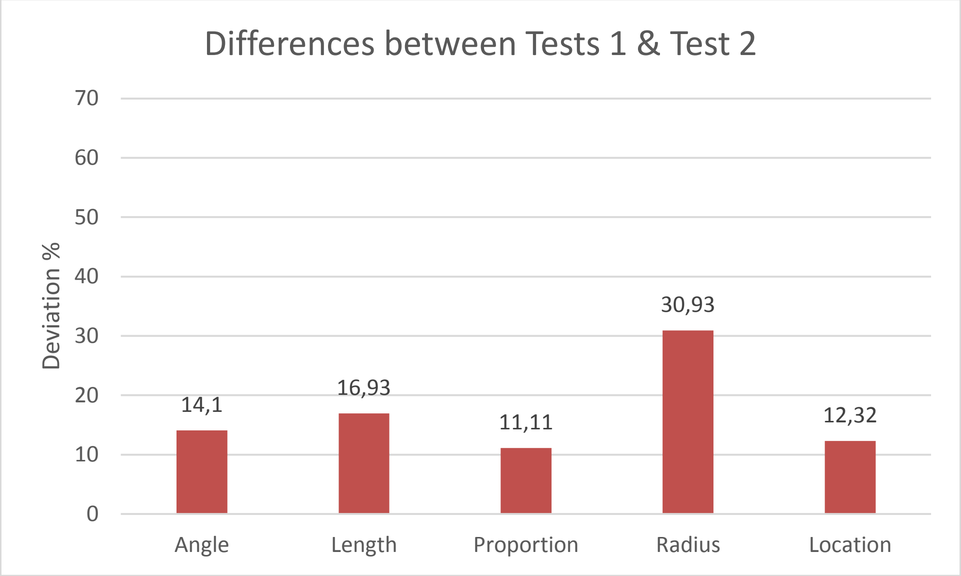


Figure 63. Deviation difference between Test 1 and Test 2.

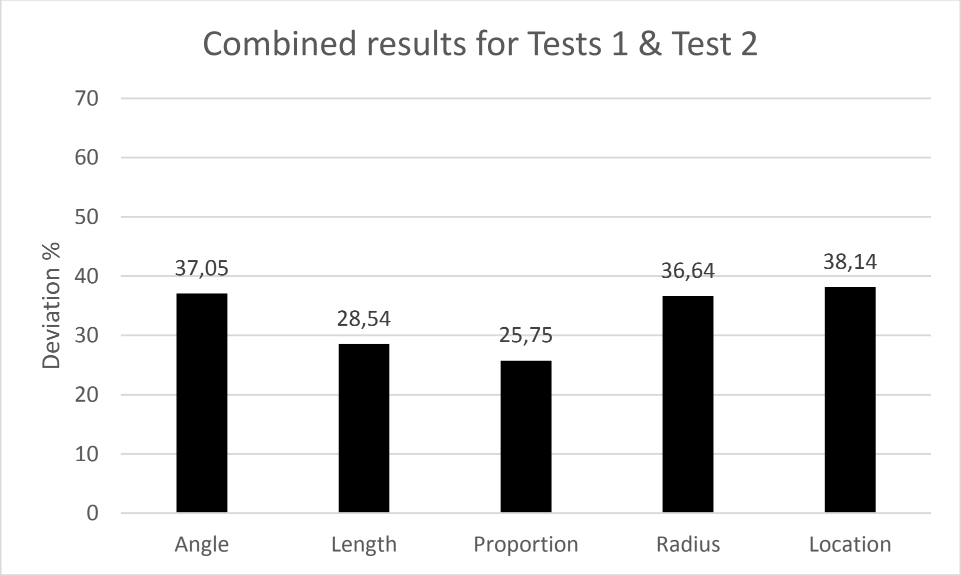


Figure 64. Students total average across products for Test 1 and Test 2.

In general, tests results reflect the accuracy of the translation from 2D images to 3D models. For instance, Figure 65 shows the outcome of a student with a low deviation percentage (left) versus the outcome of a student with a high deviation percentage (right). Appendix C reflects on similar examples for each product.

Figure 65. Example comparison between low (left) and high (right) deviation percentages.

As it was mentioned in the beginning of the document, factors influencing students' performance in 3D-modeling and CAS activities can be nourished by abilities' acquisition from other design activities, such as drawing or prototyping; they can improve students' spatial intelligence. However, this study is concerned only in reporting the behaviors of students within three-dimensional digital environments. Results thus indicate that students' ability to observe and translate shapes into 3D models is decreasing. It can also be due to lack of attention or exceeding confidence, and lack of objectivity.

All in all, it can be seen that students' strength appears to be focused on dimensioning or sizing, since they consistently perform better in linear size properties such as proportion and length. They also use to perform similarly in terms of angular orientation and location. That is, properties related to spatial orientation, dependent of a reference point. Curvature shaping, on the other hand, seems to have the most random behavior, however worsen throughout academic semesters.

Results from these two tests help to identify aspects to improve within design-related activities and domains. Specifically, for 3D-modeling courses, it is relevant to adjust pedagogical strategies if one of their goals is to improve students' performance towards the CAS field. Therefore, more attention has to be paid to coordinate-related properties such as angle and location, in order to stabilize and reduce shape deviation; strategies to improve students' performance for these properties could be closely related. For curvature shaping, more analysis might be necessary, in order to understand students' behavior and adjust class methodologies. Finally, for length and proportion or sizing-properties, efforts might be less drastic. However, they could be a key point to reinforce other properties, since academic strategies seem to be prioritizing these properties in detriment of the remaining ones.

4.4. Results: Test 3

Results for this test are based on the same sample group as for Test 1. The relevance of this analysis emerged after assuming that it was possible to find common trends or behaviors among students, based on the shape deviation of their 3D-models. This means that it might be possible to find similarities among their weaknesses or strengths. This initiative is also supported on international studies (Bar-Eli, 2013), were the relevance of students' design profiles and behaviors is acknowledged as a means to potentiate their abilities and translate them into professional practice.

4.4.1. Errors' patterns and clusters

Towards this goal, different approaches were taken. One approach included the analysis of students with similar graphics, describing their behaviors. Figure 66 shows this visually. In this case, both students present the same order of deviation (from better to worst): *length, proportion, radius, angle and location.*

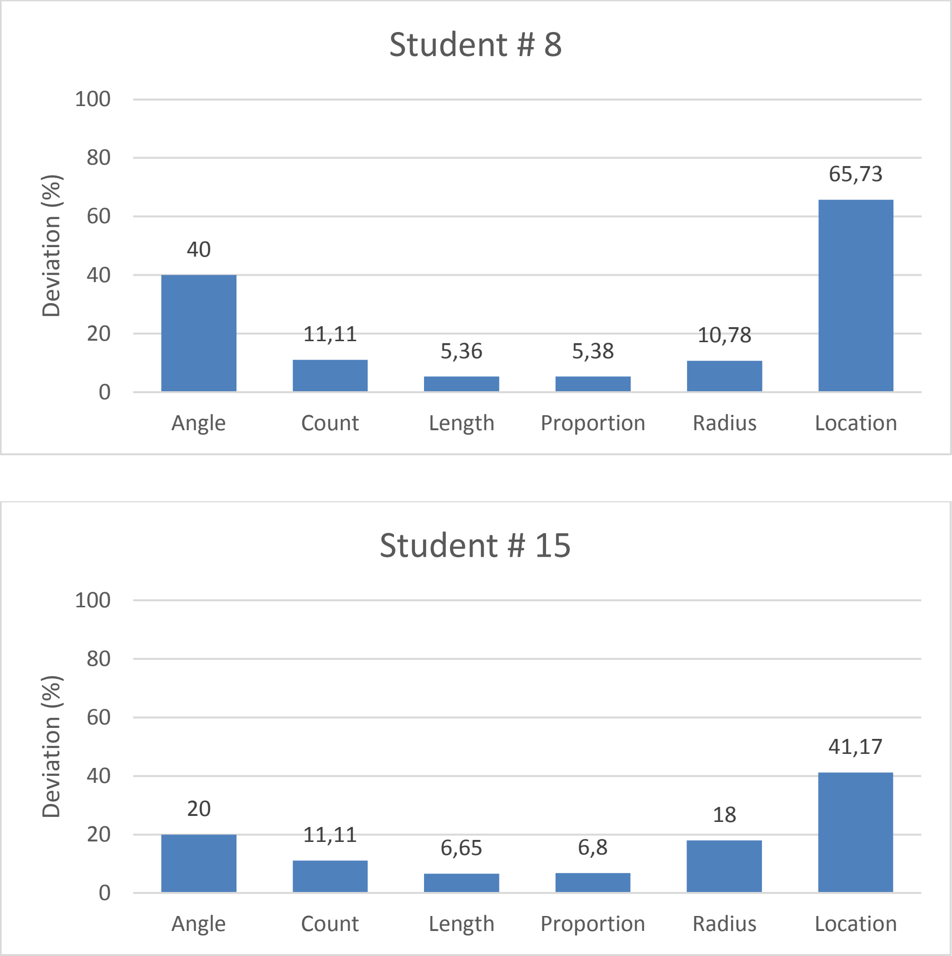


Figure 66. Analysis approach based on graphics' similarity.

An additional approach clustered students based on the property in which they performed the worst. Students were first ranked based on their position among the total sample (n = 27 students). Accordingly, they were given a position from 1 to 26 (given that two students had the same average, in position 16th). Figures 67 and 68, show that when clustered according to the mentioned approach, students tend to fit within a close range inside the general sample. In Figure 67, students having their worst deviation in the radius property, belong to the best half of the sample, with most of them being among the best five. Similarly, students having their worst deviation in the length property are located between the 16th and 21st positions (Figure 68).

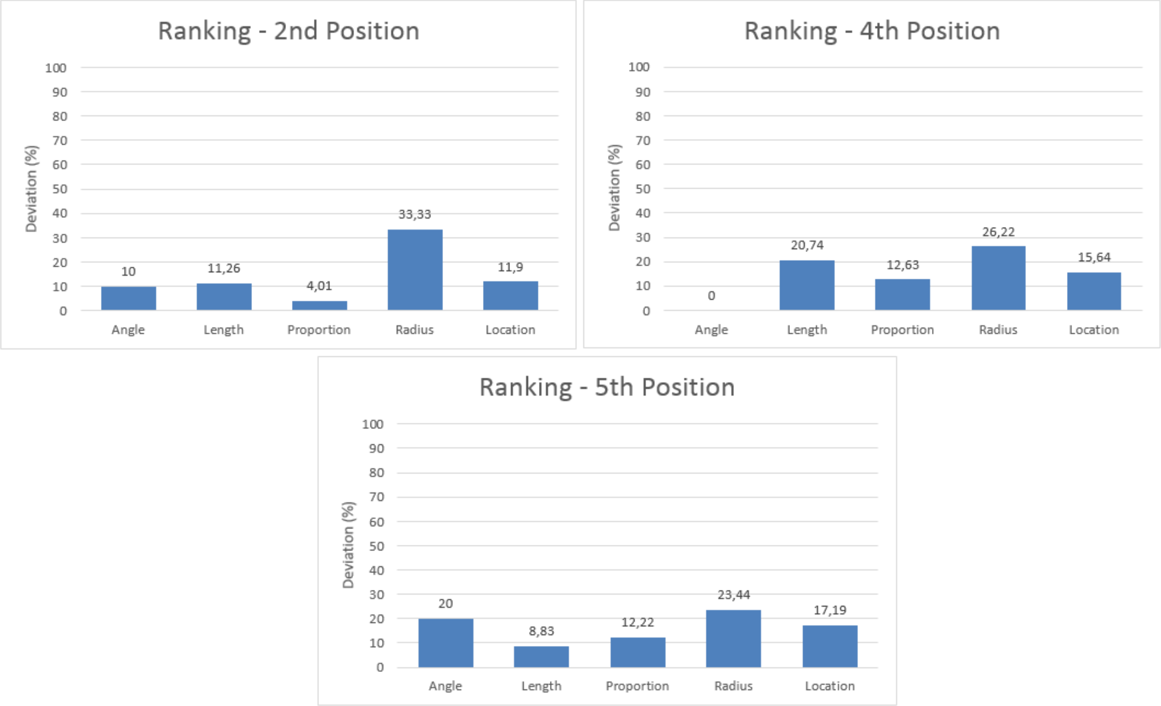


Figure 67. Students' clustering based on worst performance on Radius property.

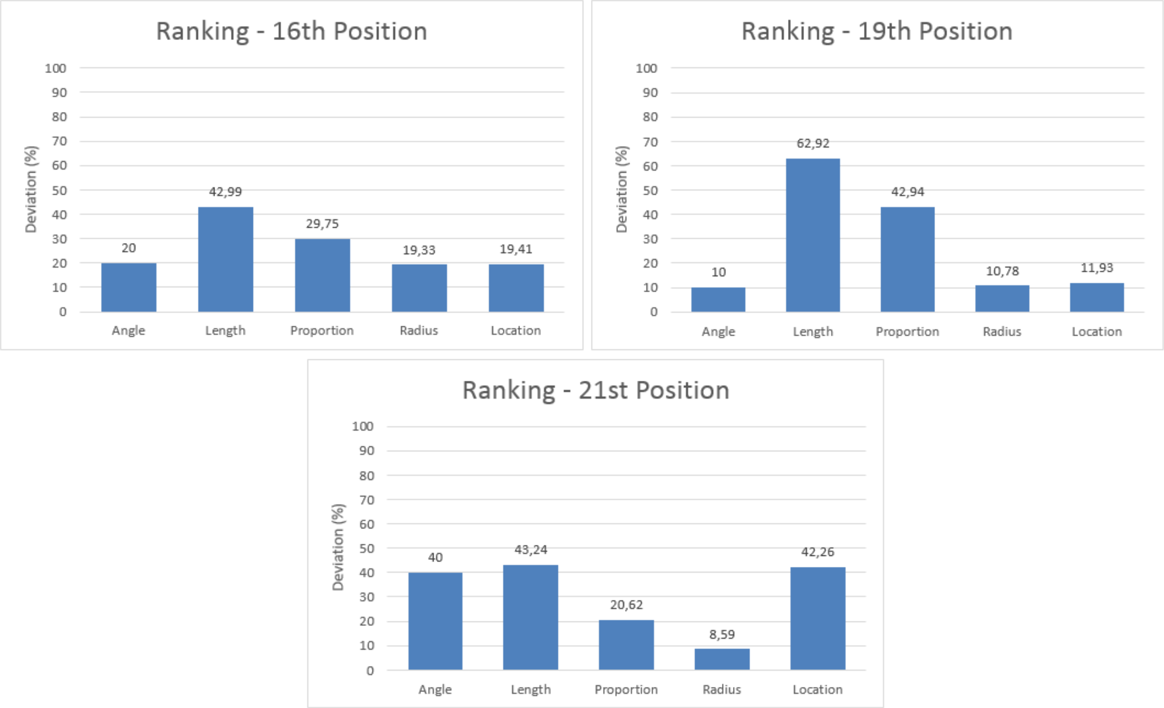


Figure 68. Students' clustering based on worst performance on Length property.

Another approach attempted to find patterns when clustering students which better performed in a given property. However, in contrast with the previously mentioned approach, trends were not easily perceived. When ranked among the 26 positions, random values appeared in each cluster. Lastly, the final approach tried to find similarities among students by means of their positions in the general ranking. Segmentation divided the sample in four groups, from about 6 to 7 positions. Lightly speaking, performance segmentation in such a way could be labeled as *Excellent, Good, Regular and Deficient*. One meaningful insight emerged from this segmentation: students with the poorest general performance (a total of 4 students) had all their best performance in the Length property, with low deviations. This can be observed in Figure 69. Apparently, students who exhibit this trend are focusing in length accuracy at the expense of the remaining properties.

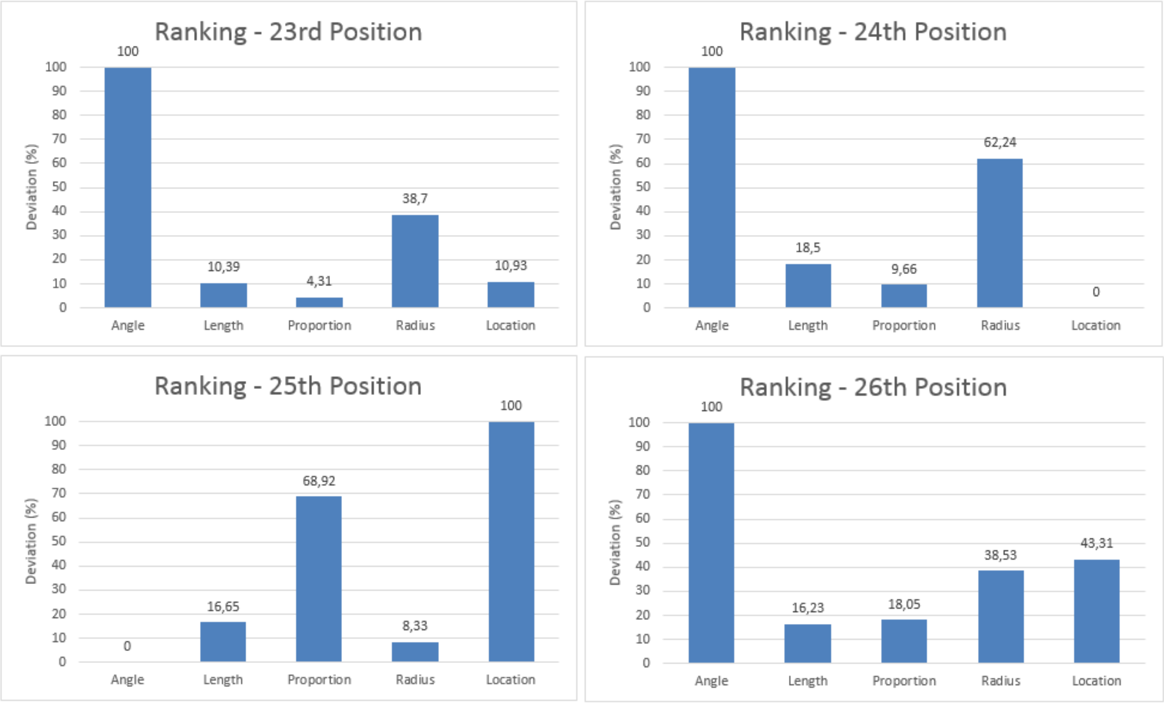


Figure 69. Students with the worst general performance have low deviations for the Length property.

4.4.2. Modeling profiles' proposal

Building on the insights casted by the approaches exposed in the last section, some 3D-modeling profiles are proposed. The most meaningful insights were found when clustering students by means of their worst performing shape property and their general ranking. From these categorizations, three different profiles were identified.

Inside-Out Modeling Profile

Students who fit within this profile were identified mainly through their behavior around the Proportion property; they had their worst performance in this property. However, for all the remaining properties their performance was rather good. These are students oriented towards the details, who apparently focus on achieving specific regions or attributes of the product. As a consequence, general measures are affected.

This could be shallowly compared with a person trying to reproduce the features of a human face when drawing. Usually, the general proportions get affected by the individual characteristics. If their workflow is to be described, they behave from the inside to the outside.

These students rank within the six best positions. Therefore, their profile fits two different approaches: worst deviation property and ranking. Figure 70 shows an example of this students' category.

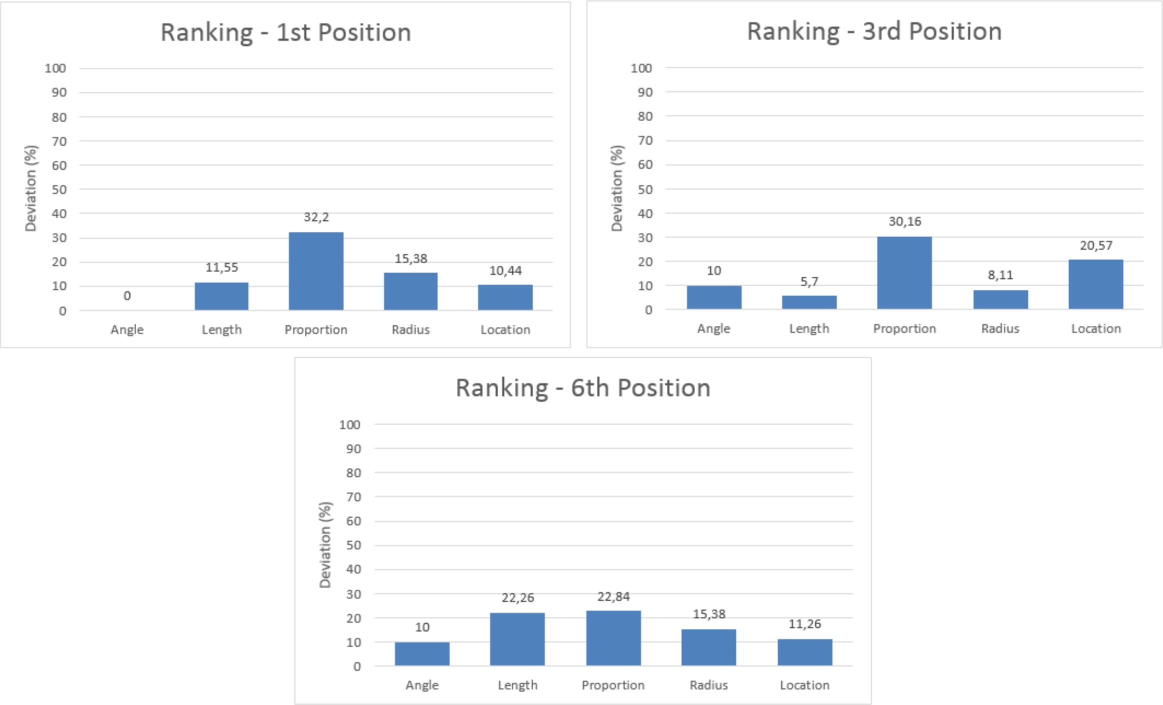
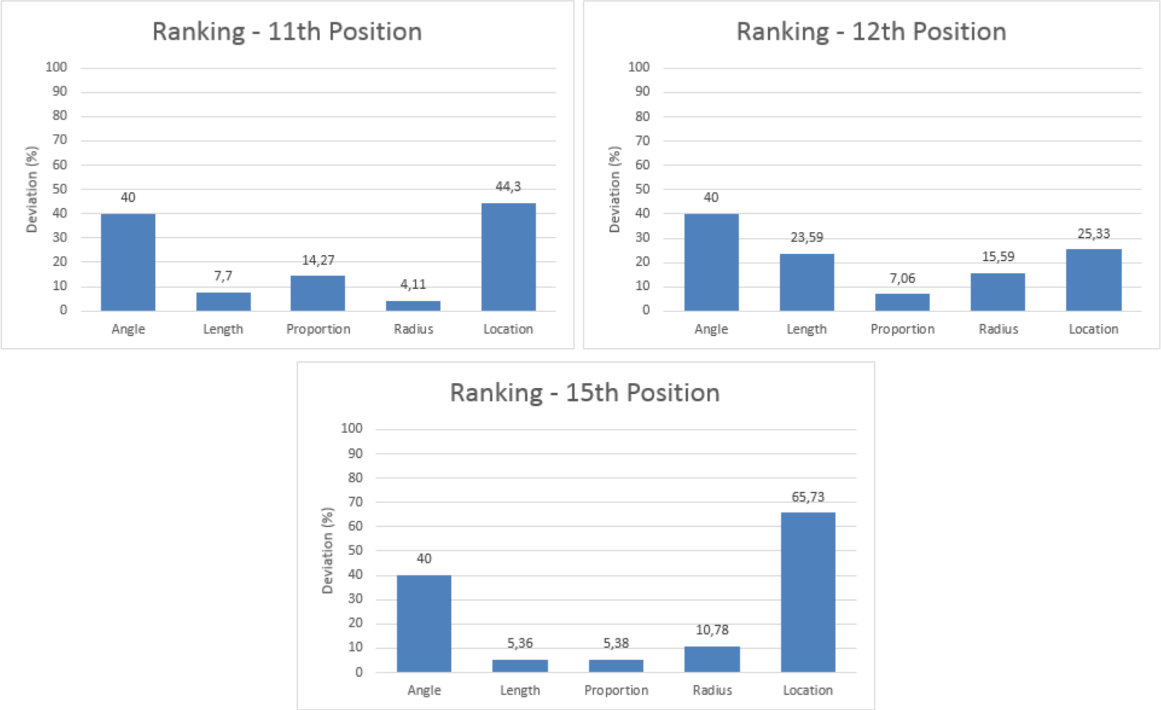


Figure 70. Example performance graphics for students fitted within the Inside-Out Modeling Profile.

Low-Coordinates Modeling Profile

Students labeled under this profile were selected based on their behaviors around the Angle and Location properties. They tend to have high values of deviation for these two properties, as well as a good performance for the Proportion property. This means that students under this profile focus on general measures, while neglecting coordinate-orientation properties. These students rank within the 10th and 15th positions. They behavior around dimensioning or sizing properties outperform spatial-orientation properties. An example of their performance graphs can be seen n Figure 71.


Ranking - 11th Position

Ranking - 12th Position

Ranking - 15th Position

Figure 71. Example performance graphics for students fitted within the Low-Coordinate Modeling Profile.

Length-Focus Modeling Profile

Students included inside this profile are remarkably focused on length accuracy. This property has always low-deviation values when observing their performance charts, although it might not be their best-performing property. However, they all belong to the worst-performing positions within the sample ranking (22nd to 26th). They also use to show high-deviation values for Angle and Location properties. For Proportion and Radius, no meaningful trends were identified. Figure 72 depicts the behaviors for students under this category.

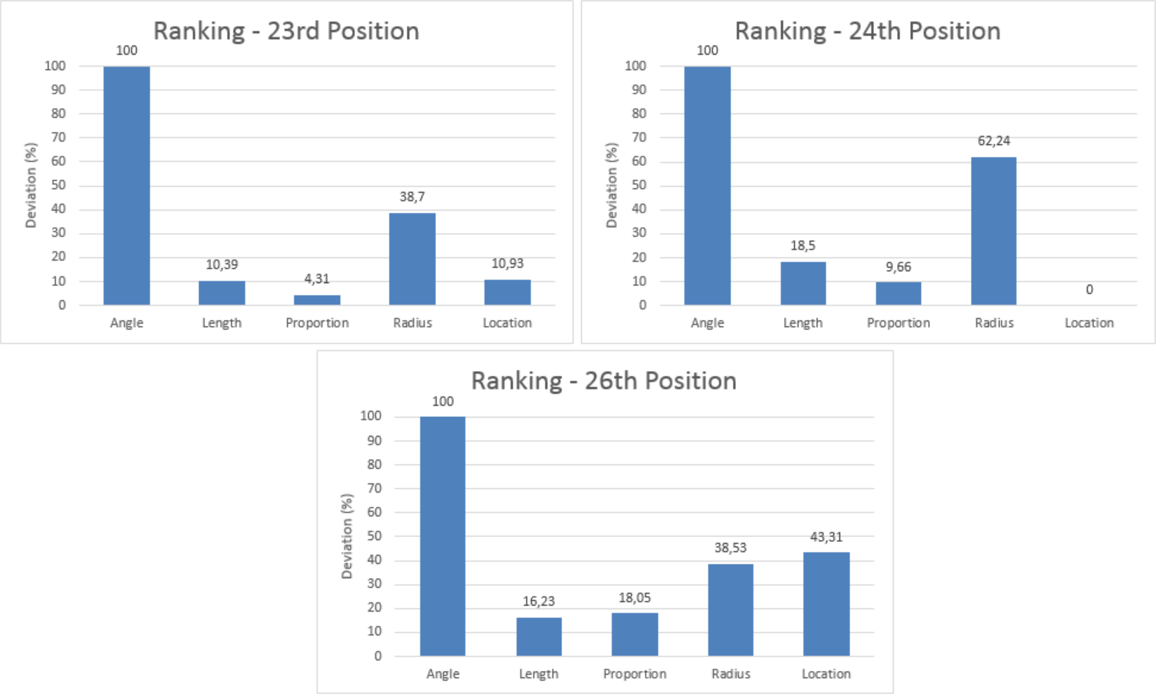


Figure 72. Example performance graphics for students fitted within the Length-Focus Modeling Profile.

It is relevant to say that the mentioned profiles do not describe the whole sample group. They summarize common trends exhibited by a significant portion of the different subject groups. In previous images, an example of three students who better fit the profile were shown. However, more than three students could be included under such profiles. These profiles, along with their characteristic performance and ranking are depicted in Table 10. Accordingly, Appendix D summarizes the subject sample, given students' number, averages and ranking.

Table 10. 3D-modeling profiles summarized by shape properties' performance and average ranking.

Shape properties	**3D-modeling profiles****		
	Inside-Out Profile	Low-Coordinates Profile	Length-Focus Profile
Angle	+	-	-
Length	+	+	+
Proportion	-	+	*N/A****
Radius	+	+	-
Location	+	-	*N/A****
Average performance*	*Good to high*	*Regular*	*Deficient*

* Global performance qualifiers across the sample.
** Signs + or – do not represent high or low global deviations (across the sample); they are high or low in comparison with the remaining properties within the same profile.
*** N/A qualifier signifies that a trend is not evident. Random values appear across the profile.

In order to avoid ambiguity, it is important to clarify that positive (+) and negative (-) signs in Table 10 describe the student performance. This means that a profile with a positive sign in a given property presents a good performance; and the contrary applies for negative signs. Such signs must not be interpreted as high or low deviations per se. All in all, the profiles here represented constitute a first approximation towards a better understanding of students' behaviors and approaches towards 3D-modeling activities. Further analysis and study sophistication are required in order to achieve higher accuracy and generalization certainty.

CHAPTER 5

Conclusions and future work

This report serves two main purposes: to introduce the notion of Computer Aided Styling (CAS) within the context of Product Design Engineering, at EAFIT University and to provide a general diagnostic on students' performance within 3D-modeling courses, around some essential shape properties present in objects or products. Both purposes aim to deepen the understanding of the field from professional practice and academic fields. Perspectives from both domains help to expand comprehension around the elements involved in form-giving design activities. In total, over 150 student outcomes were analyzed, and a general sample of over 80 students evaluated. Generally speaking, it was found that students perform poorly when trying to translate 2D views of products into 3D-matching models. Therefore, poor fidelity or correspondence implies perceptual and cognitive lacks, which might be overcame by adjusting pedagogical methodologies.

Main findings determine that students' strengths are allocated around the dimensioning or sizing shape properties, namely Length and Proportion. Higher deviation percentages from reference products are found around the so-called coordinate shape properties, namely Angle and Location. Curvature or Radius-related properties exhibit a more random behavior. However, in general terms, shape deviation seems to be increasing across subsequent academic semesters. These deviations were averaged using absolute values, used both for general conclusions as well as for the proposed modeling profiles. More in-depth analysis could also explore differences due to positive and negative deviations. Recalling, positive deviations implied modeled shapes *bigger* than the original ones; on the contrary, negative deviations implied modeled shapes *smaller* than the original ones. The influence of these two behaviors on students' performance and profiles is not accounted for within this study, and might be of relevance for future works.

With regard to the objectives and hypothesis, the study fulfilled the expectations. The general hypothesis assuming that students perform poorly within CAS related activities was confirmed. Furthermore, in order to arrive to such conclusion, the reviewed literature helped in selecting the essential shape properties relevant for shape translation, from 2D product views to corresponding 3D-models. These properties showed to be helpful for evaluating students' performance under three-dimensional digital environments. Insights from different fields and domains, such as drawing or visual recognition helped to justify their relevance and appropriateness. For instance, students' outcomes evaluated throughout these properties can be accurately categorized under a ranking system. Only one property was disregarded for testing: *Count*. This was due to the difficulty to find meaningful elements across all tested products, related to this specific property. Future works might include products where this property has more salient impact, therefore enabling the possibility to analyze its influence on students' performance. Additional properties can also emerge from further literature review.

However, some additional difficulties were encountered. Having the same number of students' outcomes (products under evaluation) for each test proved to be troublesome. Not all students effectively comply with their assigned deliverables. Therefore, products considered for evaluation were those who provided a significant sample while at the same time having enough elements for classification under the selected shape properties.

Accordingly, future works should be oriented towards study improvements. The present study attempted to set the ground for further research around *Styling* activities within the undergraduate program of Product Design Engineering. The student community might be sensitized towards active involvement within studies of similar nature. This way, it will be easier to have better subject samples. On the technical issues, it will be of relevance to have more sophisticated control over the testing variables and more statistical depth.

In terms of the proposed 3D-modeling profiles, this study provides an initial stage of insights. This initiative, along with the general findings on shape properties performance, aim to help educators in identifying students' strengths and weaknesses, in order to adjust pedagogical strategies. Findings within this domain might also help students' self-awareness and a more personalized education. Both needs are justified by different international and literature studies such as Bar-Eli (2013) and Chan (2001). All in all, these needs reflect on higher control over students' own abilities, helping them to potentiate their own design profiles and preferences.

Future research could apply *Protocol Analysis* (Ericsson & Simon, 1993), as it can be exemplified by Luck (2012), in order to deepen the understanding of students' behaviors towards the 3D-modeling activity. From a software perspective, this could be complemented by means of reviewing each student's file model-tree; this is the equivalent of the steps' history on how the student arrived to the final shape. The software currently used (PTC® Creo™ 3.0) allows for such purpose. Valuable insights might emerge in order to understand students' mental process.

Furthermore, findings might also help the general academic or professional community in terms of form-giving awareness and proficiency. Engineer-related programs which also rely on shape control and 3D-modeling skills might find valuable insights from subsequent work within this study line.

From a design perspective, traditionally, local efforts use to focus on re-engineering goals. Studies like the one here presented seek to support the development of crucial student competences in order to strengthen re-design activities with formal (aesthetic) objectives.

References

Adams, E. (2013). The Elements and Principles of Design: A Baseline Study. *International Journal of Art & Design Education*, *32*(2), 157–175.

Al-Kazzaz, D. A. & Bridges, A. H. (2012). A framework for adaptation in shape grammars. *Design Studies, 33*(4), 342–356.

Anderson, E. & Lilly, B. (2004). Visualization in the design process: introducing 2D and 3D sketching techniques to enhance creative thinking and communication. In *DS 33: Proceedings of E&PDE 2004, the 7th International Conference on Engineering and Product Design Education, Delft, the Netherlands, 02.-03.09. 2004*.

Andreasen, M. M. (2011). 45 Years with design methodology. *Journal of Engineering Design*, *22*(5), 293–332.

Anvaripour, M. & Ebrahimnezhad, H. (2013). Accurate object detection using local shape descriptors. *Pattern Analysis and Applications*, *18*(2), 277–295.

Arnheim, R. (1954). *Art and visual perception: A psychology of the creative eye*. University of California Press.

Aslan, D. & Arnas, Y. A. (2007). Three-to six-year-old children’s recognition of geometric shapes. *International Journal of Early Years Education*, *15*(1), 83–104.

Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review*, *61*(3), 183.

Bae, S.-H. & Kijima, R. (2003). Digital Styling for Designer: In Prospective Automotive Design. *Proceedings of Virtual Systems and Multi Media*, 546–553.

Bar-Eli, S. (2013). Sketching profiles: Awareness to individual differences in sketching as a means of enhancing design solution development. *Design Studies, 34*(4), 472–493.

Bassey, M. (1998). Action research for improving educational practice. *Teacher Research and School Improvement: Opening Doors from the inside*, 93–108.

Baylis, G. C. & Driver IV, J. (2001). Perception of symmetry and repetition within and across visual shapes: Part-descriptions and object-based attention. *Visual Cognition, 8*(2), 163–196.

Bennett, D. J. (2011). Seeing shape: Shape appearances and shape constancy. *The British Journal for the Philosophy of Science*.

Berlyne, D. E. (1971). Aesthetics and psychobiology.

Bermell García, P. & Ip-Shing, F. (2002). A KBE System for the design of wind tunnel models using reusable knowledge components.

Berry, J. (2008). Overcoming the Complexity of Teaching Form and Detail Aesthetics in Product Design Education. *A Grand Day Out: Empathic Approaches to Design*.

Bhattacharjeea, S. D. & Mittalb, A. (2015). Part-based Deformable Object Detection with a Single Silhouette Sketch.

Biederman, I. (1987). Recognition-by-components: a theory of human image understanding. *Psychological Review, 94*(2), 115–47.

Bilda, Z., Gero, J. S. & Purcell, T. (2006). To sketch or not to sketch? That is the question. *Design Studies, 27*(5), 587–613.

Bordegoni, M. (2011). Exploitation of designers and customers' skills and creativity in product design and engineering. In *Emotional Engineering* (pp. 63–85). Springer.

Boutonnet, B., Dering, B., Viñas-Guasch, N. & Thierry, G. (2013). Seeing objects through the language glass. *Journal of Cognitive Neuroscience*, *25*(10), 1702–10.

Catalano, C. E., Falcidieno, B., Giannini, F. & Monti, M. (2002). A survey of computer-aided modeling tools for aesthetic design. *Journal of Computing and Information Science in Engineering*, *2*(1), 11–20.

Chan, C.-S. (2001). An examination of the forces that generate a style. *Design Studies*, *22*(4), 319–346.

Chen, K. & Owen, C. L. (1998). A study of computer-supported formal design. *Design Studies*, *19*(3), 331–359.

Cheung, O. S. & Gauthier, I. (2014). Visual appearance interacts with conceptual knowledge in object recognition. *Frontiers in Psychology*, *5*, 793.

Cheutet, V., Catalano, C. E., Pernot, J.-P., Falcidieno, B., Giannini, F. & Léon, J.-C. (2005). 3D sketching for aesthetic design using fully free-form deformation features. *Computers & Graphics*, *29*(6), 916–930.

Cheutet, V., Léon, J.-C., Catalano, C. E., Giannini, F., Monti, M. & Falcidieno, B. (2008). Preserving car stylists' design intent through an ontology. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *2*(1), 9–16.

Company, P., Contero, M., Varley, P., Aleixos, N. & Naya, F. (2009). Computer-aided sketching as a tool to promote innovation in the new product development process. *Computers in Industry*, *60*(8), 592–603.

Creswell, J. W. (2012). *Qualitative inquiry and research design: Choosing among five approaches*. Sage.

Crilly, N., Moultrie, J. & Clarkson, P. J. (2004). Seeing things: consumer response to the visual domain in product design. *Design Studies*, *25*(6), 547–577.

Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity.

D'Ippolito, B. (2014). The importance of design for firms' competitiveness: a review of the literature. *Technovation*.

Dankwort, C. W. & Podehl, G. (2000). A new aesthetic design workflow—results from the european project fiores. In *CAD Tools and Algorithms for Product Design* (pp. 16–30). Springer.

Dankwort, C. W., Weidlich, R., Guenther, B. & Blaurock, J. E. (2004). Engineers' CAx education—it's not only CAD. *Computer-Aided Design*, *36*(14), 1439–1450.

Dickinson, S. J. & Pizlo, Z. (2013). *Shape perception in human and computer vision*. Springer.

Dillon, M. R. (2010). Dynamic Design: Cognitive Processes in Design Sketching. *Indiana Undergraduate Journal of Cognitive Science*, *5*, 28–43.

Doblin, J. (1987). Discrimination: The Special Skills Required for Seeing, and the Curious Structure of Judgment. *Design Processes Newsletter*, 1–6.

Dörner, D. (1999). Approaching design thinking research. *Design Studies*, *20*(5), 407–415.

Eggink, W. & Reinders, A. (2013). The Design and Styling of Technology-based Innovations. In *Proceedings 5th IASDR 2013 TOKYO*.

Elder, J. H. (2013). Perceptual Organization of Shape. In *Shape Perception in Human and Computer Vision* (pp. 71–83). Springer.

Erhan, H., Youssef, B. B., Sjoerdsma, M., Dill, J., Berry, B. & McCracken, J. (2011). Spatial thinking and communication: a course for first-year university students. *Proceedings of the Canadian Engineering Education Association*.

Ericsson, K. A. & Simon, H. A. (1993). Protocol analysis.

Farin, G. (2002). A History of Curves and Surfaces in. *Handbook of Computer Aided Geometric Design*, 1.

Fish, W. (2013). High-level properties and visual experience. *Philosophical Studies*, *162*(1), 43–55.

Fontana, M., Giannini, F. & Meirana, M. (1999). A free form feature taxonomy. In *Computer Graphics Forum* (Vol. 18, pp. 107–118).

Fung, R. Y., Chong, S. P. & Wang, Y. (2004). A framework of product styling platform approach: styling as intangible modules. *Concurrent Engineering*, *12*(2), 89–103.

Ganji, S. K., Potula, I., Ambati, V. N. P., Rao, B., Ganji, S. K. & Ganji, S. K. (2006). Image representation, scaling and cognitive model of object perception. *Cognitive Processing*, *7*(1), 37–39.

Giannini, F., Monti, M., Pelletier, J. & Pernot, J.-P. (2013). A survey to evaluate how non designers perceive aesthetic properties of styling features. *Computer-Aided Design and Applications*, *10*(1), 129–138.

Giannini, F., Monti, M. & Podehl, G. (2004). Styling Properties and Features in Computer Aided Industrial Design. *Computer-Aided Design & Applications*, *1*.

Goldman, A. (2001). The Aesthetic. In Berys Nigel Gaut and Dominic Lopes (Ed.), *The Routledge Companion to Aesthetics*. Routledge.

González, E., Adán, A. & Feliú, V. (2012). 2D shape representation and similarity measurement for 3D recognition problems: An experimental analysis. *Pattern Recognition Letters*, *33*(2), 199–217.

Gruen, A. (2012). Development and status of image matching in photogrammetry. *The Photogrammetric Record*, *27*(137), 36–57.

Guerrero, P., Auzinger, T., Wimmer, M. & Jeschke, S. (2015). Partial Shape Matching Using Transformation Parameter Similarity. In *Computer Graphics Forum* (Vol. 34, pp. 239–252).

Hara, K. (2007). *Designing design*. Lars Muller Publishers.

Hassanpour, R. (2015). A Two-Stage Matching Method for Multi-Component Shapes. *Advances in Electrical and Computer Engineering*, *15*(1), 143–150.

Hawkins, J. & Blakeslee, S. (2007). *On intelligence*. Macmillan.

Hedrick, K. A. (2012). Differentiation: A Strategic Response to Student Needs. *Education Digest: Essential Readings Condensed for Quick Review*, *78*(4), 31–36.

Hekkert, P. & Leder, H. (2008). Product aesthetics. *Product Experience*, 259–285.

Hekkert, P. & Schifferstein, H. N. (2008). Introducing product experience. *Product Experience*, 1–8.

Hill, C. S. & Bennett, D. J. (2008). The perception of size and shape. *Philosophical Issues, 18*(1), 294–315.

Hoffman, D. D. & Prakash, C. (2014). Objects of consciousness. *Frontiers in Psychology, 5*, 577.

Hoffman, D. D. & Richards, W. A. (1984). Parts of recognition. *Cognition, 18*(1), 65–96.

Hsu, S. H., Chang, W. & Chuang, M.-C. (2005). Effects of geometric form features on three-dimensional object categorization. *Perceptual and Motor Skills, 100*(3c), 899–912.

Hui, K. & Li, Y. (1998). A feature-based shape blending technique for industrial design. *Computer-Aided Design, 30*(10), 823–834.

Hummel, J. E. & Stankiewicz, B. J. (1998). Two roles for attention in shape perception: A structural description model of visual scrutiny. *Visual Cognition, 5*(1-2), 49–79.

Hummels, C., Paalder, A., Overbeeke, C., Stappers, P. & Smets, G. (1997). Two-handed gesture-based car styling in a virtual environment. In *proceedings of the 28th International Symposium on Automotive Technology and Automation (ISATA'97), D. Roller* (pp. 227–234).

Ibrahim, R. & Pour Rahimian, F. (2010). Comparison of CAD and manual sketching tools for teaching architectural design. *Automation in Construction*, *19*(8), 978–987.

Jean-Francois, O., Carole, B., Fabrice, M. & Améziane, A. (2007). Formalizing Design Rules Appearing in Early Design: An Application of Agglomerative Clustering. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Jonson, B. (2005). Design ideation: the conceptual sketch in the digital age. *Design Studies*, *26*(6), 613–624.

Kandinsky, W. & Rebay, H. (1947). *Point and line to plane*. Courier Corporation.

Kara, L. B. & Shimada, K. (2008). Supporting early styling design of automobiles using sketch-based 3d shape construction. *Computer-Aided Design and Applications*, *5*(6), 867–876.

Kavakli, M. & Gero, J. S. (2001). Sketching as mental imagery processing. *Design Studies*, *22*(4), 347–364.

Knoop, W., Breemen, E. van, Vergeest, J. & Wiegers, T. (1996). Towards more effective capturing of empirical data from design processes. In *Proceedings of 1st Conference in Descrptive Design, Istanbul*.

Kókai, I., Finger, J., Smith, R. C., Pawlicki, R. & Vetter, T. (2007). Example-based conceptual styling framework for automotive shapes. In *Proceedings of the 4th Eurographics workshop on Sketch-based interfaces and modeling* (pp. 37–44).

Krish, S. (2011). A practical generative design method. *Computer-Aided Design*, *43*(1), 88–100.

Lamb, D. & Bandopadhay, A. (1990). Interpreting a 3D object from a rough 2D line drawing. In *Proceedings of the 1st conference on Visualization'90* (pp. 59–66).

Lees-Maffei, G. & Houze, R. (2010). *The design history reader*. Berg Publishers.

Les, Z. (2001). Shape understanding: possible classes of shapes. *International Journal of Shape Modeling*, *7*(01), 75–109.

Les, Z. & Les, M. (2003). Shape understanding system: the visual reasoning process. *International Journal of Pattern Recognition and Artificial Intelligence*, *17*(04), 663–683.

Les, Z. & Les, M. (2008). Thinking, visual thinking, and shape understanding. *Shape Understanding System: The First Steps toward the Visual Thinking Machines*, 1–45.

Levet, F., Granier, X. & Schlick, C. (2006). 3d sketching with profile curves. In *Smart Graphics* (pp. 114–125).

Lewis, C. I. (1929). *Mind and the world-order: outline of a theory af knowledge*. New York: Dover Publications.

Li, Y., Sawada, T., Shi, Y., Steinman, R. M. & Pizlo, Z. (2013). Symmetry is the sine qua non of shape. In *Shape perception in human and computer vision* (pp. 21–40). Springer.

Luck, R. (2012). Kinds of seeing and spatial reasoning: Examining user participation at an architectural design event. *Design Studies*, *33*(6), 557–588.

Ma, C., Huang, H., Sheffer, A., Kalogerakis, E. & Wang, R. (2014). Analogy-driven 3D style transfer. In *Computer Graphics Forum* (Vol. 33, pp. 175–184).

Marr, D. (1982). A computational investigation into the human representation and processing of visual information. *San Francisco: Freeman and Company*.

Masry, M. & Lipson, H. (2007). A sketch-based interface for iterative design and analysis of 3D objects. In *ACM SIGGRAPH 2007 courses* (p. 31).

McGown, A., Green, G. & Rodgers, P. A. (1998). Visible ideas: information patterns of conceptual sketch activity. *Design Studies*, *19*(4), 431–453.

McKim, R. H. (1972). Experiences in visual thinking.

Menezes, A. & Lawson, B. (2006). How designers perceive sketches. *Design Studies*, *27*(5), 571–585.

Monti, M. (2011). Styling features for industrial design. In *Innovation in Product Design* (pp. 79–95). Springer.

Muller, W. (1989). Design discipline and the significance of visuo-spatial thinking. *Design Studies*, *10*(1), 12–23.

Muller, W. (2001). *Order and meaning in design*. Boom Koninklijke Uitgevers.

Nadal Roberts, M. (2007). *Complexity and aesthetic preference for diverse visual stimuli*. Universitat de les Illes Balears.

Olsen, L., Samavati, F. F., Sousa, M. C. & Jorge, J. A. (2009). Sketch-based modeling: A survey. *Computers \& Graphics*, *33*(1), 85–103.

Olsen, L., Samavati, F., Sousa, M. C. & Jorge, J. (2008). A taxonomy of modeling techniques using sketch-based interfaces. *Eurographics State of the Art Reports*, *1*(1.4), 1.

Ommer, B. (2013). The Role of Shape in Visual Recognition. In *Shape Perception in Human and Computer Vision* (pp. 373–385). Springer.

Owen, C. (2013). Style, Styling and Design: Beyond Formalism. *Design Processes Laboratory*, *4*(3).

Oxman, R. (1999). Educating the designerly thinker. *Design Studies*, *20*(2), 105–122.

Oxman, R. (2002). The thinking eye: visual re-cognition in design emergence. *Design Studies*, *23*(2), 135–164.

Özkar, M. & Stiny, G. (2009). Shape grammars. In *ACM SIGGRAPH 2009 Courses* (p. 22).

Peacocke, C. (1983). Sense and content: Experience, thought, and their relations.

Peng, H. (2008). *Design and evaluation of affective features in automobiles.*

Person, F. (2011). *The strategic relevance of styling and the management of design styles*.

Piaget, J. (2013). *Child's Conception of Space: Selected Works* (Vol. 4). Routledge.

Pittalis, M. & Christou, C. (2010). Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics*, *75*(2), 191–212.

Podehl, G. (2002). Terms and measures for styling properties. In *Proceedings of the 7th International Design Conference-DESIGN 2002* (pp. 879–886).

Poltoratski, S. & Tong, F. (2014). Hysteresis in the dynamic perception of scenes and objects. *Journal of Experimental Psychology: General*, *143*(5), 1875.

Prats, M., Lim, S., Jowers, I., Garner, S. W. & Chase, S. (2009). Transforming shape in design: observations from studies of sketching. *Design Studies*, *30*(5), 503–520.

Purcell, A. & Gero, J. S. (1998). Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, *19*(4), 389–430.

Raizman, D. (2003). *History of modern design: graphics and products since the Industrial Revolution*. Laurence King Publishing.

Rios, D. (2012). *Development of a collaborative-work model to assist product design processes through the use of computer tools*. Medellín, Colombia.

Santos, P., Stork, A., Filipe, R. & Jorge, J. (n.d.). An integrated Approach to Virtual Tape Drawing for Automotive Design.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action* (Vol. 5126). Basic books.

Simon, H. A. (1996). *The sciences of the artificial* (Vol. 136). MIT press.

Singh, K. (2006). Industrial motivation for interactive shape modeling: a case study in conceptual automotive design. In *ACM SIGGRAPH 2006 Courses* (pp. 3–9).

Smyth, S. N. & Wallace, D. R. (2000). Towards the synthesis of aesthetic product form. In *Proc. DETC2000/DTM-14554, ASME, New York.*

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*(3), 459–480.

Stiny, G. (1980). Introduction to shape and shape grammars. *Environment and Planning B, 7*(3), 343–351.

Stiny, G. & Gips, J. (1971). Shape Grammars and the Generative Specification of Painting and Sculpture. In *IFIP Congress (2)* (Vol. 2).

Suwa, M. & Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies, 18*(4), 385–403.

Takala, R., Keinonen, T. & Mantere, J. (2006). Processes of product concepting. In *Product Concept Design* (pp. 57–90). Springer.

Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C. & Kimura, F. (2009). Design methodologies: Industrial and educational applications. *CIRP Annals-Manufacturing Technology, 58*(2), 543–565.

Tovey, M. (1989). Drawing and CAD in industrial design. *Design Studies, 10*(1), 24–39.

Tovey, M. (1994). Form creation techniques for automotive CAD. *Design Studies, 15*(1), 85–114.

Tovey, M. (1997). Styling and design: intuition and analysis in industrial design. *Design Studies*, *18*(1), 5–31.

Tovey, M. (2002). Concept design CAD for the automotive industry. *Journal of Engineering Design*, *13*(1), 5–18.

Tovey, M. & Owen, J. (2000). Sketching and direct CAD modelling in automotive design. *Design Studies*, *21*(6), 569–588.

Tovey, M., Porter, S. & Newman, R. (2003). Sketching, concept development and automotive design. *Design Studies*, *24*(2), 135–153.

Treisman, A. M. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Van Dijk, C. G. (1995). New insights in computer-aided conceptual design. *Design Studies*, *16*(1), 62–80.

Van Elsas, P. & Vergeest, J. (1998). New functionality for computer-aided conceptual design: the displacement feature. *Design Studies*, *19*(1), 81–102.

Verstijnen, I. M. (1997). *Sketches of creative discovery: A psychological inquiry into the role of imagery and sketching in creative discovery*. Technische Universiteit Delft, Faculteit van het Industrieel Ontwerpen.

Verstijnen, I., van Leeuwen, C., Goldschmidt, G., Hamel, R. & Hennessey, J. (1998). Sketching and creative discovery. *Design Studies*, *19*(4), 519–546.

Vignesh, R., Suganthan, R. & Prakasan, K. (2007). Development of CAD models from sketches: a case study for automotive applications. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *221*(1), 41–47.

Wagemans, J. (2013). Two-Dimensional Shape as a Mid-Level Vision Gestalt. In *Shape Perception in Human and Computer Vision* (pp. 85–101). Springer.

Wallschlaeger, C., Busic-Snyder, C. & Morgan, M. (1992). *Basic visual concepts and principles for artists, architects, and designers*. McGraw Hill.

Wang, H. (1995). An approach to computer-aided styling. *Design Studies*, *16*(1), 50–61.

Wang, Z., Yang, W., Le, Z. & Zhao, F. (2013). A Design Method for Future Automobiles. In *Proceedings of the FISITA 2012 World Automotive Congress* (pp. 109–121).

Warell, A. & Young, K. (2011). Interior aesthetics: an experience-focused approach for the design of brand-specific automotive identity. *International Journal of Vehicle Design*, *55*(2), 278–303.

Won, W.-J., Yeo, J., Ban, S.-W. & Lee, M. (2007). Biologically motivated incremental object perception based on selective attention. *International Journal of Pattern Recognition and Artificial Intelligence*, *21*(08), 1293–1305.

Yin, R. K. (2013). *Case study research: Design and methods*. Sage publications.

Youssef, B. B. & Berry, B. (2012). Learning to think spatially in an undergraduate interdisciplinary computational design context: a case study. *International Journal of Technology and Design Education*, *22*(4), 541–564.

Zhang, H., Liu, J. & Zhang, Q. (2013). Neural correlates of the perception for novel objects.

Zhang, W. & Wang, X. (2014). A Graph-Based Object Structural Representing Method. In *Computational Intelligence and Design (ISCID), 2014 Seventh International Symposium on* (Vol. 2, pp. 263–267).

Zimmermann, P. (2008). Virtual reality aided design. A survey of the use of VR in automotive industry. In *Product Engineering* (pp. 277–296). Springer.

APPENDIX A

The Problem-Solving Process and Form Generation Model

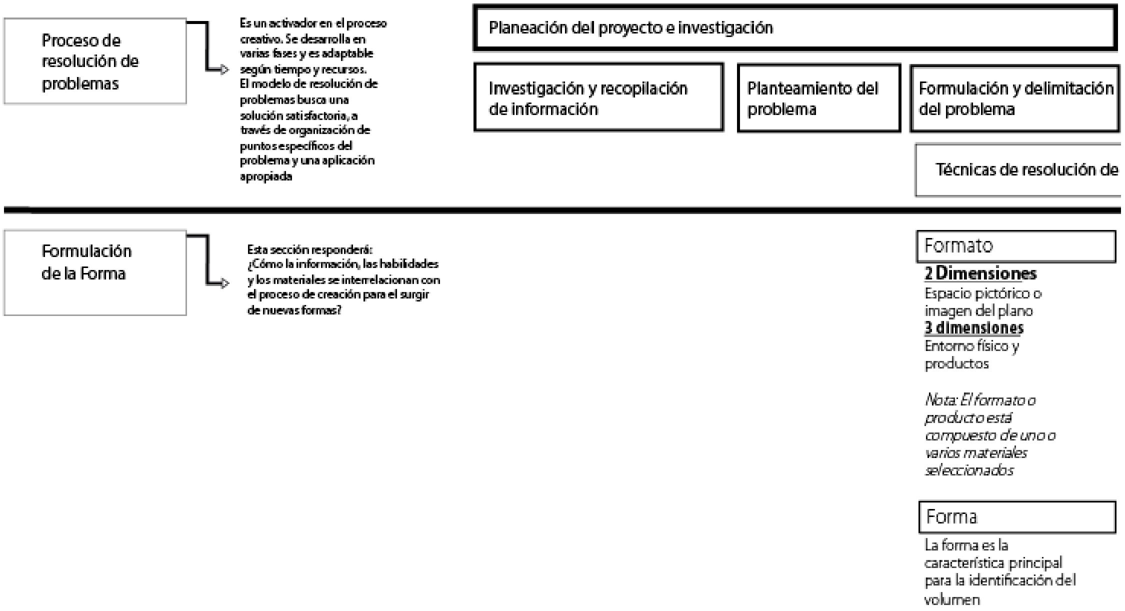
In order to frame the concepts and boundaries of the study, a model able to provide a general picture of the complexity and relations among the different aspects of the form-giving activity as a problem-solving process was selected. Towards this purpose Wallschlaeger et al. (1992) model accurately describes the steps usually involved in the creative form-giving activity and the elements involved. Furthermore, it includes different theories, such as perceptual and communicative ones, as well as laws, principles, systems and other conditioners of such domains.

The whole model, however, is not necessary for the understanding of the present work. As mentioned in Section 2.2.1, just the Visual Elements of Form and Perception Theory stages are crucial to frame the project. This stages are more closely related with the concepts and elements that the project aims to understand and use for effectively evaluate students' performance. These include the shape elements and properties that constitute a first level of recognition and differentiation among shapes. Domains such as composition require higher levels of cognition sophistication and were not included for analysis.

Table 11 depicts the general model layout, with full detail of stages and sub-stages. It is a Spanish version (translation by Jorge Hernan Maya, Ana Maria Cadavid, Stefany Vanessa Ruiz) of the original model expected to be used inside the local context of Product Design Engineering at EAFIT University.

Future work in line with the project around this model might include relational properties. Thus, composition, organization, Gestalt rules among others, could help to expand the understanding of students' approaches and behaviors towards form generation.

Table 11. The Problem-Solving Process and Form Generation Model (Spanish translation).



Es un activador en el proceso creativo. Se desarrolla en varias fases y es adaptable según tiempo y recursos. El modelo de resolución de problemas busca una solución satisfactoria, a través de organización de puntos específicos del problema y una aplicación apropiada

Esta sección responderá: ¿Cómo la información, las habilidades y los materiales se interrelacionan con el proceso de creación para el surgir de nuevas formas?

2 Dimensiones
Espacio pictórico o imagen del plano
3 dimensiones
Entorno físico y productos

Nota: El formato o producto está compuesto de uno o varios materiales seleccionados

La forma es la característica principal para la identificación del volumen

Desarrollo: Formulación de la forma

Conceptualización / Ideación

problemas: Incubación, creatividad y evaluación del concepto

Elementos visuales de la forma

Generación de la forma

Atributos visuales y físicos de la forma. Valor/ Tono

Point Elemento conceptual **SIN** dimensión
- Color

Línea
- Color
- Dirección
- Textura
- Dimensión de longitud

Plano
- Color
- Textura
- Proporción
- Dimensiones: largo y ancho.
- Dirección formal y estabilidad visual

Volumen es el resultado de: puntos (vértices) líneas (bordes) planos (superficies)
- Color
- Textura
- Dirección formal
- Dimensiones: largo, ancho y profundo

Teoría de percepción

Espacio, profundidad y distancia

Percepción formal en 2 y 3 dimensiones
- Umbral de contraste de luz o brillo
- Ilusiones
- Señales Monoculares:
    - Tamaño
    - Superposición parcial
    - Valor
    - Color
    - Perspectiva: aérea, detallada y lineal*
    - Gradiente de textura
    - Sombras
    - Difuminación de detalles
    - Transparencia
- Señales Binoculares:
    - Musculares
    - Paralaje
- Posición
- Orientación
- Movimiento
- Tiempo

Sistemas de dibujo o proyección

Ortográfico, perspectiva, dibujo lineal axonométrico y oblicuo

Principios de organización en 2 y 3 dimensiones

Conceptos o principio de percepción visual. Basado en la Teoría de Gestalt

Leyes de la figura
- Distinción de la figura según su contexto
- Figura ambigua
- Estabilidad / Inestabilidad
- Ley de cierre
- Ley de inclusividad. Fondo con figura inversa
- Patrón con figura inversa
- Figura superpuesta

Composición y organización visual
- Balance simétrico y asimétrico
- Repetición
- Armonía
- Ritmo
- Variedad
- Contraste
- Dominio

Leyes de agrupación o Asociación adquirida
- Asociación libre
- Familiaridad
- Jerarquías de información: de específico a general, de general a específico o en orden cronológico

Principios prescriptivos de organización

Organización espacial
- Centralizado
- Lineal
- Radial
- Agrupados
- Guía espacial. Rejillas.

Grupos simétricos
- Identidad
- Inicio (0,0) o eje de simetría.
- Operaciones: traslación, rotación, reflejo y efecto espejo con traslación lateral.
- Simetría
- Transformaciones: Afín, perspectiva, dilatación, topológica, sección Áurea y rectángulos de raíz.

Simetría dinámica /Geometrización
- Sistemas de proporción:
    - Aritmética
    - Armónica
    - Geométrica
- Teoría de proporción:
    - Sección Áurea
    - Renacimiento
    - Modulor
    - Antropométrica

Lenguaje o Teoría de Comunicación

Comunicación verbal y no verbal

Reconocimiento de patrones

Comunicación humana
- Relacionado con factores sociales o culturales

Lenguaje visual
- Códigos y símbolos

Semiótica (Teoría de signos)

Teoríapropuesta porCharles Morris

Semiosis
- Significante: Símbolo o nombre. Es el aspecto físico o concreto.
- Significado: Noción, la idea o parte conceptual del signo. También es pensamiento o referencia.
- Referente: Parte de la naturaleza a la que el signo hace referencia.

Sintaxis
- Concepto formal de la lengua
- Reglas sintácticas:
    - Reglas de formación
    - Reglas de transformación

Semántica
- Relación de los signos con su significado
- Reglas semánticas
- Estructuras lingüísticas
- Estructuras no lingüísticas

Pragmática
- Relación de los signos con el usuario
- Reglas pragmáticas

Proceso de comunicación

Proceso propuesto porD. Berlo

Fuente
↓
Mensaje
↓
Canal*
↓
Receptor

**Medios de comunicación*

Gráficos a mano
- Lápices
- Comic/Caricatura
- Estampados
- Cinta

Impresión
- Offset u ófset
- Litografía
- Serigrafía

Película
- Still*
- Movimiento
- Multimedia

Video

Computador
- Asistido por computador

**Fotografía tomada dentro o fuera del set de una película o programa de televisión durante la producción.*

Materiales, Procesos y Producción

Solución y Evaluación

Desarrollo de conceptos preliminares y prototipos

Procesos de manufactura y tecnología

Producción del modelo final

Evaluación/ Pruebas

Factores humanos y dimensiones

- Requerimientos del usuario
- Factores socio culturales
- Factores económicos
- Antropometría y dimensiones humanas

Configuración de la forma, estructura y materiales

Configuraciones de polígono y poliedro

2 Dimensiones

- Polígonos
- Mosaicos

3 Dimensiones

- Poliedro
- Intersección de poliedros para generar ciertas formas. Diferente de operaciones Booleanas.
- Espacio lleno de poliedros: Donde la mayoría de sus puntos son congruentes.
- Estructuras empaquetadas, abiertas y cerradas.

Sistemas estructurales

Estructuras estáticas

- Solido
- Chasís
- Plano / Superficie

Estructuras dinámicas

Mecanismos en movimiento

- Niveles
- Bielas
- Levas
- Ruedas
- Engranajes
- Acoples
- Embragues
- Rodamientos

Cargasestructurales, fuerzas y equilibrio

- Fuerza
- Gravedad
- Fatiga
- Tensión
- Compresión
- Cizalla
- Torsión
- Tensión
- Equilibrio
- Resistencia

Materiales y sus características

- Madera
- Papel
- Plástico
- Metal
- Tejido
- Cerámico
- Vidrio

Herramientas y maquinaria de manufactura

- Máquinas de madera y metal
- Termo formado
- Impresiones, plegadoras y troqueladoras

Unidad de la forma

Formas de arte

Arquitectura

Formas de diseño

- Mensajes visuales o diseño gráfico
- Productos
- Estructuras
- Interiores

APPENDIX B

Survey's fact sheet

Within the study, it was important to understand the students' perception of 3D-modeling, framed inside the general design process and from some field specificities. This information might reveal preference, trends, limitations, etc. The general sample included 49 students (n = 49), from which 24 were female and 25 male. Furthermore, students could be coursing different academic semesters, ranging from the 2nd to the 8th; the majority of which pertained to the 4th semester, which is the recommended situation (Figure 73).

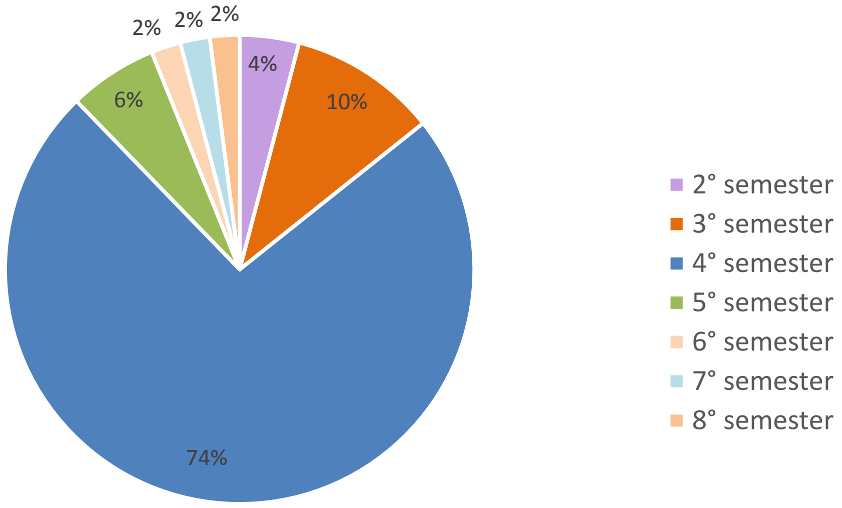


Figure 73. Student´s academic semester sample.

A review of the layout, questions and answers are hereby presented:

1) Do you consider yourself as having the ability to design the shape (aesthetics) of a product in its whole?

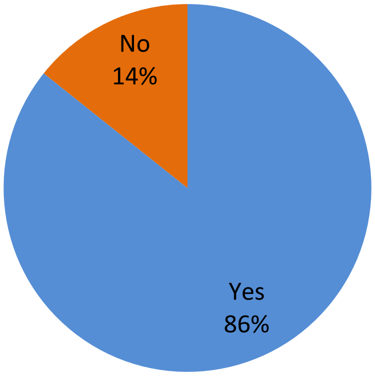


Figure 74. Students' self-perceived capacity to design a product´s (aesthetic) shape.

2) Which activity do you think fits you better (Feel more related or skilled)?

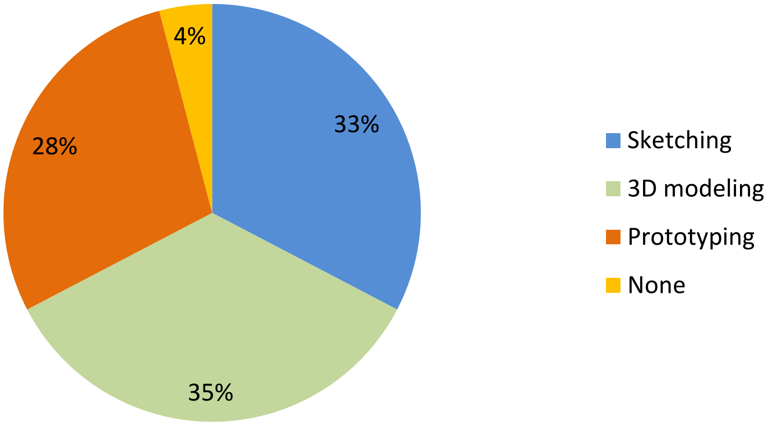


Figure 75. Students' preferred design-related activities.

3) Which method do you prefer for designing a product's shape?

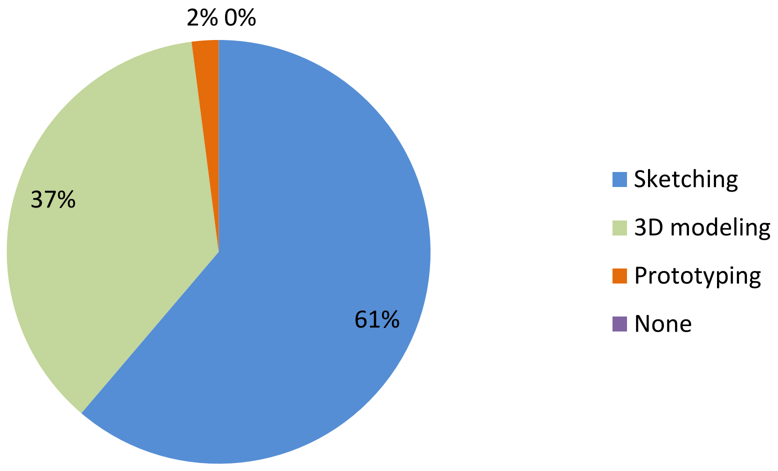


Figure 76. Students' preferred form-giving activities

4) If you had the responsibility of designing a product's shape and had to choose, which set of tools would you use?

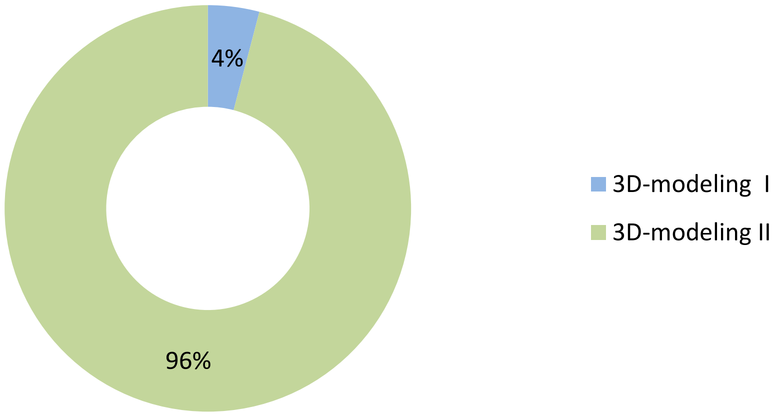


Figure 77. Students' preferred course-related set of tools.

5) When modeling, do you prefer to add, remove material or create contours in order to achieve the desired shape?

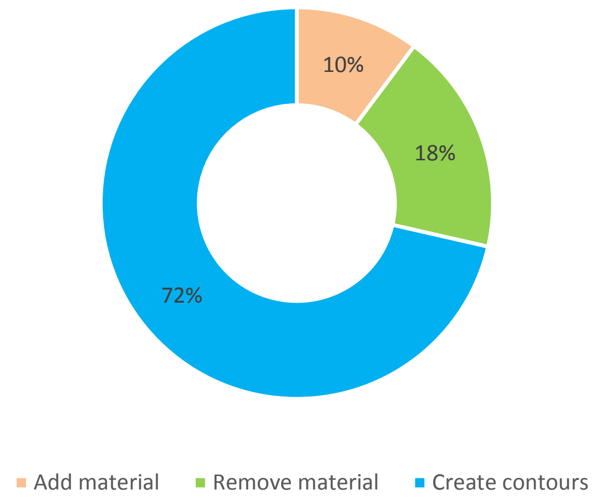


Figure 78. Students' preferred 3D-modeling approaches.

6) Which method do you consider easier to use?

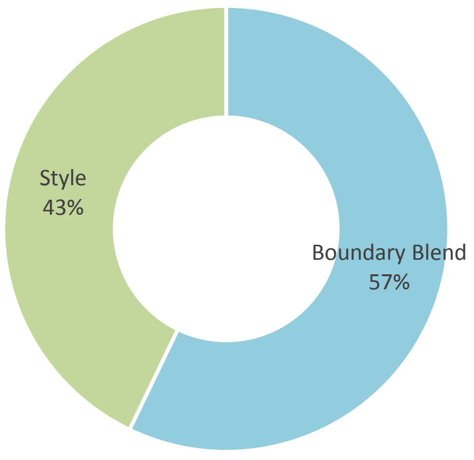


Figure 79. Students' perceived ease of usage, for 3D tools or modules.

7) Do you feel in TOTAL control over a product’s shape using the 4 views provided by the *Style* module?

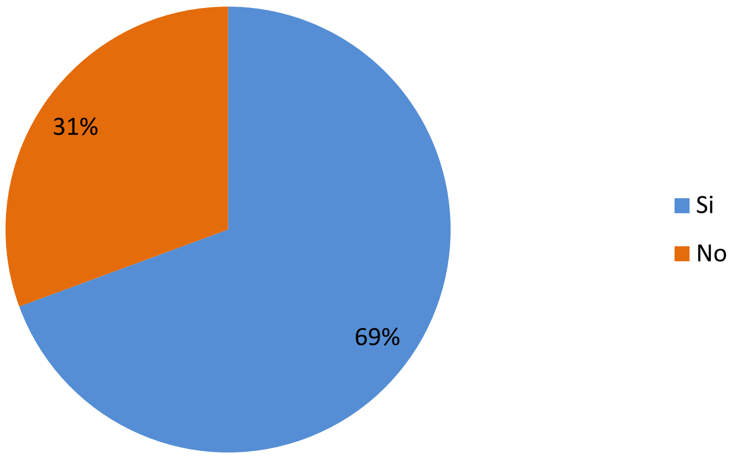


Figure 80. Students’ perceived control over the 4 viewport windows.

8) What *drawing* skill level do you consider to have? 1: Deficient – 10: Excellent

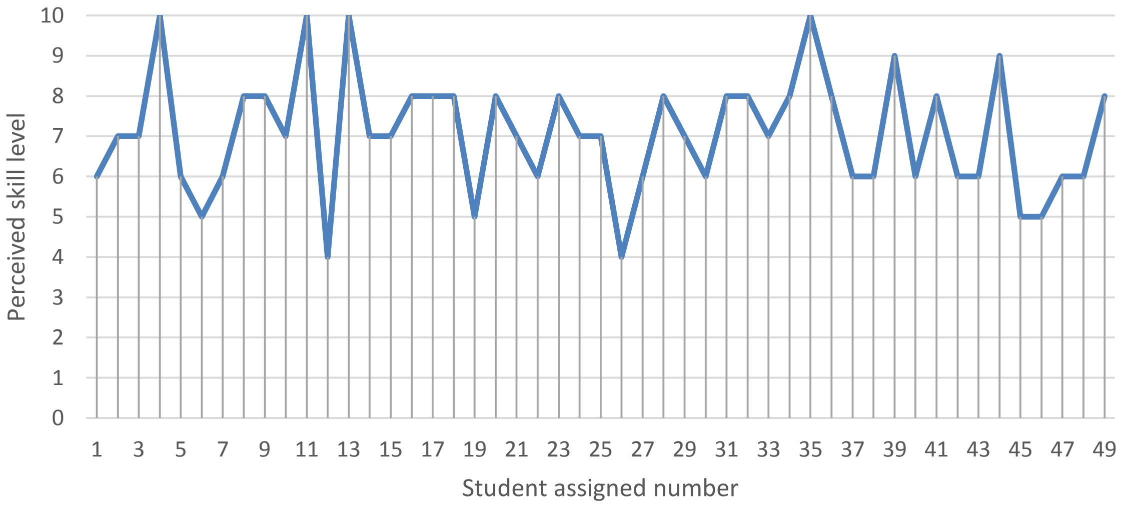


Figure 81. Students' perceived own skill for drawing (mean value of 7.1 over 10).

9) What *3D-modeling* skill level do you consider to have for aesthetic parts of a product? 1: Deficient – 10: Excellent

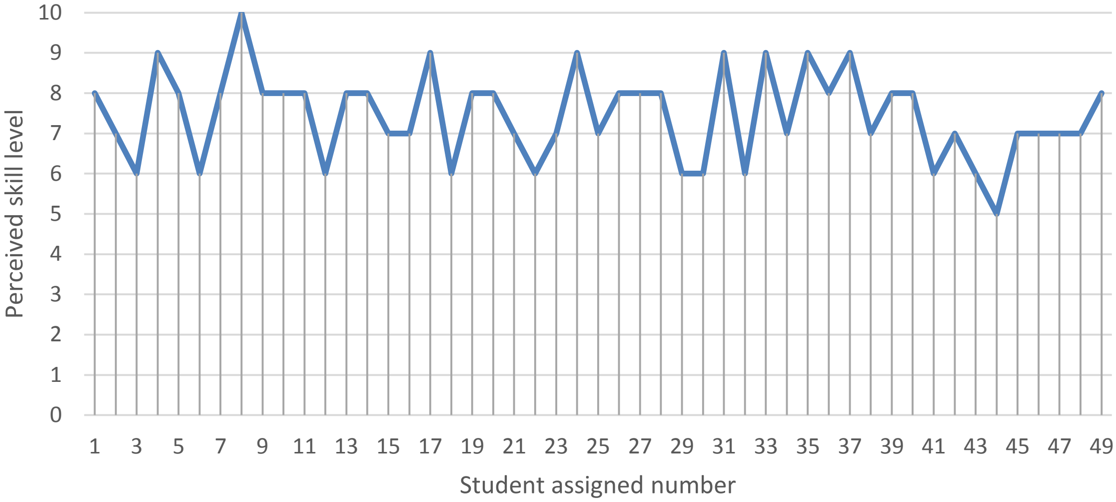


Figure 82. Students' perceived own skill for aesthetic 3D-modeling (mean value of 7.4 over 10).

10) What *3D-modeling* skill level do you consider to have for functional parts (gears, chassis, etc.) of a product? 1: Deficient – 10: Excellent

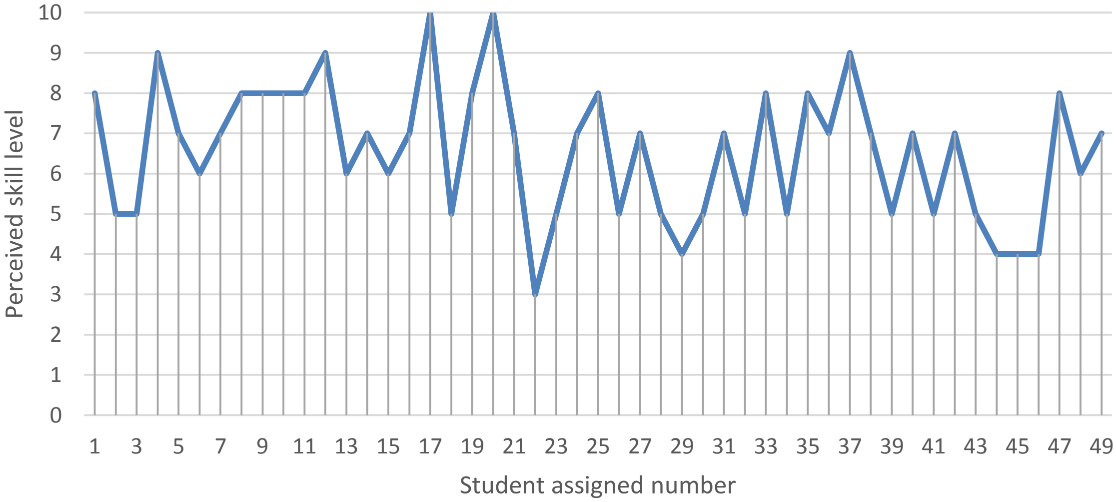


Figure 83. Students' perceived own skill for functional 3D-modeling (mean value of 6.6 over 10).

11) What *prototyping* skill level do you consider to have? 1: Deficient – 10: Excellent

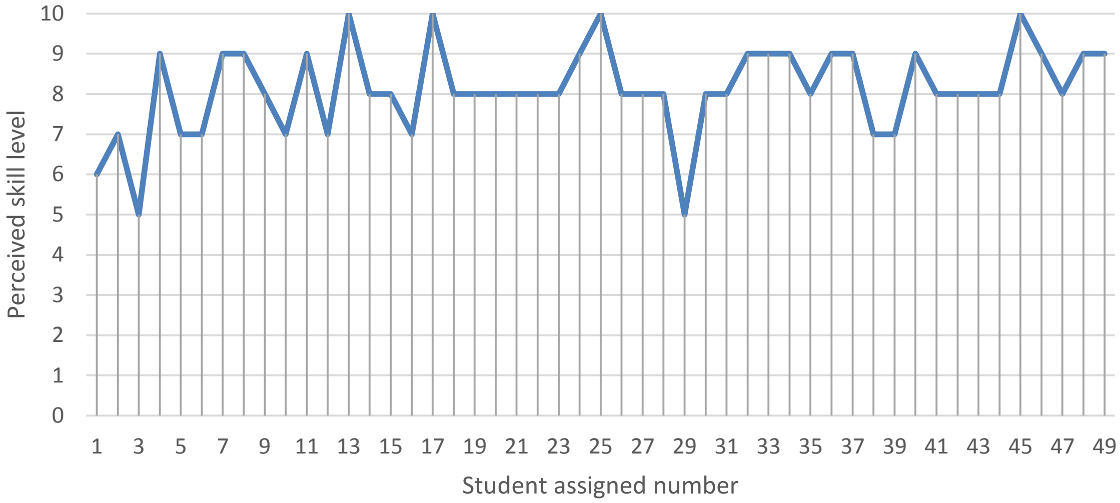


Figure 84. Students' perceived own skill for prototyping (mean value of 8.1 over 10).

12) When modeling based on a reference image, how similar do you think the outcome is? 1: No similarity – 10: Exact similarity

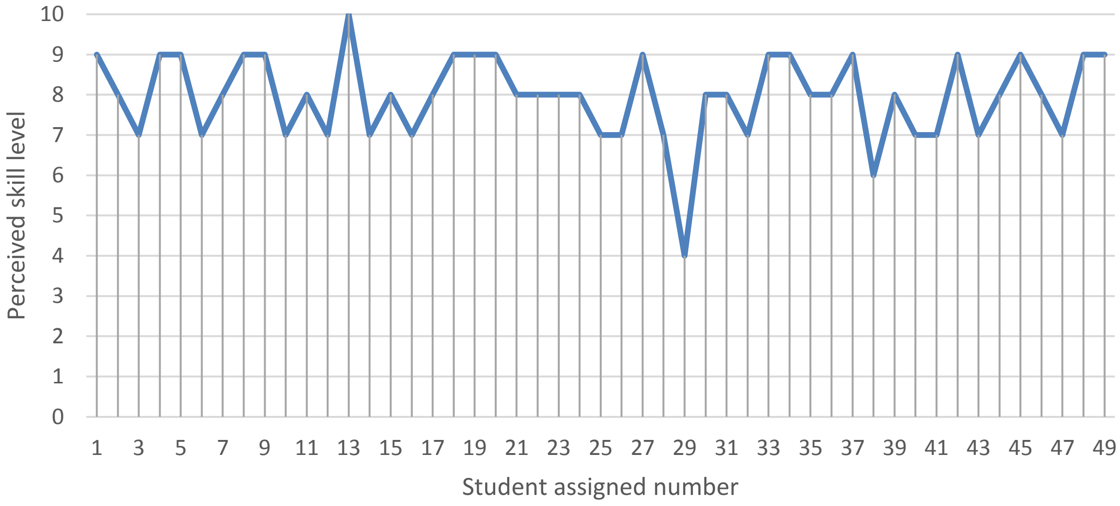


Figure 85. Students' perceived outcome similarity from a 2D reference image (mean value of 8.0 over 10).

13) How intuitive (easy to work with and to memorize features' usage) do you think the 3D-modeling class software (Creo 3.0) is?

1: No intuitive – 10: Completely intuitive

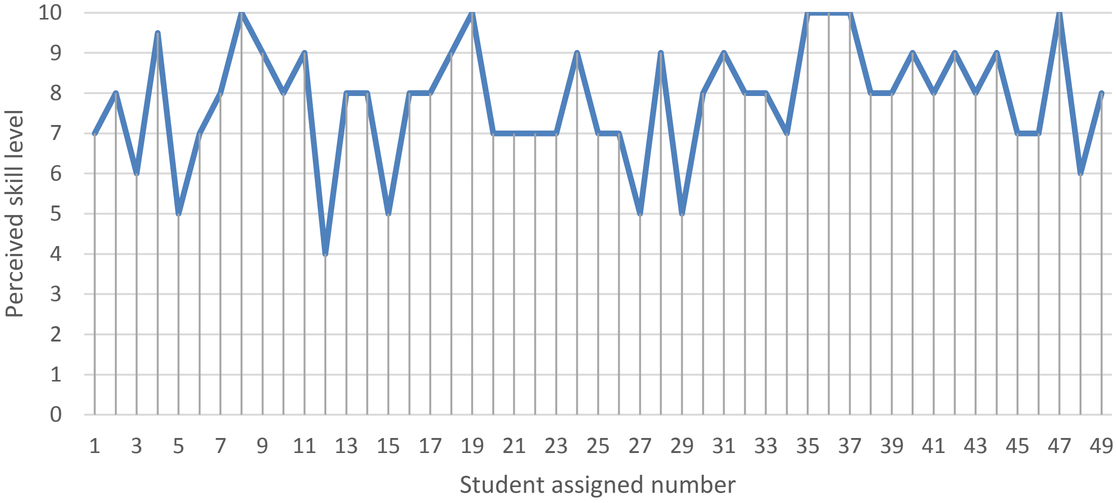


Figure 86. Students' perceived software ease of use (mean value of 7.8 over 10).

14) How conscious of your modeling mistakes (formal/aesthetic) are you?

1: No conscious – 10: Completely conscious

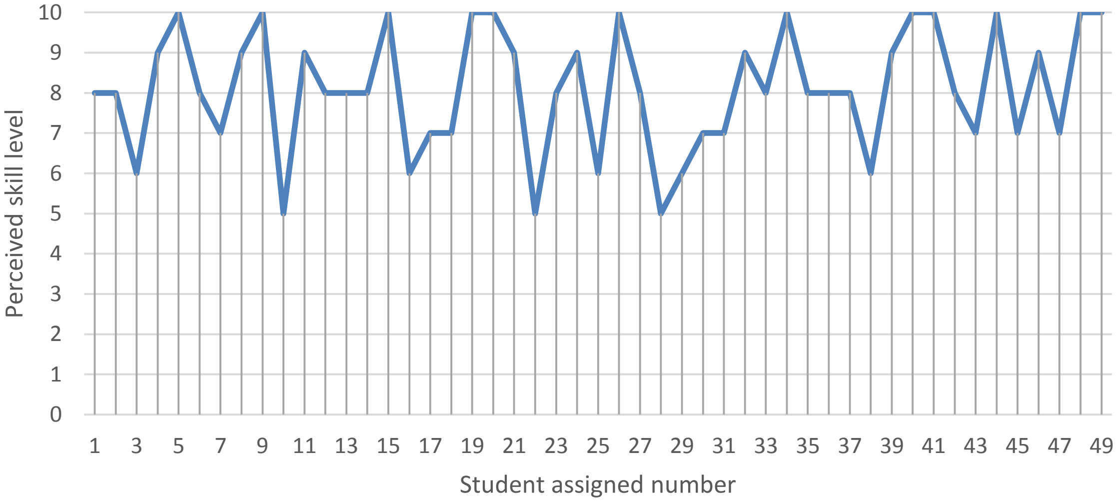


Figure 87. Students' awareness of aesthetic mistakes (mean value of 8.1 over 10).

15) How conscious of the technical modeling mistakes that prevent you to use a feature or achieve the desired shape are you?

1: No conscious – 10: Completely conscious

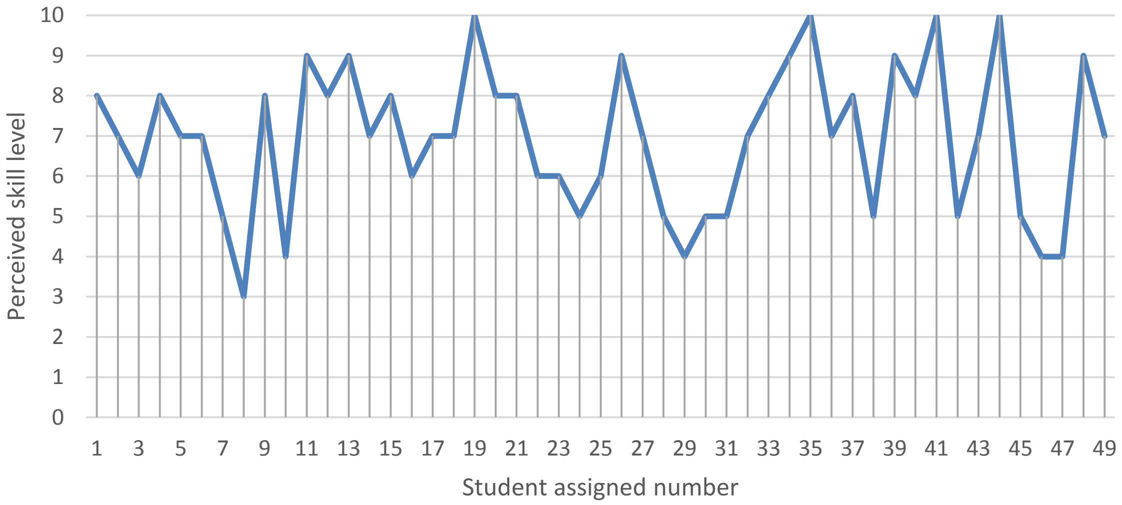


Figure 88. Students' awareness of aesthetic mistakes (mean value of 6.9 over 10).

APPENDIX C

Deviation percentages and outcomes

The purpose of this appendix is to illustrate the performance of some of the students and to relate them with some of their outcomes. Hereby, their average deviation values is presented visually; towards this goal, three examples are shown, synthetizing what it could be a *Deficient, Regular* and *Good performance*. Figure 89 illustrate performances for Allessi's Piripicchio; Figure 90 illustrate performances for a simplified Bike Seat; and Figure 91 illustrate performances for Water Can.

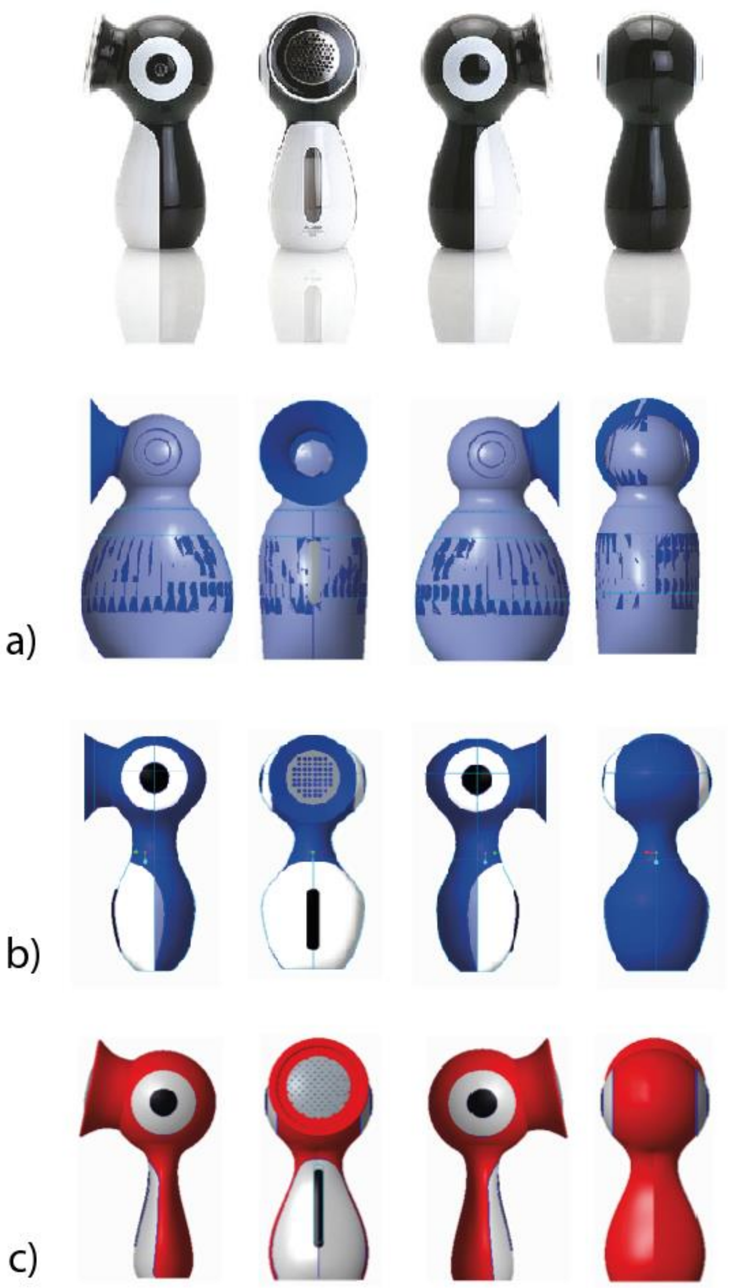


Figure 89. Example of a ***(a)*** *Deficient (38.2% deviation),* ***(b)*** *Regular (24.2% deviation) and* ***(c)*** *Good (6.4% deviation) shape translation based on mean deviations for Alessi's Piripicchio.*

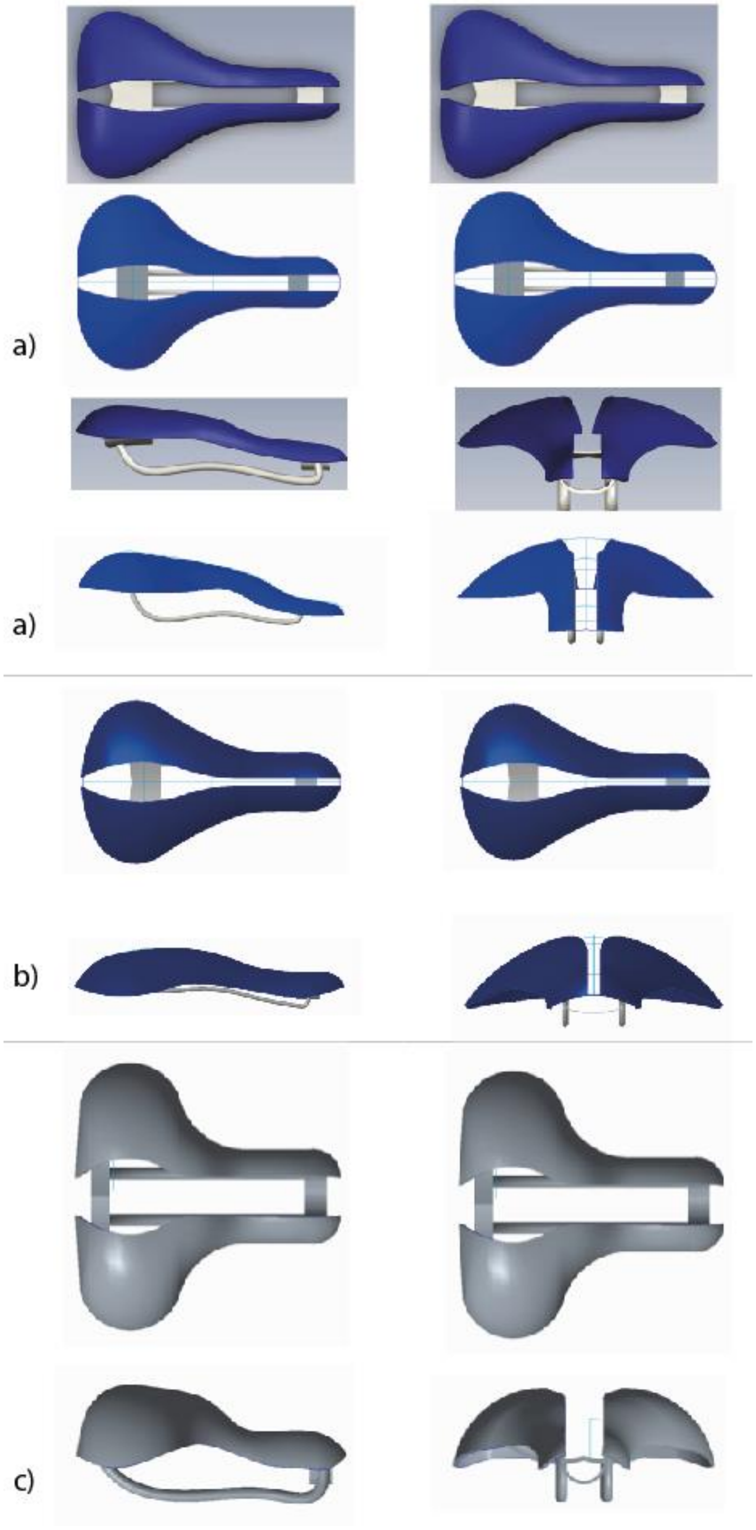


Figure 90. Example of a ***(a)*** *Good (9.9% deviation),* ***(b)*** *Regular (28% deviation) and* ***(c)*** *Deficient (73.6% deviation) shape translation based on mean deviations for a simplified Bike Seat.*

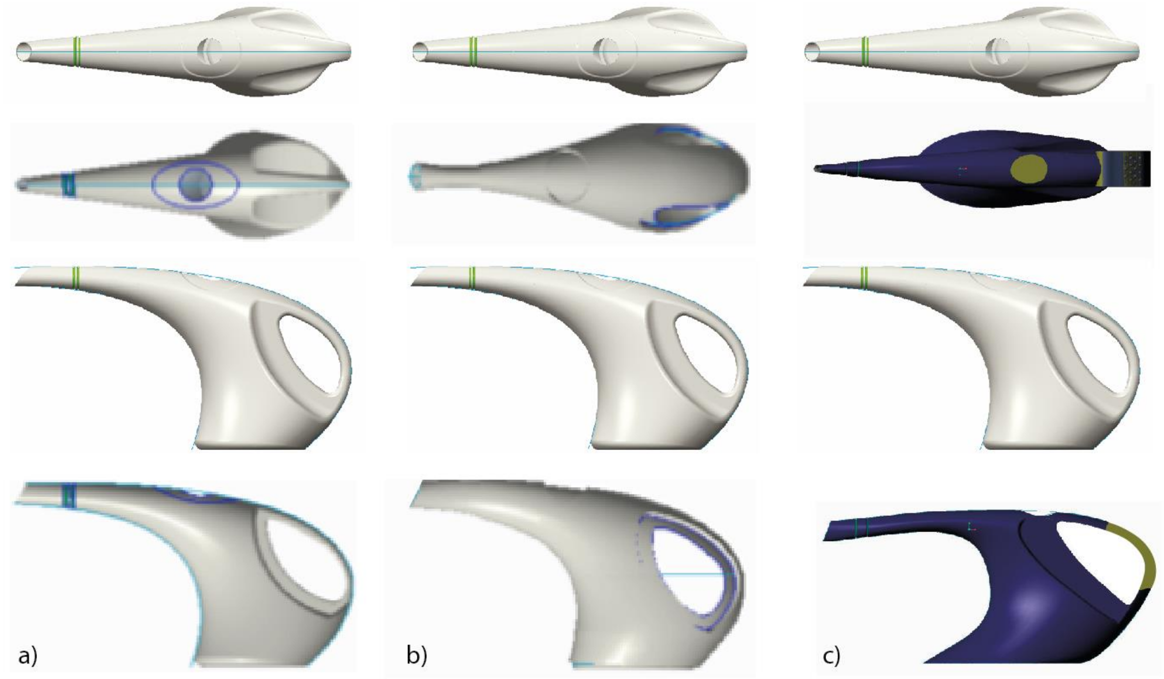


Figure 91. Example of a ***(a)*** *Good (15.3% deviation),* ***(b)*** *Regular (31% deviation) and* ***(c)*** *Deficient (70% deviation) shape translation based on mean deviations for a simplified Bike Seat.*

Hopefully, these examples provide a notion of how the selected properties helped to evaluate shape translation performances. However, there is still a long way towards complete accuracy in terms of complete translation evaluation. More items of the same or additional properties are required to properly describe the performance of a student for a given product. Within the scope of this study, items for each property were used to describe different parts of a product, in order to cover as much representative regions as possible. Limitations of time and resources prevented a more comprehensive evaluation of properties for each product. In general, a range between 5 and 7 items were included across products. Future works could include more items as well as more properties, assuring better deviation descriptions of students' shape correspondence.

APPENDIX D

3D-modeling profiles' sample and ranking

As mentioned in Section 4.4, students' classification within a ranking was used as a means to find possible trends and behaviors. A sample consisting in 27 test subjects was analyzed through various product outcomes. Averages for each of the selected shape properties were found for each student as well as for the whole test group. These values were used during Test 3 in order to propose 3D-modeling profiles based on their shape translation performances. Students' anonymity is assured by assigning a number, which facilitates their allocation inside the proposed profiles. Table 12 shows the general sample performance sorting students by their assigned numbers. Table 13, on the other hand, depicts the same information by sorting students based on their average performance and their corresponding position among the general sample ranking.

Table 12. Sample group for Test 3 sorted by their assigned number.

Student #	Angle	Length	Proportion	Radius	Location	Average Deviation	Ranking Position
1	10	5,7	30,16	8,11	20,57	14,91	3
2	10	22,26	22,84	15,38	11,26	16,35	6
3	40	16,2	20,82	17,2	9,87	20,82	10
4	20	8,83	12,22	23,44	17,19	16,34	5
5	40	17,83	12,14	4,11	69,84	28,78	20
6	10	11,26	4,01	33,33	11,9	14,10	2
7	40	18,19	9,65	39,71	27,73	27,06	18
8	40	5,36	5,38	10,78	65,73	25,45	15
9	10	15,82	30,9	8,11	66,67	26,30	16
10	40	18,09	30,22	35,44	38,54	32,46	22
11	40	21,13	25,15	8,11	8,4	20,56	9
12	0	16,65	68,92	8,33	100	38,78	25
13	0	6,77	22,84	9,63	50,05	17,86	7
14	40	7,7	14,27	4,11	44,3	22,08	11
15	20	6,65	6,8	18	41,17	18,52	8
16	10	62,92	42,94	10,78	11,93	27,71	19
17	20	30,25	21,15	13,44	42,31	25,43	14
18	100	18,5	9,66	62,24	0	38,08	24
19	20	42,99	29,75	19,33	19,41	26,30	16
20	100	10,39	4,31	38,7	10,93	32,87	23
21	40	23,59	7,06	15,59	25,33	22,31	12
22	40	43,24	20,62	8,59	42,26	30,94	21
23	0	11,55	32,2	15,38	10,44	13,91	1
24	0	20,74	12,63	26,22	15,64	15,05	4
25	100	16,23	18,05	38,53	43,31	43,22	26
26	20	30,5	9,21	45,44	13,49	23,73	13
27	0	32,5	21,22	33,67	45,24	26,53	17
Property Average	30,00	20,07	20,19	21,17	31,98		

Table 13. Sample group for Test 3 sorted by their ranking position.

Student #	Angle	Length	Proportion	Radius	Location	Average Deviation	Ranking Position
23	0	11,55	32,2	15,38	10,44	13,91	1
6	10	11,26	4,01	33,33	11,9	14,10	2
1	10	5,7	30,16	8,11	20,57	14,91	3
24	0	20,74	12,63	26,22	15,64	15,05	4
4	20	8,83	12,22	23,44	17,19	16,34	5
2	10	22,26	22,84	15,38	11,26	16,35	6
13	0	6,77	22,84	9,63	50,05	17,86	7
15	20	6,65	6,8	18	41,17	18,52	8
11	40	21,13	25,15	8,11	8,4	20,56	9
3	40	16,2	20,82	17,2	9,87	20,82	10
14	40	7,7	14,27	4,11	44,3	22,08	11
21	40	23,59	7,06	15,59	25,33	22,31	12
26	20	30,5	9,21	45,44	13,49	23,73	13
17	20	30,25	21,15	13,44	42,31	25,43	14
8	40	5,36	5,38	10,78	65,73	25,45	15
19	20	42,99	29,75	19,33	19,41	26,30	16
9	10	15,82	30,9	8,11	66,67	26,30	16
27	0	32,5	21,22	33,67	45,24	26,53	17
7	40	18,19	9,65	39,71	27,73	27,06	18
16	10	62,92	42,94	10,78	11,93	27,71	19
5	40	17,83	12,14	4,11	69,84	28,78	20
22	40	43,24	20,62	8,59	42,26	30,94	21
10	40	18,09	30,22	35,44	38,54	32,46	22
20	100	10,39	4,31	38,7	10,93	32,87	23
18	100	18,5	9,66	62,24	0	38,08	24
12	0	16,65	68,92	8,33	100	38,78	25
25	100	16,23	18,05	38,53	43,31	43,22	26
Property Average	30,00	20,07	20,19	21,17	31,98		

The purpose of this appendix, therefore, is to provide a general picture on how students behave within the selected properties. For each student, graphics like the ones shown in Chapter 4 were used to visually support the same information and help in achieving connections among students from a different perspective.