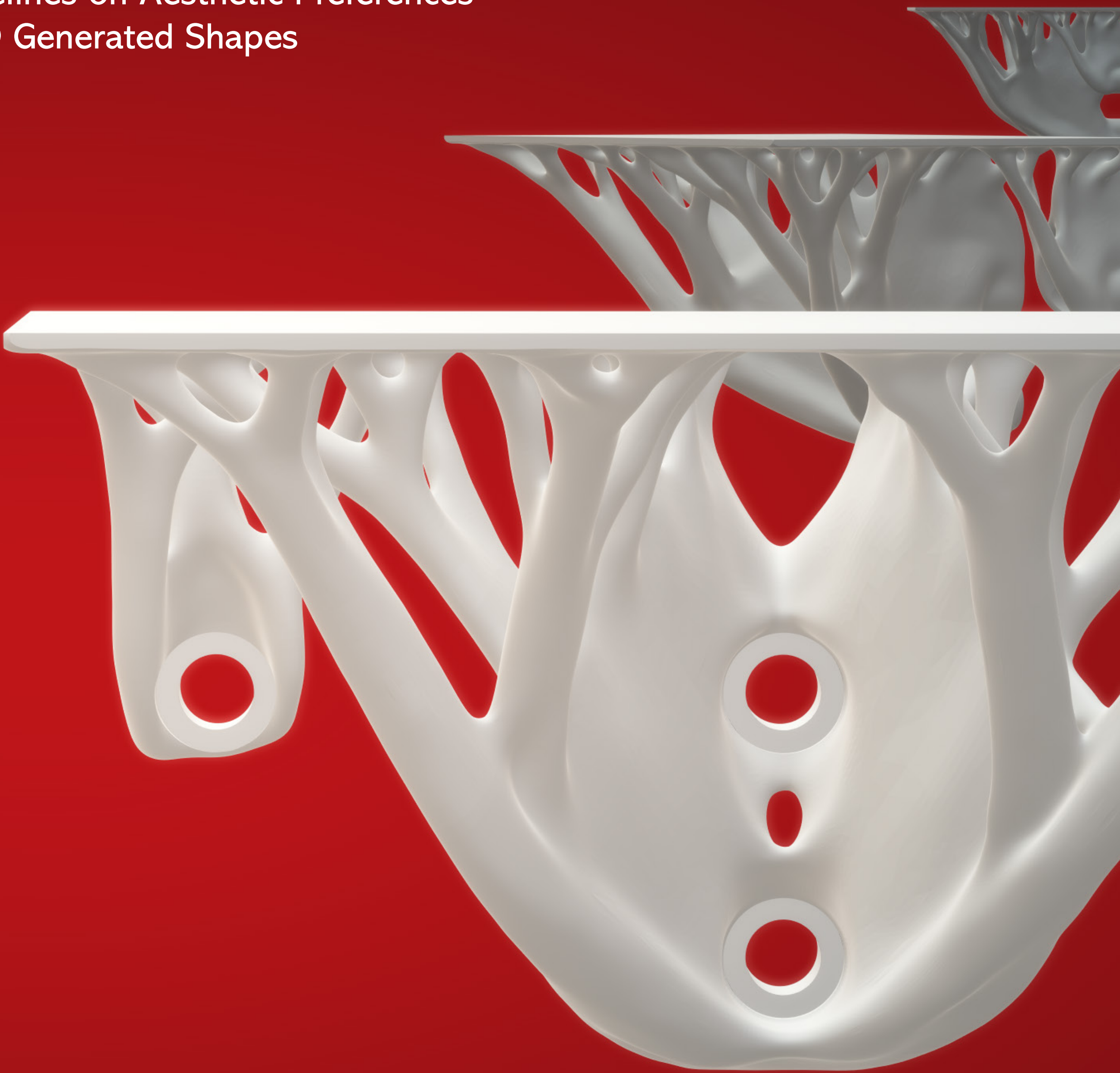
Intentional Aesthetics in 3D Generative Design

An Empirical Study on the Influence of Design Guidelines on Aesthetic Preferences in 3D Generated Shapes



Jesse Hols
Integrated Product Design
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TU Delft

INTENTIONAL AESTHETICS IN 3D GENERATIVE DESIGN

An Empirical Study on the Influence of Design Guidelines on Aesthetic Preferences in 3D Generated Shapes

By

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Abstract

Performance-driven generative design has been commonly used in engineering applications. In addition to performance metrics, aesthetics play an important role in the acceptance of generatively designed forms. When generating these shapes using generative programs, it is not clear in advance what the outcome will be, and thereby what they will look like. However, the appearance of these shapes can currently almost always be described as quite novel and organic. This affects the acceptance of these shapes and the number of iterations or post-processing needed to end up with a shape that is aesthetically acceptable.

This graduation project aims at exploring, identifying and validating aspects of 3D generated designs that contribute to a more aesthetic appearance in order to increase aesthetic acceptance and move towards intentional aesthetics in 3D generative design.

A review of existing literature was done on the history of aesthetics, aesthetics in product design and aesthetics in generative design. This resulted in useful insights in aesthetic principles. These existing principles were then reviewed in relation to 3D generative designed forms. Through that analysis, hypotheses were synthesised on how the aesthetic appeal of these shapes could be increased.

A first user study was conducted to test these hypotheses and to gain valuable insights into what aspects of a 3D form are important for aesthetic appreciation. For this study, many 3D generated designs were created across different product groups. The products were placed in a virtual environment in order for the participants to view them in true 3D through a virtual reality headset. Via an open discussion with the participants during the viewing of the different designs, valuable insights were gathered on aspects that positively or negatively contributes to the aesthetic appreciation of these forms.

These insights resulted in guidelines to increase aesthetic appreciation for 3D generated designs. A second, quantitative user study was then set up to validate the desired effect of the new guidelines. Twenty new designs were created and selected to be put in pairs containing designs that did and did not display features from the new guidelines. Through an online survey, these pairs were judged by 90 respondents on the desired effects, resulting in an extensive data set. Data analysis was conducted, and Pearson correlations showed a positive effect between the effects from the guidelines and the aesthetic appreciation of the generated forms.

These guidelines can therefore be used as actionable recommendations for designers, engineers and architects seeking to optimize both the structural and aesthetic qualities of generatively designed product.

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1. Introduction

The last couple of years, the use of generative tools has risen tremendously. These tools have changed the way we create content. No longer is this technology a fascination for tech enthusiast but it has become widely adopted. People turn to ChatGPT to help them with coding, managing projects and to generate text. Tools like DALL-E and Midjourney are used in the generation of images. The rise of generative design has changed the way designers and engineers develop products. Complex optimisation problems have to be solved through iterations, refining an engineer's best guess through simulations and refinements. With today's technology, algorithms can automatically adjust the geometry of a part between simulations, with minimal or no manual refinement required. These generative design tools represent a significant advancement in automating the design process and optimizing outcomes.

Structural optimisation is a common use of generative design algorithms, with the aim of creating components that provide sufficient strength, stiffness and fatigue resistance while using as little material as possible and keeping manufacturing methods in mind. This is used in fields where it can be advantageous to decrease the weight of a part while keeping or maximising mechanical properties. Aerospace and automotive industries are examples of fields where these tools are commonly used. This can be done for more efficient fuel consumption or extended travel range. But the technology can also be used in fields where lightweight parts can be beneficial, such as for ergonomic improvements in the design or structural parts for handheld tools or to enhance performance with sports equipment. Also when material is a primary cost driver, greater efficiency in material use through optimisation in combination with additive manufacturing can lead to both cost and sustainability savings.

Generative design, including topology optimization, is widely acknowledged as a crucial design approach for digital fabrication. It has the capability to automatically generate mechanical parts that maximize stiffness while minimizing material consumption. By changing certain parameters within the topology optimization program, it can produce numerous designs that are structurally comparable yet have a different appearance.

Generative algorithms produce designs of which the appearance can be radically different from human-designed parts, see Figure 1. These designs are commonly more organic and novel looking. The novelty of the appearance can hinder the acceptance of generative solutions by stakeholders, even when the proposed designs are technically superior (Miller, 2019). Similar challenges arise when using generative designed parts for consumer products, as aesthetics is an essential factor for customers and should be balanced with engineering and performance (Kang, 2014). Enhanced aesthetics in these outcomes can benefit consumer acceptance of these products, as they have an edge over those perceived as having lower aesthetic value (Bloch, Brunel, & Arnold, 2003) (Hagtvedt & Patrick, 2008).

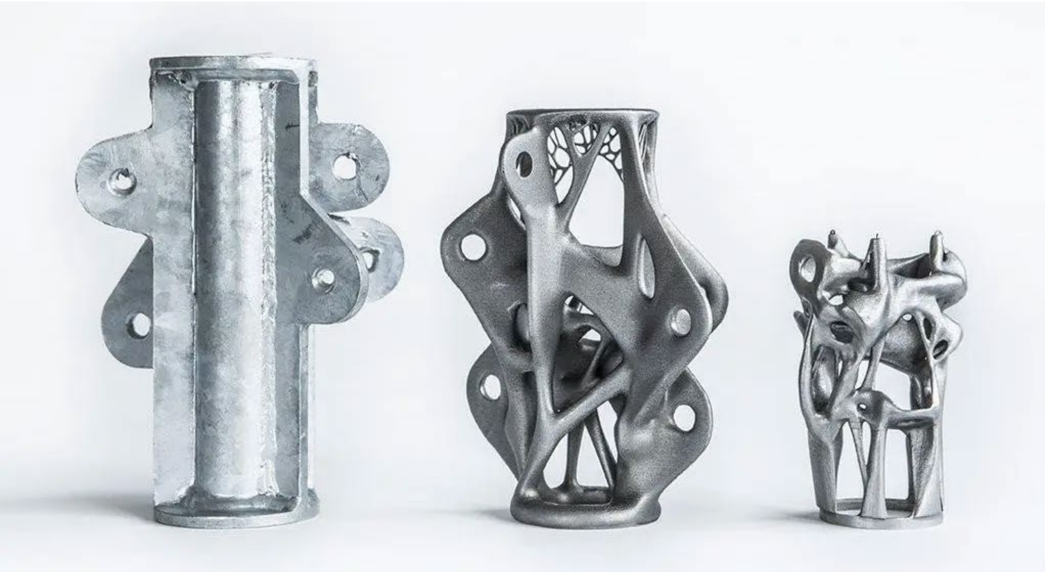


Figure 1. Human designed (left) vs generative designed brackets (middle, right). Generative designed parts by engineering firm Arup.[1]

1.1. Problem Statement and Challenges

Common practice in topology optimization in achieving aesthetically pleasing results involves generating a multitude of designs, allowing designers to choose the final design based on their aesthetic preferences. This current selection process however, is both labour-intensive and subjective. Many differences can exist between designers' and users' perceptions and values of the same designs (Hsu, Chuang, & Chang, 2000). Currently there is no principle that guides the generative design process in order to maximise its aesthetic value of 3D generated designs.

This project is aimed at answering the question whether it is possible to identify aspects of 3D generated designs that contributes to a more aesthetically pleasing result. In doing so, open the door to the possibility of increasing intentional aesthetics in 3D generative design.

Earlier study has showed that the gap between designers and users can be closed by implementing objective methodologies to understand and measure aesthetic preferences. Such approaches would give designers clear guidelines to shape product forms. Moreover, quantifying aesthetic preferences can serve as supporting evidence for designers when making technical and manufacturing decisions that may affect the visual appeal of the product (Orsborn, Cagan, & Boatwright, 2009). In this light, quantified gestalt principles have also already been used to measure aesthetics in product design, including a study on wheel rims in 2D (Lugo, Schmiedeler, Batill, & Carlson, 2016).

[1] Image sourced from: https://formlabs.com/blog/generative-design/

1.2. Applications and Impacts

Generative design can currently be described as mainly freeform design: the user provides the computer with a design space and it will find a form that matches the boundary conditions and load cases. Structurally, the design is optimized, but the user has little control over topology and overall outcome of the appearance.

Additive manufacturing (AM) has made it possible for these complex, organic looking shapes as generated by 3D generative tools, to manufacture. AM is becoming a staple of the manufacturing industry. Children are currently already being taught how to use 3D-printers in primary school. And in many cities, there are makerspaces where 3D-printers can be used. The youngest generation is being brought up additive manufacturing and generative design. A trend in increased use of these technologies is therefore likely and can have a positive impact to the world.

With the current global climate goals and fight for the environment it is important to look at ways it is possible to contribute as a designer or engineer. Not all materials are infinite, and the production of these materials and components also produce CO_2. The expected increase in world population will inevitably be accompanied by a rising demand in products and product parts. These products and parts include consumer products, building materials and items within the health care system. If we are constrained in limiting products demand, a way of decreasing emission is through decreasing the amount of material that is needed. Additive manufacturing en generative design go hand in hand in creating material efficient products with little variety in parts and materials, which helps the recyclability.

Topology optimisation is ideal in making objects lighter, while keeping the mechanical function. Reducing material in production of parts using additive manufacturing, directly influences the amount of CO_2 emitted. A recent paper from Johns Hopkins University argues that topology optimisation can be an effective way to decrease carbon emission in the building sector (Smith & Carstensen, 2023).

However, the appearance of these simulations look very different from what is known today. And without much control to steer the outcome of what the shape will look like, it can take a lot of time through multiple iterations or post-processing to finding a shape that is -next to being structurally compliant - also visually desirable. Because, while forms designed by generative design tools may look aesthetically appealing, this is not always the case. It would be beneficial to be able to decrease the time it takes to result in an acceptable design. Next to working more time-efficient, increasing the perceived aesthetics of initial design outcomes can lower the barrier to start using this technique in the first place, making these generative tools more accessible to designers, engineers and architects.

This can be achieved by increasing the acceptance of the appearance and decreasing the time needed to be satisfied with a design outcome due to less iterations and less post processing. This research aims to delve into the aesthetic preferences of people of 3D generative design. It seeks guiding principles that steer people in their selection process in choosing a preferred design and establish connections between this process and recognized aesthetic principles.

1.3. Project approach

An important step towards synthesising aesthetic guidelines, is to first get better acquainted with aesthetics in design and generative design. This will be done through a literature review of existing studies.

An analysis will then be done on how the literature and existing aesthetic principles relates to 3D generated designs. From this analysis, hypothesis will be set up which will be the base of the first user study.

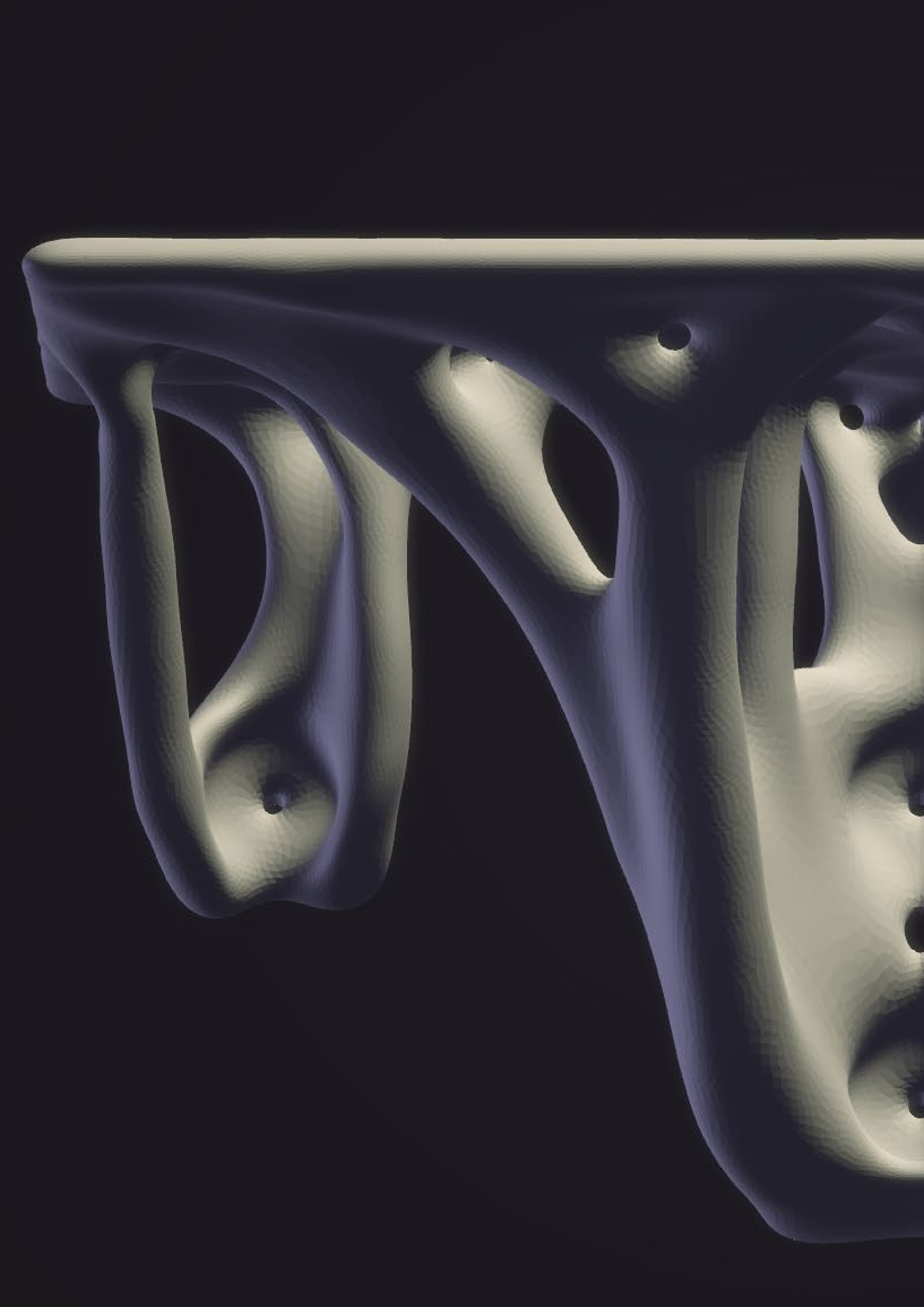
The first user study is a qualitative study and has two goals. The first goal is to test the before drafted hypotheses. The second goal is to identify aspects that positively or negatively influence the aesthetic appreciation of 3D generated designs.

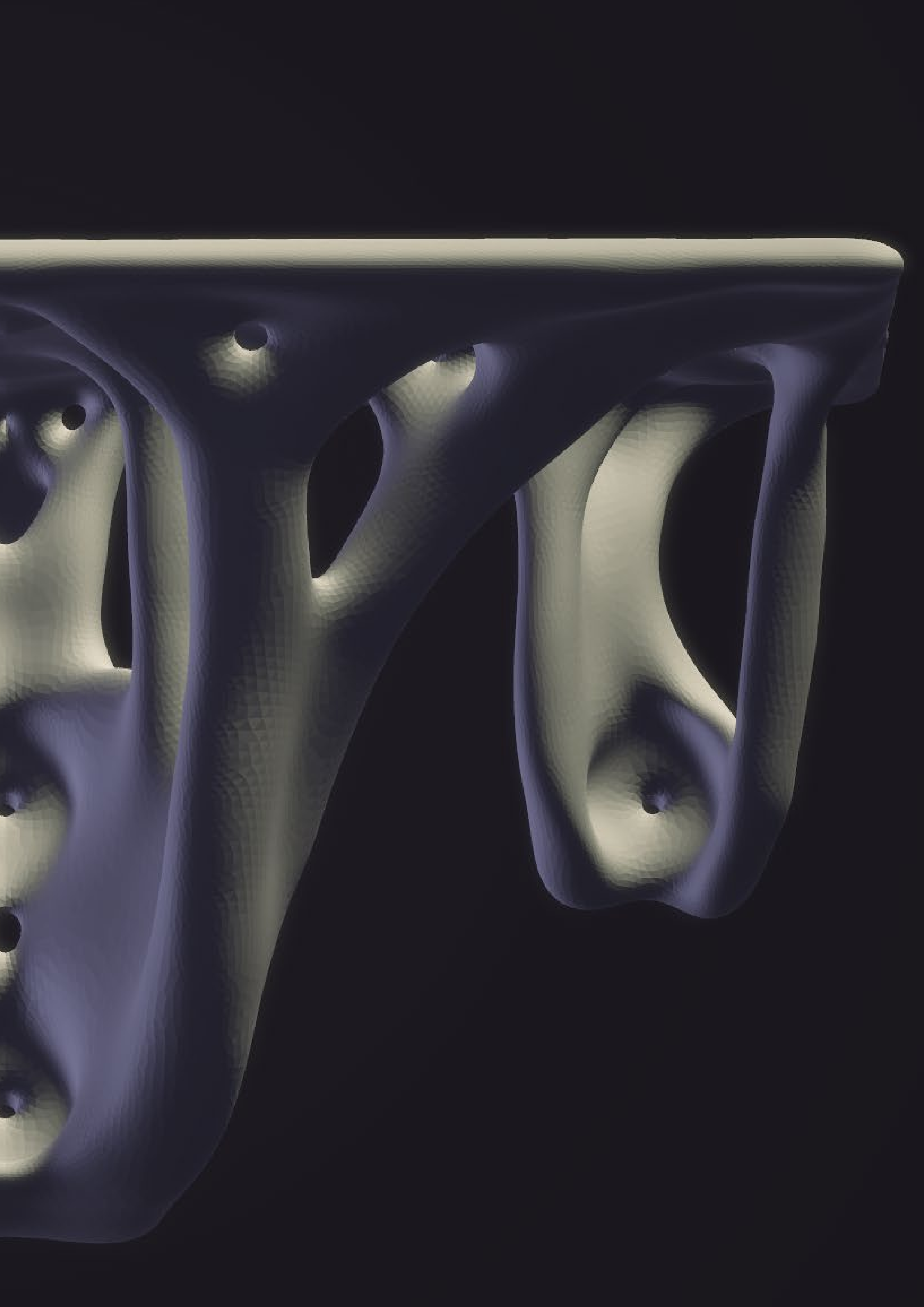
The results from the first user study can then be used to synthesise aesthetic guidelines. These guidelines are then tested in a second, quantitative user study with the goal of validating the newly setup guidelines.

1.4. Boundaries of this research

This graduation project is focussed on the exploration of generative design aesthetics within the field of product design. The project confines itself to the development and testing of aesthetic guidelines aimed at the aesthetic appeal of 3D computer generated forms. The aim is to understand aesthetic properties that can result in increased aesthetics in generation of 3D forms. The goal is to identify and verify these aspects. This project is not aimed at implementing these aspects into a generative software tool.

This project confines itself to the visual aesthetics of 3D shapes, excluding other visual features like colour and fine texture. This research also is not aimed at the different aesthetic subjective preferences of people including cultural differences in aesthetic preference.





2. Literature

2.1. A Brief History of Design Aesthetics

The term aesthetic as we know it today finds its origin in the book *Asthetica*, by the German philosopher Alexander Gottlieb Baumgarten from 1750. In this book the term is first used to refer to the study of sensory perception, beauty, and the nature of art.

Although nature itself can be described as aesthetically pleasing, the term aesthetics is most common in fields that are forms of human expression and creativity like art, philosophy music, literature and design. It is where human senses combine with intellect. An artwork can result in an aesthetic response through intellectual response it creates or the emotional response it creates. But what they all have in common is that aesthetics is about the human experience of beauty across different senses and in different domains, with the goal of gratifying our senses.

We will explore what was seen as aesthetic design in the past and how this has changed over the different periods. Starting from the industrial revolution to the time of post modernism.

1. Industrial Revolution

The production of consumer goods changed with the transition from hand production to the development of machinery for machine-based manufacturing. This revolutionised the production process. Products could be made faster and with less manual labour. This mechanical revolution also called for -and therefor resulted in- standardisation of parts. This impacted the aesthetics of products by making them more uniform. Designs were influenced by efficiency and functionality, with little emphasis on individuality or ornamentation. As the era progressed, movements like the Arts and Crafts movement emerged, advocating for a return to craftsmanship and a focus on handmade aesthetics.

A classic example for this time was the number 14 chair in 1859 by Michael Thonet (Figure 2). It was made using a new manufacturing method to bend wood with steam. This allowed for elegant curves to be made without the skill of a craftsman. The product was planned and designed by designers and engineers and could be manufactured by machines and unskilled workers.

It became one of the bestselling chairs ever made. This chair is closely associated with the transition from the ornate styles of the early 19th century to the simplicity and organic forms embraced by the later 19th-century design movements like Art Nouveau.

Figure 2. Michael Thonet with the no. 14 chair.[2]

2 Sourced from https://medium.com/detaux/time-travel-through-the-evolution-of-product-design-957221705313

2. Art Nouveau

Art Nouveau emerged as a response to the rise of industrial-style products. It represents a departure from the angular and solid characteristics, the rigidity of mass-produced products. Born out of a desire for a more organic approach, Art Nouveau utilizes natural, free-flowing curves and shapes.

The influences on Art Nouveau extended beyond its rejection of industrial norms. Many of its elements drew inspiration from geometric forms found in Japanese art, an aftereffect of the western world discovering Asian culture (Lee, 2001). This incorporation of diverse cultural elements added a layer of sophistication to Art Nouveau. In this period aesthetics can be defined as a focus on natural forms, curves, and asymmetry (Figure 3).

3. Bauhaus and Modernism

The Bauhaus movement originated from the Bauhaus school, founded by Walter Gropius in Weimar Germany in 1919. The school moved away from traditional education with separate disciplines, but instead integrated multiple disciplines under one roof. Rejection the division between art and technology, bringing together architects, engineers and artists.

The Bauhaus movement changed product design by promoting a blend of form and function, encouraging experimentation, embracing minimalism, and enabling for accessibility through mass production. Its impact is evident in the enduring influence of Bauhaus principles on contemporary product design and aesthetics.

In this period aesthetics can be categorised by simplicity, clean lines, and a rejection of unnecessary ornamentation. An identifiable Bauhaus design is set of tubular steel chairs by Marcel Breuer, see Figure 4.

Figure 3. A Buffet by Hector Guimard during the Art Nouveau movement. [3]

Figure 4. Tubular steel chairs, designed by Marcel Breuer, 1928[4]

3https://upload.wikimedia.org/wikipedia/commons/5/5b/Buffet%2C_Hector_Guimard%2C_Paris%2C_1899-1900%2C_cherry%2C_brass%2C_glass_-_Br%C3%B6han_Museum%2C_Berlin_-_DSC03965.JPG
4 https://dengarden.com/interior-design/Bauhaus-Furniture

4. **Mid-20th Century and Postwar Design**

This continued after the second world war, when European countries was recovering. During the war, all resources were directed towards the development of military equipment and communication means. Limiting resources, created the necessity of designs to be simplified and rational. Practicality and functionality was wat was needed in designs.

The American economy was less affected and took a lead in a new design age. The aftermath of the war brought about not only physical reconstruction but also a desire for renewal and a departure from the sombre and grim designs of the war years where people wanted change. This happened through the designs of Charles and Ray Eames and Raymond Loewy. Their designs could be described more as 'style over function'.

In Europe, Italy and Germany emerged a few years later as strong design nations. Italy produced the Vespa and the Fiat 500. But also fashion and furniture became major export successes with brands like Cassina, Zanotta and Capellini. In Germany one of the most influential designers was Dieter Rams (Figure 5). Different from Loewy, Rams went back to minimalistic design and very clean design, resulting in his *Ten Principles of Good Design*.

5. **Postmodernism**

Postmodernist design was a reaction to the 'blandness' and rigid principles of modernism design. The strict functionalism of modernism was rejected and ornamentation and historical references were embraced. This movement had a large impact on design and aesthetics by introducing a more inclusive, context-aware approach. Aesthetics became diverse, designers experimented more with colour, form, and cultural references also resulting in the concept of personality in a design. The Juicy Salif from Philippe Starck is an example of postmodernism design (Figure 6).

Figure 5. Dieter Rams with the T1000 radio. Photo by Gary Hustwit [5]

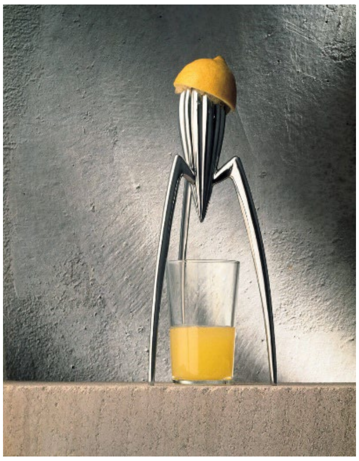


Figure 6. The Juicy Salif by Philippe Starck. [6]

5 https://edition.cnn.com/style/article/dieter-rams-film-exhibition-style-intl/index.html

6 http://www.meilleure-en-plus.com/nl/en-plus/1-alessi/

Takeaways

Overall, aesthetic taste seems to fluctuate between opposing aspects. Aesthetic preference has varied along the historic evolution of design. When the industrial revolution came, there was a big shift to uniform mass-produced designs from the earlier hand crafted products. However, when time progressed, the Arts and Crafts movement emerged, advocating the return of craftmanship. This continues with the Art nouveau and back to the sobriety and function-driven design of modernism. It is also not difficult to see the similarities between Thonet's number 14 chair and Marcel Breuer's tubular chairs. Both designs utilising new industrial manufacturing processes while keeping a hand crafted look. As time progresses, this change in aesthetic taste seems to swing back and forth, like a pendulum seeking balance. However, this sense of balance cannot exist without there being these opposites.

Another observation can be made looking at the stability or distress that exists in a part of the world. In United States, the situation was relatively safe, where you see a possibility and impulse to freely explore elaborate designs, like Loewy. While Europe, still recovering from war, first longed for a sense of safety and practicality in design, before feeling the ability to depart from the grim war years by exploring more stylised designs.

We see functionality and sleek design alternating more stylistic and organic designs. The design changes continuously changed what was currently the norm. What may have seemed weird in one timeframe may become widely accepted in the next. Referring to this project, this may mean that although currently 3D generated designs may be less accepted due to their distinctive look, it is possible that a broader acceptance of the designs can follow. This is only the case, however if these designs will used more and seen more in the first place.

2.2. Aesthetics in Product Design

In industrial design, aesthetics play an important role in the way how users interact an perceive products. Many researchers have done studies in understanding the relationship between design aesthetics and human experiences. This chapter will highlight the results of different studies, giving insight in the way people experience aesthetic pleasure and suggesting an hypothesis on how this might be a by-product of our evolution.

Framework of product experience

In 2007, Pieter Desmet and Paul Hekkert from the Technical University of Delft have introduced a *framework of product experience (*Figure 7*)*. This framework applies to responses that are experienced during human-product interaction (Desmet & Hekkert, 2007). The framework consists of three components: aesthetic experience, experience of meaning, and emotional experience. The authors explain that people have a concern for experiencing aesthetic pleasure and avoiding aesthetic displeasure, by highlighting the relation between aesthetic experiences and emotional experiences. Aesthetic pleasure can cause emotion experiences, as people are motivated to seek products that provide pleasure and avoid products that provide displeasure.

Experiences of human-product interaction are naturally shaped by the characteristics of both the product itself (shape, colour etc.), as well as the user (experiences, cultural background, etc.). Experience is not a property of the product but the outcome of human-product interaction.

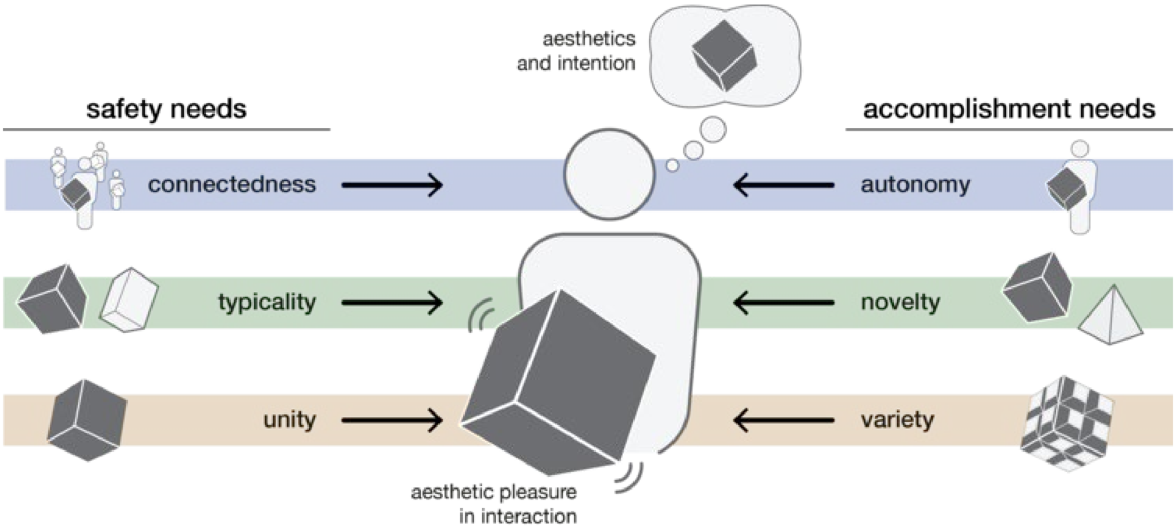


Figure 7. Unified model of Aesthetics (Berghman & Hekkert, 2017).

Relevance of function

An experiment using subjective measures was conducted in order to clarify the role of attractiveness in aesthetic judgement. In this experiment the researches showed design students different images of what is later clarified as a black tablet where the brand name is removed. In one of the images the tablet lies face-up on an empty table, in another image office supplies are placed on it, suggesting the function of a tray. The students are asked to rate the pictures on levels of *pleasantness*. The result of the experiment shows that, with the same design elements, subjects have a more common opinion on the level of pleasantness when the function of the product is known. This means that the knowledge of the function is important in the judgement of aesthetics of a product (S. Khalighy, 2014).

Another article from 2010 also stated that consumers expect a congruity between function and form (Hoegg, Alba, & Dahl, 2010). In addition, there is a general expectation from people that better designed products function better (Norman, 2004).

Principles of Pleasure

In an article published in 2015 by P. Hekkert, aesthetic responses are discussed. Hekkert has defined an aesthetic response as *the pleasure or displeasure derived from sensory-motor understanding*. By adopting this definition, it separated aesthetic phenomena from other types of experiences. People have a concern for experiencing aesthetic pleasure and will therefore seek stimuli that provide that pleasure.

Hekkert explains that aesthetic preferences are always a battle or trade-off between two opposing forces and that these opposing forces are linked to safety and accomplishment. People will seek the perfect balance between these two forces. The opposing forces are linked to our evolutionary instinct to survive. On the one hand people want to explore to seek new experiences that can help us evolve (learning new things, find food, shelter and a partner) but also can bring risks. On the other hand it is beneficial to be careful, taking less risk to increase chance of survival and reproduction.

Examples of positive effects that are related to aesthetic appeal are websites that are considered more useful, task performance enhancement and customer loyalty. By linking beauty to the enhancement of order or lack of disorder, the author argues further, that people may even be less prone to violating social norms when their environment is more beautiful (Hekkert P. , 2015).

This *battle of impulses* is the basis of the aesthetic <u>*principles of pleasure*</u> as introduced in 2006 (Hekkert P. P., 2006). These principles are: maximum effect for minimum means; *Unity-in-Variety*; *Most Advanced, Yet Acceptable*; and *Optimal Match*. These principles are further explored the next chapter.

Evolutionary by-product

Why we receive pleasure from certain, why we experience aesthetic responses may be explained by looking at our evolution. A widely adopted concept as to why, is the by-product hypothesis, as explained by Hekkert in his 2006 paper on design aesthetics (Hekkert P. P., 2006). This states that the aesthetic pleasure we are able to experience, is a by-product of the evolutionary process called natural selection. To explain this, we must first understand that in natural selection, a species is able to survive and ultimately reproduce by performing better than other species. This is done by adapting to their environment in a way that is beneficial to their survival.

An example of this is that our brain has been wired to seek cues and patterns that indicate a threat (a predator or dangerous terrain) or an opportunity (finding nutritious food or shelter). These cues and patterns create order in the stream of information. Another example is that we know that sticking to the known, like a familiar environment or shelter, is a safe option. However, we have also learned that it can be advantageous to explore and learn new things. As it is beneficial to the our species' survival, humans therefor have come to derive pleasure when these cues and patterns are spotted.

With the by-product hypothesis it is believed that people can experience aesthetic pleasure because they recognise these cues and patterns that they have come to derive pleasure from as a by-product of their evolutionary past. These examples are linked to two aesthetic principles named Unity-in-Variety and *Most Advanced, Yet Acceptable* or MAYA. These will be explained later in this chapter.

Conclusion for this research

The aesthetic experience a person can encounter is both dependant on the properties of the product and the background, experience and expectations of the user. It is, therefore, not possible to separate a products aesthetic value from the person experiencing that product. Aesthetic principles are always a balance between contradictions: unity and variety, novelty and typicality, safety and risk. Where exactly that balance lies, is therefore dependant on the person experiencing the design. However, by creating a general balance between those opposing forces, the aesthetic value can be increased. A challenge is that multiple principles are working at the same time and that the balance of one principle may not go together with the balance of another principle. This uncertainty is why it is hard for people to know exactly what they find beautiful and what not.

The uncertainty of multiple principles working at the same time together with everyone's own reference framework of what they find typical or innovative or weird, makes it impossible to create a golden formula in creating the perfect aesthetically pleasing designs that applies to everyone. Reference frameworks of people in the same culture are more aligned with each other. Experiences and norms and values of people in western culture are more aligned with each other than Asian culture or African culture for example. However the principles are universal principles that do apply to every individual. Focussing on a group or culture allows to apply aesthetic principles that will appeal to a larger group of people.

2.3. Aesthetics in Relation to Generative Design

In 2022, a study was conducted that combined the aesthetic principle of *Unity-in-Variety* together with topology optimisation that was co-authored by Jun Wu and Paul Hekkert, chair and mentor of this thesis (Loos, van der Wolk, de Graaf, Hekkert, & Wu, 2022). It is highlighted that despite the subjective nature of aesthetic appreciation, it has been demonstrated that preferences or taste judgments obey certain rules or principles. They argue that because topology optimised designs create a great deal of variety, the aesthetic value can be increased by increasing unity, resulting in a better balance between unity and variety. Only 2D topology optimised results were used in the study.

Three Gestalt principles were used to increase unity: Similarity, Continuity and Closure. Similarity refers to achieving uniform thickness throughout the design. Continuity involves ensuring the orientation of beam-like sub-structures across joints where they meet. Closure focuses on achieving a balance between solid and void regions, as well as balancing the sizes of voids.

It was found that the application of the Gestalt principles increased the sense of unity in topology optimized designs and that the increased unity resulted in enhanced aesthetic appeal. Out of the 12 altered designs to increase unity, 11 were found to be more aesthetically pleasing then the original shapes. Of the one shape that was not found more aesthetically pleasing, they found that participants also found the shape more varied than the original one. The complex topology of the shape may have played a role.

Conclusion for this research
The results show that increasing unity of 2D topology optimised results does have a positive effect of the perceived aesthetics. This could be promising for 3D topology optimised designs as well.
The study is however limited to one principle (unity-in-variety) and three gestalt principles to increase unity. It is also unclear how this result will translate into 3D topology optimised designs. The researchers propose that structures, that become visible in 3D, will have an effect on the aesthetic appreciation.

2.4. Existing Research on User-Control in Generative Design

The goal of this research is to increase visual aesthetics in generated designs. To achieve this, certain principles could be integrated in generative algorithms or a form of user control should be considered. An exploration has been done in user control in generative design, including topology optimisation.

Topology optimisation considering subjective preferences: current progress and challenges
In a recent article of 2023, researchers of RMIT University in Melbourne have categorised topology optimisation techniques that consider subjective preferences (Zhi, Ting-Uei, & Yi Min, 2023). The motivation of the study was that although topology optimisation can produce efficient structural designs, the solution can be of low value due to not matching other design requirements including aesthetic preferences. By creating an overview, the authors hope to create a helpful guide to designers and engineers.

Subjective interventions were categorised in three groups: pre-processing, post-processing and interactive processing strategies. And advantages and disadvantages were discussed.

Pre-processing is said to be limiting in determining the final outcome as they can only be performed once. It does not support designers in further explorations based on the results.

Post-processing allows for greater control of the visual outcome of the design, however the alterations may be contrary to the initial goal of topology optimisation. This can result in the altered design failing the initial set requirements of the optimisation.

An interactive topology optimisation method is explained which considers subjective preferences. This uses both drawing and scoring system. This works as follows: The designer first draws a preferred pattern after which a first set of solutions is generated. Preferred solutions are then scored by higher by the designer, after which a next set of solutions is generated, etcetera. This combines the best of both pre- and post-processing techniques, where a subjective preference can be given, while still being structurally efficient. Designers may need, however, to make multiple refinement before a design has met their preferences.

The authors note that all strategies outlines in the paper have not yet been extended to 3D cases. And that there is undoubtedly a significant potential in further development of techniques considering subjective preferences that can be applied to create appealing, efficient and reliable structures.

Simple and effective strategies for achieving diverse and competitive structural designs
Researchers, again from the RMIT University in Melbourne, have expressed the desire of having more choice in the shape outcome of optimisation techniques and propose techniques for achieving diverse and competitive designs in existing topology optimisation techniques (Yang, et al., 2019).

They proposed strategies, divided in two methods: sensitivity dependent method and a senility independent method. The sensitivity dependent method makes use of the information of previous designs, while the form-finding process of the sensitivity independent method relies on the prescribed geometrical constraints. For example, setting a void space or a non-design space.

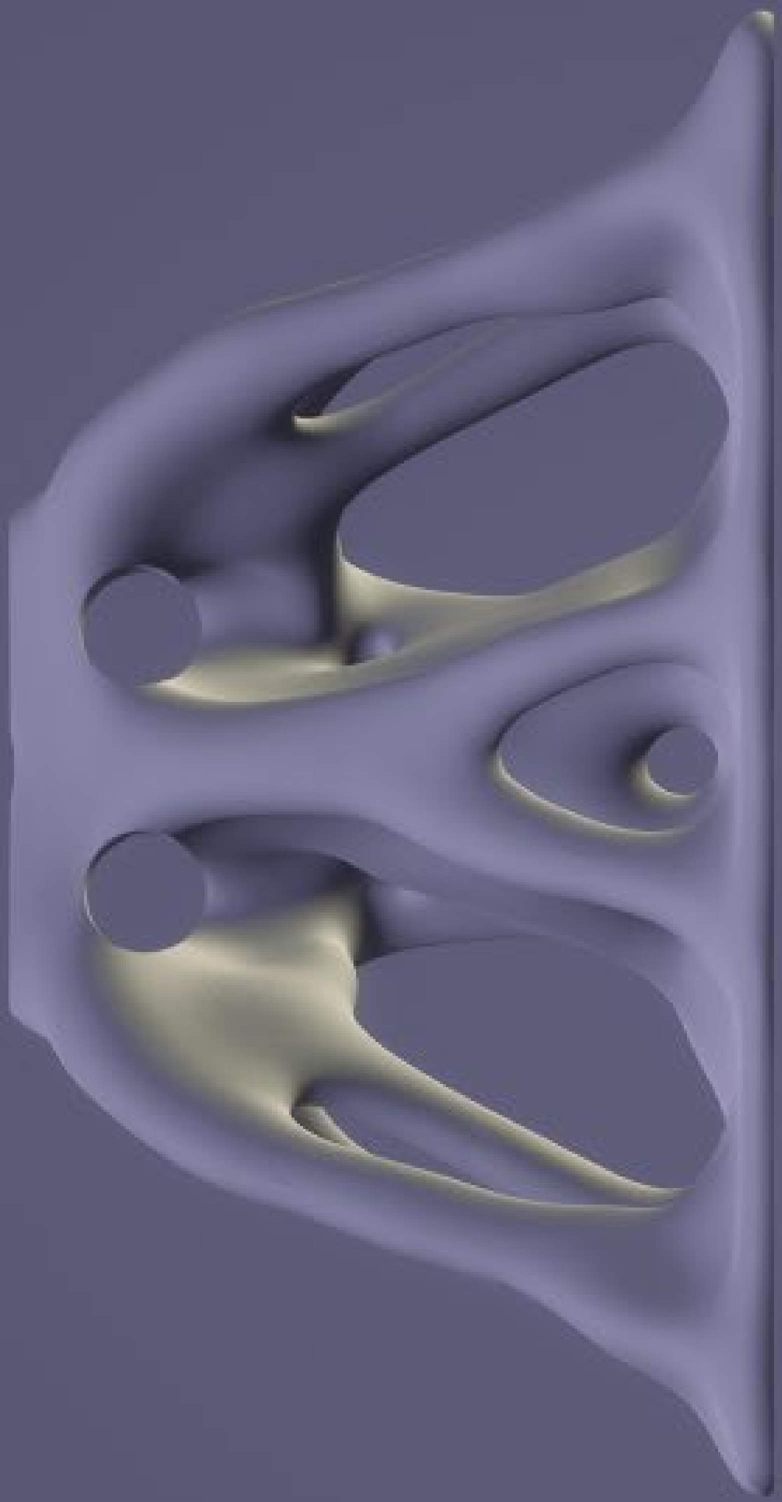
While these techniques do result in visually different designs, it still requires extra time in the setup to achieve them. Also, there is little control in the visual outcome of the design other than limiting the design space. So while this does help a user in having a wider variety of designs to choose from, it is still limiting in the control of visual aesthetics.

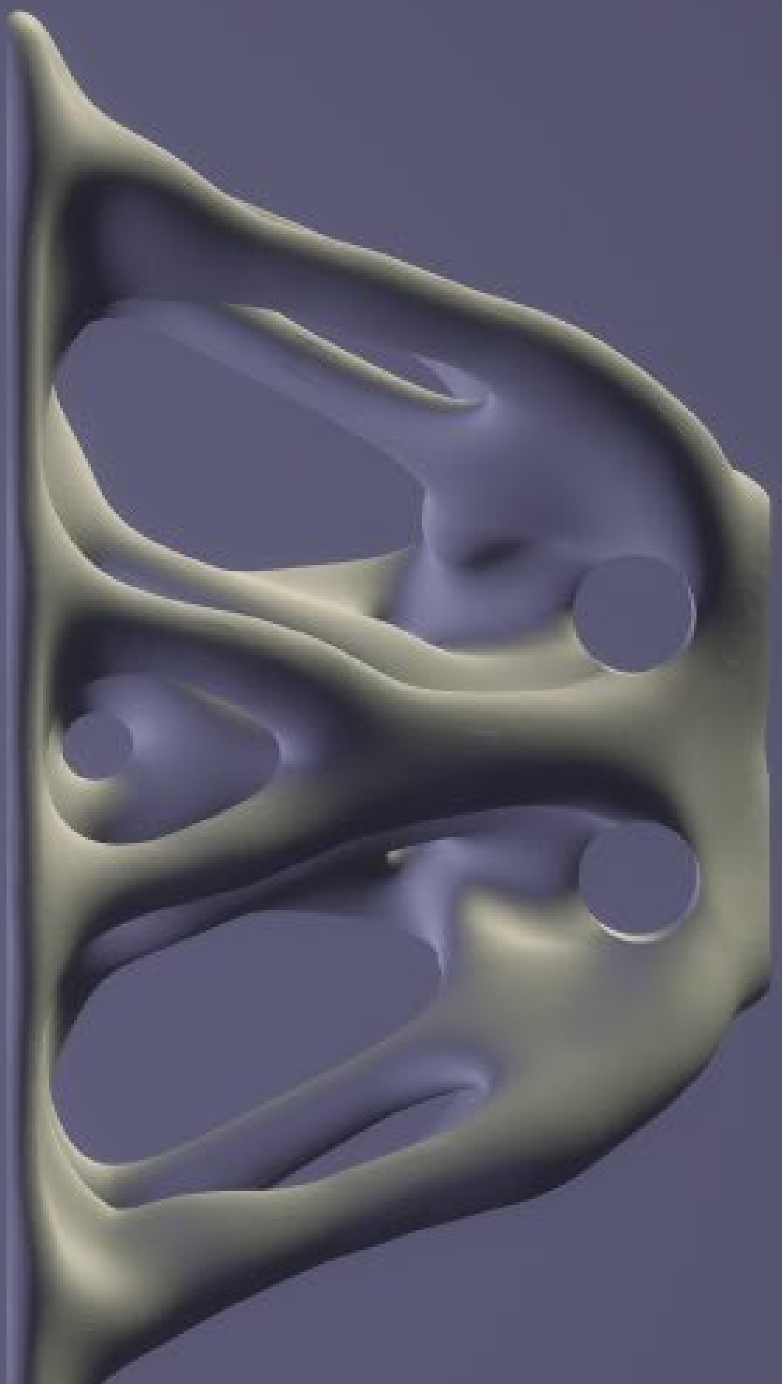
Conclusion for this research

While there is currently no good technique to incorporate subjective preference in 3D, insights are given in both the desire of subjective preference as well as what a good method should consider. Mainly, the disadvantages discussed are that post processing and interactive processing can be compromising to the structural performance. Also, it can be time-consuming to reach a final outcome that is satisfactory.

A good method of influencing a design outcome should not compromise the structural integrity too much, and should not be time-consuming.

The researchers of this graduation project will firstly identify aspects that can be used in the selection of aesthetic designs from a variety of generated outcomes. This is meant to provide designers and engineers with substantiated guidelines. Secondly, these guidelines could be a starting point in incorporating aesthetics into 3D generative tools.





3. Principles of Pleasure in Relation to 3D Generated Designs

The principles of pleasure propose four principles that can explain why some things are perceived as aesthetically pleasing and what is not. How do these principles relate to 3D generated forms?
These principles are used to set up hypotheses for increasing visual aesthetics for 3D topology optimised forms. The four principles of pleasure are: *Maximum Effect for Minimum Means*, *Unity-in-Variety*, *Most Advanced, Yet Acceptable* and *Optimal Match*.

3.1. Maximum Effect for Minimum Means

Maximum effect minimum means in sensory experiences means that a user has to do minimal effort in order to reach maximum effect. This principle rests on the idea that people will want to work efficiently, and will therefor prefer quicker and less demanding means over more demanding ones, in order to reach the same effect. The means can refer to time, effort and brain capacity, where the effects can be learning, exploring and understanding.

To see how these principles might be used in generative designs, we will use a topology optimised shelf bracket as an example design (Figure 8).

Looking at material use, the form is optimised to reach its desired effect with minimum means by removing material where it is not necessary to reach a form that is able to resist the forces that will be exerted on it. Following the principle, the product should evoke aesthetic pleasure due to its minimal material use for maximum resistance.

Figure 8. Topology optimised shelf brackets created in Autodesk Fusion 360. By Varun Heta[7].

7 https://twitter.com/varunheta/status/1043811382695620608/photo/1

The unique looking shape can, however, differ drastically from its human designed alternatives. This can mean that when people see a product with a generated form for the first time, it may not be directly identified as the product it is. This is due to the assumption that this kind of product has a certain typical appearance. Looking at it this way, one could argue that it will take more means (brain capacity) to reach its effect (to understand the intended function of the product), therefor evoke less pleasure. It must be said that this would only be the case as long as these shapes are not yet broadly known to the user.

Looking at it yet another way, one could say that the shape looks too complex for its function. Where a simple wooden triangular shape would suffice, this complex form is being used. It is likely that the topology optimised form would take more means (time, resources like a 3D printer) to reach its effect (holding up a bookshelf) than a simple wooden triangle.

For the study: is it true that:

- People find topology optimised forms aesthetically pleasing because there is beauty in the minimal material use to reach the desired mechanical function.
- People find topology optimised forms less aesthetically pleasing than human-designed alternatives, because their intended use is harder to identify.
- People find topology optimised forms less aesthetically pleasing than human-designed alternatives due to their unnecessary complexity.

It should be noted that for these hypotheses, the recognisability of the function of the products plays an important role.

3.2. Unity and Variety

Unity-in-Variety suggests that our sensory systems are inclined to detect order and relationships in the chaotic environment as mentioned previously. With a general overload of information to the senses all around, we naturally seek patterns, connections, and coherence to understand the world. The evolutionary idea behind this is that is beneficial to be able to recognise patterns and cues (a snake moving through the leaves) in order to survive. The *Unity-in-Variety* principles states that aesthetic pleasure can be increased by striking a balance between unity and variety, also referred to as a balance between order and chaos, or pureness as a balance between simplicity and complexity (Norman, Living with complexity, 2010).

When looking at generated forms and comparing them to human-designed forms, we see that the level of variety is typically higher in the computer generated forms. Therefor it might be beneficial to increase unity in these forms, thereby creating more of a balance in order to increase aesthetic pleasure. Unity can be increased by applying rules from the Gestalt principles.

The application of this principle has been done on 2D topology optimised forms in 2022 and had a positive effect on the perceived aesthetics. The researchers tested three aspects of the Gestalt principles to increase unity in topology optimized designs: similarity, continuity, and closure. These aspects were chosen based on their general applicability and their potential to enhance unity in the designs. Similarity refers to achieving uniform thickness throughout the design. Continuity involves ensuring the orientation of beam-like sub-structures across joints where they meet. Closure focuses on achieving a balance between solid and void regions, as well as balancing the sizes of voids. It was found that increasing unity in topology optimized designs can enhance their aesthetic appeal, Out of the 12 altered designs to increase unity, 11 were found to be more aesthetically pleasing then the unmodified originals (Loos, van der Wolk, de Graaf, Hekkert, & Wu, 2022).

For this study:

- Will increasing unity also be able to increase the perceived aesthetic pleasure in 3D topology optimised forms?
- This study tested three Gestalt rules, are other rules applicable too, for instance symmetry?

3.3. Most Advanced, Yet Acceptable: MAYA

A study performed in 2003, also co-authored by Hekkert, explored the joint effects of typicality and novelty. It brings together the notion that we prefer the most familiar looking product – as it is a safe choice with known results – and the notion that people are drawn to the unfamiliar, wanting to explore and find original things (Hekkert, Snelders, & van Wieringen, 2003). They found that people prefer products that have a optimal combination of both typicality as well as novelty, calling it *Most Advanced, Yet Acceptable*, or MAYA in short.

For this principle there is a connection to an assumption that is related to its function, knowing the product, there is an expectation on what it usually looks like. Generated forms organically score high on novelty at this moment in time. It must be noted that the perception of both the novelty as well as the typicality of a product will change over time.

For this study:

- Will increasing typicality in generated forms with a clear function increase the aesthetics appeal?

3.4. Optimal Match

This principle emphasizes the importance of consistency and coherence across various sensory impressions when experiencing a product. Humans prefer products that convey similar messages to multiple senses simultaneously. However, the coherence also extends to the function of a product; form follows function. This would be consistent with the research from chapter 2.2. The function in this case can also be to inspire or to enjoy. Based on this principle a form should have a similarity across the senses when experiencing a product, when it looks smooth, feels smooth, perhaps has a certain smooth sound to it and also has function that matches those treats, it pleases the mind.

For this study:

- Is there relevance to the congruity between the visual appearance and the products function.

3.5. To conclude

3.5.1. Minimal Means for Maximum Effect:

People find beauty in the minimal material to reach maximal mechanical strength. Making the generative form more typical looking, (to look like known products with same function), the function of the product is more easily identifiable and therefor people find the form more aesthetically pleasing. This regards to minimal brain capacity needed, for receiving maximum information about intended function.
The complexity of the form (means) needs to be lower than the complexity of its function (effect). If the product is intended for a simple function, and the form looks complex. Means and Effect is not in proportion.

3.5.2. Unity-in-Variety

Generated forms are generally more complex and chaotic-looking (variety) than human-designed parts. Increasing unity in a topology optimised form could increase a balance in unity-and-variety and therefor increase aesthetic pleasure.

3.5.3. Most Advanced, Yet Acceptable - MAYA

The organic look that generated forms now typically have, may look too *advanced* to be *acceptable*. By making these forms look less novel, the forms may be more aesthetically pleasing.

3.5.4. Optimal Match

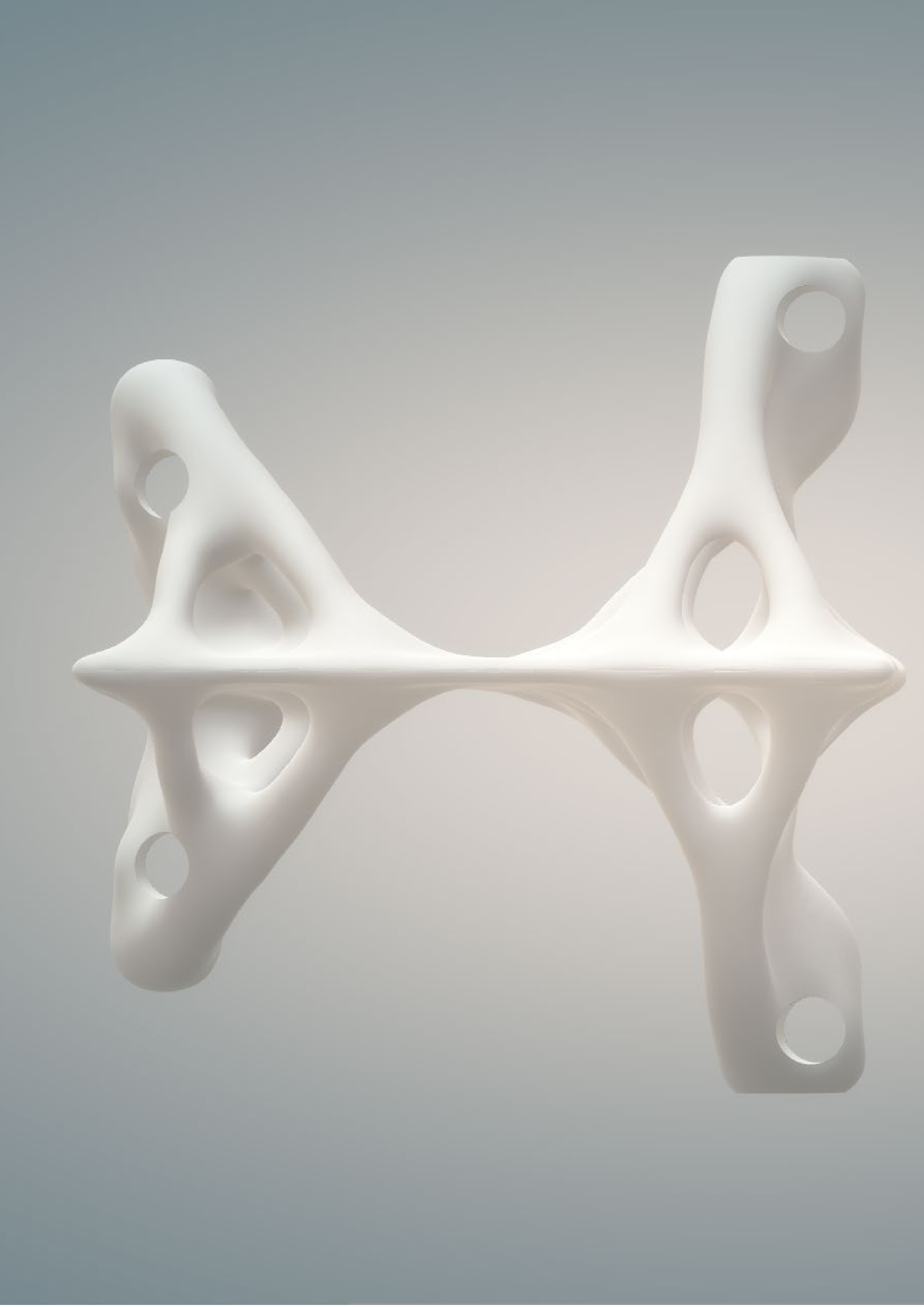
As with minimum means, maximum effect, the complexity of the form needs to match complexity of its function. If the product is intended for a simple function, and the form looks complex, the means to effect is not in proportion. Making the form look more typical to known products with same function, the function of the product will be more easily identifiable. This may increase the notion that the design better matches its function, and therefor people find the form more aesthetically pleasing.

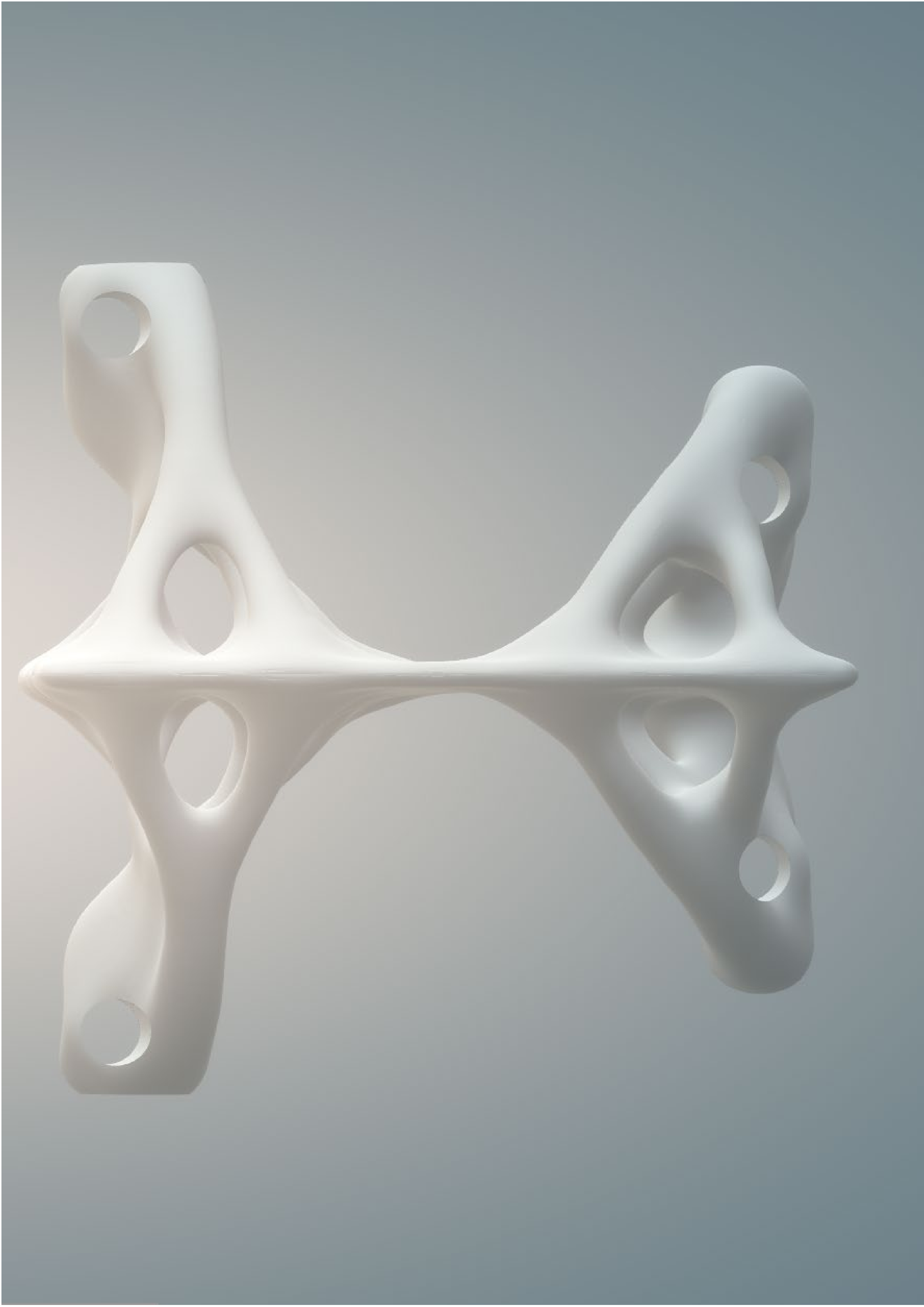
Some overlap is can be seen in the interpretation of the principles towards 3D generated designs. In the following diagram, the connection is made between principles. This diagram is used to formulate the hypotheses for the first user study.

3.6. Hypotheses

From the analysis in the previous chapter of the aesthetic principles of pleasure in relation 3D generative designs, the following hypotheses are constructed. The corresponding principles are shown within brackets.

1) Hypothesis 1:
   a) [MM,ME] People find beauty in the minimum material used necessary to achieve the desired function.
   b) [*Unity-in-Variety*] A balance between void and solid material volume creates a more aesthetically pleasing form.
2) Hypothesis 2: [*Unity-in-Variety*] A designs that convey similar geometric forms, are perceived as more aesthetically pleasing.
3) Hypothesis 3: [*Unity-in-Variety*] A symmetric design is perceived as more aesthetically pleasing.
4) Hypothesis 4: [*Unity-in-Variety*] Equal spacing between beams creates a more aesthetically pleasing form.
5) Hypothesis 5: [MM,ME + MAYA + Optimal Match] Higher perceived typicality creates a more aesthetically pleasing form, while a design perceived as too typical is not exciting enough.
6) Hypothesis 6: [MM,ME + Optimal Match] A form with low complexity creates a more aesthetically pleasing form, while too little complexity is not exiting enough.





4. Qualitative User Study

4.1. Introduction

The purpose of this study is twofold. This study is firstly set up to test the hypotheses on aesthetic preferences on 3D generated designs that have been drawn up in the previous chapter. The second purpose is to gain new insights into what aspects of 3D forms people find aesthetically pleasing or displeasing. To test the hypotheses, designs will be generated for six different sets. Each set has a the goal of testing the corresponding hypothesis. However, all designs can be used to test the other hypothesis as well by comparing remarks that participants make about each design during the user study. The purpose of the study is therefor to gather preference data within the given sets as well as qualitative data in the form of expressions and remarks given by the participants.

4.2. Methodology

4.2.1. Stimuli

Three product categories will be used in the study: a chair, a bike rack and a wall mounted shelf. Some hypotheses depend on the perception of form combined with the knowledge of the function of the generated object, and some hypotheses do not. This ensures that there should be at least two categories of generated objects, one where the function is clear and known, and one where the function is not known, where purely aesthetic value of the form is considered. However, only 1 category of a product with a function, can create a too one-sided picture in the results. As a result, three categories of shapes were chosen, two whose function is known, and one whose function is not known or disclosed. The stimuli are created in sets.

A variety of stimuli's are needed for the sets on: material use, geometric shapes, symmetry, order, typicality vs novelty and complexity.

The first two sub-hypotheses (a and b) are both about material use: whether there is a preference for minimal material use or a balance between void and solid. They are therefore combined in one set. To serve both hypotheses the set contains three designs per product category: one that is thin, one that is thick in material and a third that is in between.

For the second hypothesis designs were created that contained similar geometric shapes. These can be more beam-like shaped or plate-like shaped. The generation of these designs was the most difficult to achieve. No clear correlation was found between the settings and the outcome in relation to this aspect.

The third hypothesis was about symmetry. This set contained two designs, one with symmetry applied over one axis, and one design that isn't symmetric.

In the fourth set regarding order, designs were manually modified using Fusion 360 in order to created shapes that had equally spaced beams. These modified designs were placed in a set next to the unmodified designs they originated from.

The fifth hypothesis explores the concept of typicality versus novelty. In this section, designs were selected based on their resemblance to existing consumer products within the same category. Two distinct sets of designs were created: one set comprised of the most typical-looking designs, while the other set consisted of the most novel-looking designs. These two sets showed a more pronounced contrast compared to earlier sets. To provide participants with a middle-ground option, a design was included that represented a compromise between these two extremes.

To test preferences for low and high complexity. Designs varying in complexity were created, where complexity is defined by the number of individual beams visible.

The diverse range of appearances, that is a result of these different requirements, also enables participants in the user study to express themselves across variety topologies, contributing to a varied analysis. All designs used in the study are displayed in Figure 9.

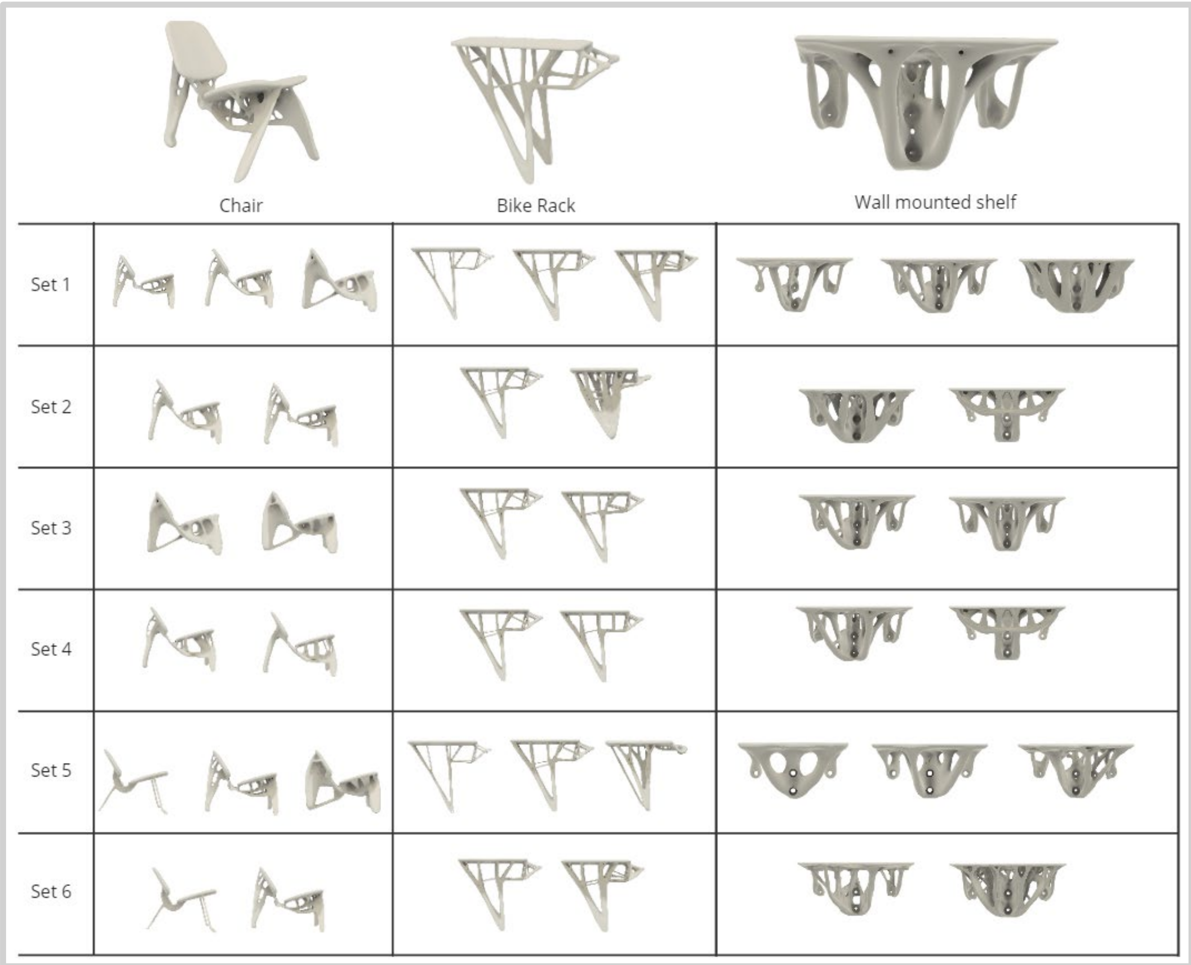


Figure 9. Overview of generated designs per set, pet product category placed in an VR environment

In total 42 designs were created. Two programs were used in the generation of the designs: Autodesk Fusion 360 and Synera. Autodesk Fusion 360 allows for generative design with little control next to setting the design space, constraints and loading conditions. Besides the controls fusion 360 has, Synera allows for more control options like complexity, strut density, iteration count and resolution Figure 10. The choice to use two different programs, using their own different algorithms, allows for more diverse design outcomes while having the same loading conditions.

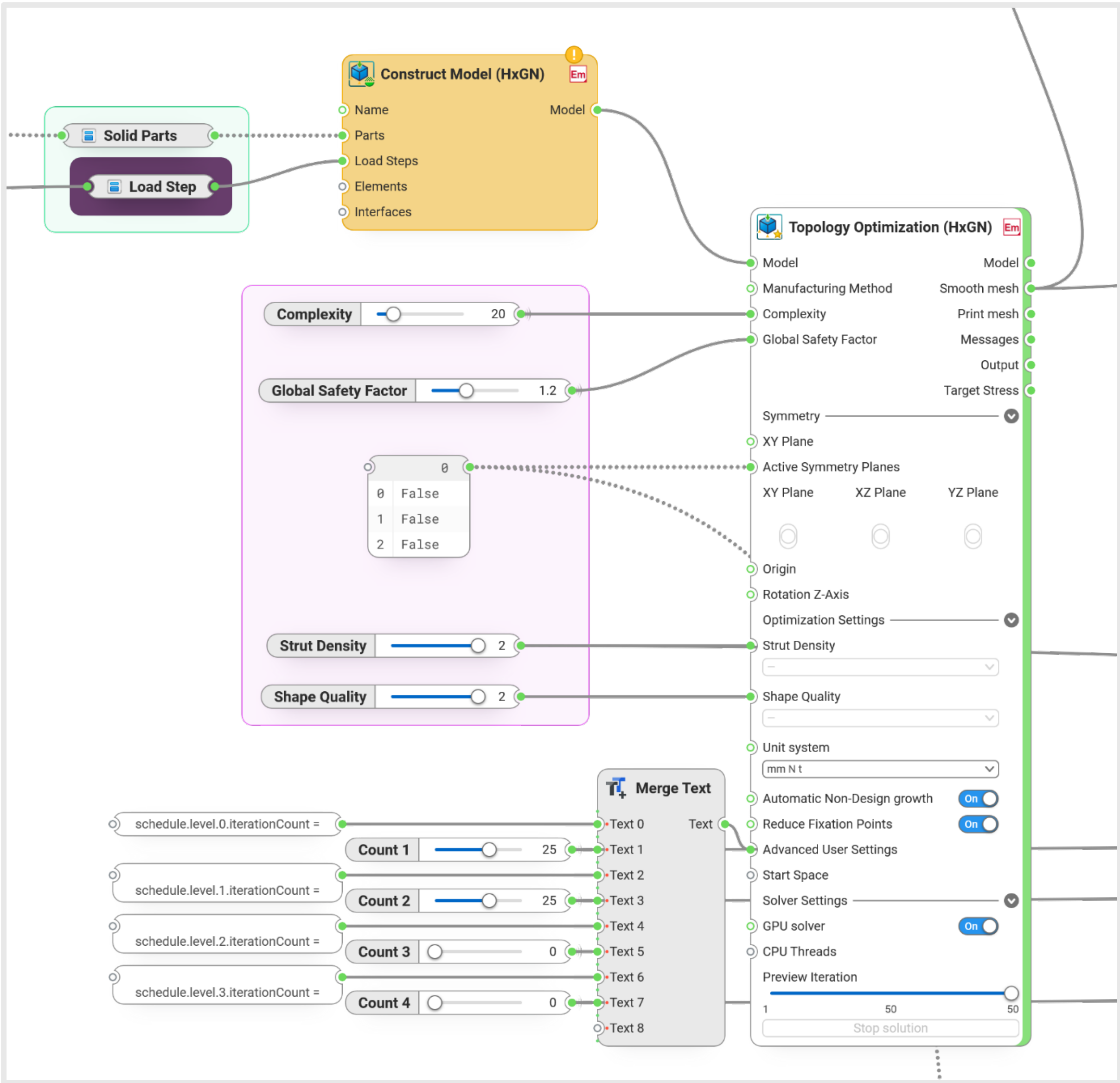


Figure 10. Advanced control settings for topology optimisation in Synera.

4.2.2. Procedure

The purpose of this study was to test the hypotheses on aesthetic preferences on 3D generated designs and gain new insights on what aspects are important for aesthetic appreciation. It is therefore important that a participant was able to view the designs in those three dimensions. Three options were considered. The first option was to use screenshots from multiple angles. The second option was to 3D print the designs so that the participants can handle them. The third option was to use virtual reality to show the designs.

The first option, while being more accessible to a larger participant group, would have significant drawbacks in the perception of the design in all dimensions. 3D printing would tackle that concern. However, the 3D printing technique available, FDM, can have the side effect of creating certain textures that are not part of the generated design. Furthermore, the design would have to be printed at a smaller scale for practical reasons what would alter the perception. Lastly, to provide the participants of the user study with something tangible like 3D print, would also allow for other senses to weigh in on the perception of the design, like feeling the weight and texture.

Virtual reality solves the disadvantages of the other two options. It allows the participants to experience the designs in true 3D, without the risk of influencing their perception through other senses. The study was conducted using an Oculus virtual reality headset. Unreal Engine was used to load the designs in a virtual environment.

In the virtual environment, participants were able to look around while sitting down. They were able to rotate the designs using a joystick of one of the controllers. The researcher is viewing what the participant is seeing on their VR-glasses in real-time through a computer screen. The location of the participants hands and the movement if individual fingers were visible in the virtual environment through hand-controllers. This way the participants were able to express themselves by pointing at (aspects of) the design during the study.

The aesthetic preference was recorded together with positive and remarks made by the participants about (aspects of) the designs. Remarks that highlighted positive aspects regarding the appearance were separated from remarks that were meant negatively. Remarks were documented per set (set-specific remarks). All remarks made were later also grouped together to allow for a separate analysis of all positive and negative remarks.

4.2.1. Participants

Eleven participants were asked and took part in the user study. Their ages ranged from 23 to 27 years, and the group consisted of both male and female individuals. All participants were either current design students or former design students affiliated with the faculty of Industrial (Product) Design Engineering at Delft University of Technology, Rotterdam University of Applied Sciences, or The Hague University of Applied Sciences.

These (former) students with a background in design were chosen as their familiarity with design principles and training in aesthetic evaluation would enable them to provide insightful observations on the aesthetics of the shapes. Given their academic exposure to design processes and aesthetics, they were deemed well-suited to assess the visual appeal and aesthetic qualities of the generatively designed forms, and have the ability to express themselves using varied vocabulary on design and aesthetics. Informed consent was obtained from all participants prior to their involvement in the study.

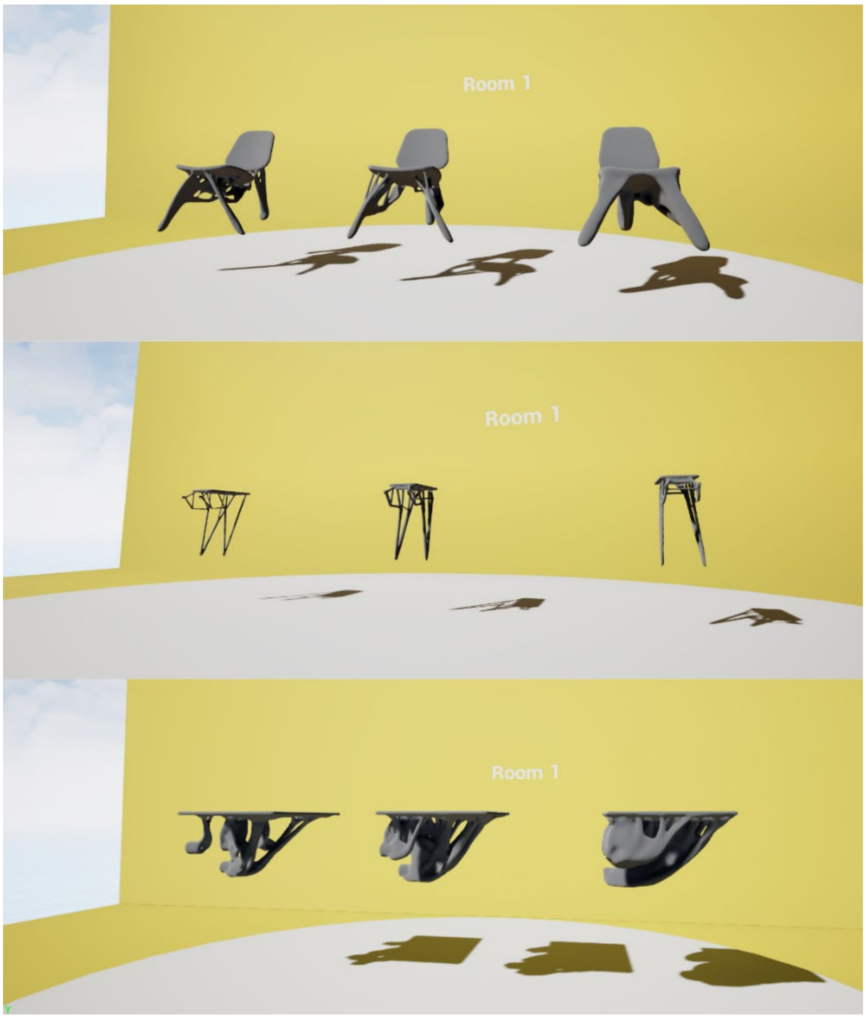


Figure 11. Screenshot of the VR-environment: Room 1 containing set 1 of chair-, bike rack- and shelf designs.

Participants were given a 5 minute introduction where the aim of the study and the procedure was explained. They were then asked to sign a consent form which included the research aim, risks of the study (e.g. dizziness due to the virtual reality headset), and to allow for their answers to be used in this study. An empty copy of the consent form is added in the appendices.

Following the explanation, the participants were instructed to put on the headset and hold the controllers. The participants were then guided through different virtual rooms. Each room contained one of the sets of from the corresponding hypothesis (Figure 11). The participants were asked to describe properties of the designs that they found either positive or negative regarding the visual aesthetics. Last, they were asked to choose one design in the set that had their aesthetic preference.

4.3. Results and discussion

4.3.1. Overview of remarks

An overview is created by grouping the remarks made by participants about the design appearances. Positive and negative remarks are split and similar remarks have been combined in a frequency count. In total 693 remarks were recorded across participants and designs, of which 395 individual positive remarks, and 298 individual negative remarks. Table 1 gives an overview of the most frequent remarks made, containing remarks from a frequency of 5 and upward. Similar remarks were grouped together. In Figure 12 a word cloud of the remarks is shown. An overview of all remarks is in the appendix.

Table 1. Most frequent remarks made, with a frequency of 5 or higher, across all designs.

Positive remarks	frequency	Negative remarks	frequency
(More) symmetric, symmetry	42	Non symmetric	29
Balance, balance void/solid	19	Too much material/ fat / bulky	21
Simple, simpler	15	Fragile, flimsy, weak	14
Organic/nature-like	14	Scary, creepy, eerie	10
Continuous lines, flowing line	10	Weird, crazy	8
Thin, lean	10	Ugly	7
Typical/recognisable	9	Organic	6
Sturdy	8	Busy	5
(Most) interesting (structure/to look at)	8	Heavy	5
Sleek, sleeker	7	Messy	5
Clean	7	Restless	5
Flowing	7		
Elegant	5		
Smooth	5		
More to explore/see/look at	5		
Unique/novel/new	5		
Uniform thickness/ balance in thickness	5		

Figure 12. Word cloud based on frequency of positive (left) and negative (right) remarks made.

Symmetry emerged as a dominant theme in the positive remarks and participants also expressing a clear preference for designs that exhibit symmetry. This preference was reinforced by the negative remarks, which highlighted non symmetrical designs as undesirable.

Next to symmetry, participants consistently mentioned balance as a positive attribute in designs, particularly in terms of balancing void and solid elements. This desire for balance aligns with the preference for symmetry and indicates a tendency towards visually coherent compositions. A tendency towards balance can also be derived from the many negative remarks on both too much material usage as well as too little material usage with remarks like *fat* and *bulky* for too much material and fragile and weak for too little material.

In the positive comments, also simplicity and cleaner designs were often mentioned as attractive features. This suggests that participants preferred designs with fewer elements or visual clutter. This is supported by the negative comments about undesirable qualities as being too busy or messy.

Overall, looking at both positive and negative remarks made across all the designs, the clearest distinction is that symmetry is the most made remark to describe aesthetic preference of a design over another design. These observations further highlight the importance of balance, simplicity, and material efficiency in shaping participants' aesthetic preferences. Designs that embody these qualities are more likely to be positively evaluated, while those deviating from these principles may be perceived less favourably.

4.3.2. Results Per Set

Results on the aesthetic preference of participants towards a design within a set is visualised in Figure 13. The results are shown per set and within the set results are visible per product category.

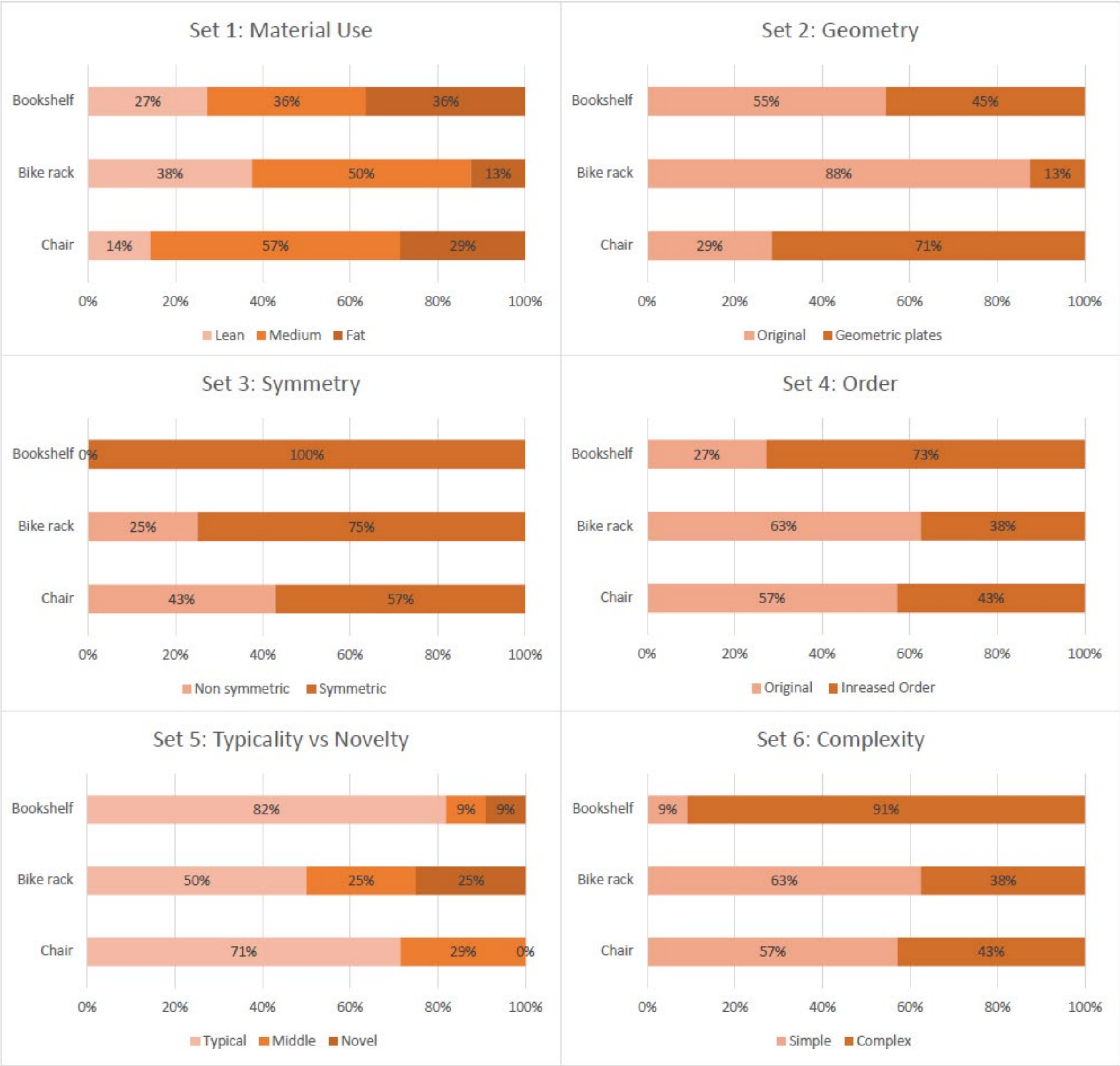


Figure 13. The ratio of the designs that were aesthetically preferred per set and per product category.

The results were examined to test the hypotheses. The participants aesthetic preference within a given set is examined first. Then, the set-specific remarks as well as an analysis of all remarks is used to judge the hypotheses.

Set 1

Hypothesis 1a: People find beauty in the minimum material used necessary to achieve the desired function.

Hypothesis 1b: A balance between void and solid material volume creates a more aesthetically pleasing form.

Looking at the aesthetic preferences of the participants, designs that are balanced in material thickness generally are preferred over designs that seem to use too much or little material. With both the chair as well as the bike rack the design with medium material use was preferred. From the bookshelf design, medium and fat drew in preference. The preference of participants that choose one of the other two designs was not consistent, thereby it appears to matter what the function the product is. The bike rack is preferred medium to thin, whereas the chair was preferred medium to thick.

The preference expressed in the first set is for the design that is most balanced in material use. This not in line with hypothesis 1a, as it would be expected that the design with the least amount of material would be preferred. It does, however, support hypothesis 1b.

When looking at set-specific remarks, a quarter (24%) of the positive remarks made by participants that chose the medium material design as their aesthetic preference, can be related to the material use (remarks like balance, body, efficient, etc.). This, together with the preference data, is in line with hypothesis 1b.

Looking at all the remarks, the second most made positive remark is related to balance between void and solid. However there are also many remarks made that can be related to minimal material use like efficient, simple, sleek, thin, less material, minimalistic.

When adding the positive remarks on minimal material use, a total of 28 positive remarks can be found against 19 remarks about balance. It can be concluded that both efficient material use and balance in material vs void, are contributing to the aesthetic preferences of 3D generated designs.

Set 2

Hypothesis 2: A designs that convey similar geometric forms, are perceived as more aesthetically pleasing.

For this hypothesis to be true, it is expected to find an aesthetic preference within the set, as well as supporting remarks about the geometric shape of the designs.

The aesthetic preferences is in the set is split between the unmodified design and that was modified to convey more geometric similarity. The preference data therefore does not support or deny the hypothesis.

Figure 14. Two views of the shelf design from set 2 with similar geometric shapes that evoked the associations 'automotive' and 'grill'.

There were no remarks identifiable towards the shape being more unified. Due to the 'organisation' of the material in this way, participants made remarks about associations they got. Remarks like *grill*, *engine block* and *automotive* were made (Figure 14). These were made as both positive and negative remarks.

In general when looking at all remarks, there were more remarks made about flat- or plate-like geometry in a negative way than in a positive way. But apart from the 6 negative against 3 positive remarks, no other remarks can directly be connected to this hypothesis. No clear conclusions can be drawn from these remarks regarding the hypothesis.

Set 3

Hypothesis 3: A symmetric design is perceived as more aesthetically pleasing.

There was a consistent preference for the symmetric design over the non-symmetric design across all three product categories. This supports the hypothesis that symmetry contributes to the aesthetic appeal of a form. This preference is also notable when looking to the remarks made only in the third set where again symmetry was the most made positive remark about the design.

Looking at all remarks, while it should be noted that the aspect of asymmetry was mentioned three times as reason to (partly) *like* one design, the majority of the remarks are in favour of the hypothesis. In both the positive and negative remarks, symmetry was most frequently mentioned as a reason to prefer a design or not due to the lack of symmetry.

Set 4

Hypothesis 4: Equal spacing between beams creates a more aesthetically pleasing form.

While the data shows mixed results for the designs with increased order compared to the unmodified designs, there is a noticeable preference for this option in the wall mounted shelf product category. This indicates that participants may perceive equal spacing between beams as aesthetically pleasing, supporting the hypothesis that equal spacing contributes to the visual appeal of a design. Positive remarks such as “unity” and "orderly" may reflect participants' preference for designs with balanced and well-organized structures.

In the set-specific remarks *‘parallel beams and plates’* were both pointed out as negative aspects of the designs in this set. Also grill, referring to parallel, equally spaced beams was named negatively. The organisation of equally spaced beams was also once described as *boring*. On the other hand, some participants positively referred to the equally spaced beams as more in order or more unified.

Increasing order by equally spaced beams, can make the design look less organic and more engineered. Looking at all remarks made *organic* is the fourth most frequent made remark that would go against the hypothesis. Only three participants can be identified as preferring an engineered look over an organic look.

Set 5

Hypothesis 5: Higher perceived typicality creates a more aesthetically pleasing form, while a design perceived as too typical is not exciting enough.

For the book shelf, bike rack and chair, respectively 82, 50, and 71 percent of the participants had an aesthetic preference for the most typical design (out of three). This suggest, in the case of 3D generated forms that are from themselves more novel looking, a preference for designs resembling existing consumer products. This preference for typicality aligns with the hypothesis that higher typicality contributes to the aesthetic appeal of a design.

Positive remarks such as "simple" and "typical/recognisable" imply that familiarity and recognizability play a significant role in determining aesthetic preferences.

Set 6

Hypothesis 6: A form with low complexity creates a more aesthetically pleasing form, while too little complexity is not exiting enough.

For both the chair and bike rack, participants expressed a preference for the more simple, less complex design. For the bookshelf however, the vast majority of 91% preferred the aesthetics of the more complex design. It must be noted that the more complex design was also perceived as more symmetrical, which could have had a large effect on the perceived aesthetics.

Both the positive and negative remarks support the idea that a simpler shape is being preferred over one that has too many branches or looks too busy. Although complexity is also a property that participants have expressed liking.

Simplicity together with typicality score high when looking at all remarks. When stating that generated forms are generally more complex looking, the preference for typicality could mean that this is towards the design that is therefore less complex. Although with a frequency of 8, ‘interesting’ is also a remark that is made when describing an aesthetic preference. For some participants this referred to the many branches and that there is more too look at, to explore, talking about the more complex design.

4.3.1. Unwanted results

During the interview, participants expressed their opinions on the designs. In a few cases some opinions were based on associations that were evoked by the design. Examples of associations that were made were: Scary or eerie looking, automotive or engine-like and even elephant-like associations.

These associations might serve as confounding factors. These associations may have influenced the participants in choosing which design got their aesthetic preference. The choice is then based not only on the visual aesthetics of the shape, but also by the association. This makes the result of the preference data less reliable. The effect of the confounding factors needs to be managed in the preference data. In order to do this, the remarks made by the participants were examined.

It is important to note that there is a distinction to be made between associations (which may have changed preferences) and words used to describe certain characteristics of the form

26 Remarks indicating an association were collected. Associations that were found were:

Association	Positive or negative
Spaghetti	-
Alien/spaceship	-
Chewing gum	-
Creepy/scary/eerie	-
Elephant	-
Eyes	-
Fingers	-
Halloween Pumpkin	-
Ice cave	-
Old wrinkly	-
Organs	-
Skeleton/bone like	-
Spider	-
Tentacles	-
Voldemort/monster	-
Wiry	-
Automotive/ grill	+
Dinosaur skull	+
Fatboy (bean bag)	+
Neck vertebrae	+
Panther/jaguar stripes	+
Pelvis woman	+
Swamp (funny)	+
Young smooth	+
Music Note	**+/- (both)**
Tree	**+/- (both)**

4.4. Discussion

The goal of this study was to test the hypotheses and to identify aspects that positively or negatively influence the aesthetic appreciation of 3D generated designs. The user study showed that there are certain aspects that will contribute to a better aesthetic experience in 3D generative designs.

The most prominent aspect was the preference for symmetry. There was a clear preference for designs that were perceived as symmetric. A design didn't have to be perfectly symmetrical, some degree of symmetry was sufficient for participants to mention this as a positive aspect towards aesthetic appreciation. It was also noticed among the negative comments that the lack of symmetry was the most frequent mentioned remark made as to why a design was not preferred.

Another large recurring theme in the remarks of the participants was balance. Balance between void and solid, balance in uniformity of the beam thickness or balance in the amount of beams. A recurring negative remark is about the design using too much material for the participants taste. Designs were referred to as *fat*, *heavy* or *bulky*. On the other hand designs wit little material were called *fragile*. Material efficiency was also mentioned as to why more voluminous designs were disliked.

Smoothness also played a part in the preference. Designs were preferred when their surface was smooth and transitions in the geometry were fluid. Flowing, continuous lines were perceived as aesthetically pleasing in contrast to *chaotic* or *bumpy* topology.

A preference for simplicity became apparent. Generated designs are currently more novel and complex looking than their human-made counterparts. It was shown that, when participants were asked about their aesthetic preference, the more simple looking design was preferred. *Simple* was made as a positive remark many times. Only once was it used in a negative sense. There were also more positive remarks made about simplicity then there were about complexity.

However, simplicity is not always preferred. It is preferred unless the novel look of the design is meant to be one of the main functions. The user study showed that some participants choose the complex or novel looking design over a simpler looking design. The reasoning behind this was that when considering the design more of an *art piece*, or statement piece, the complexity would benefit this function. It would make the design more interesting, thought provoking and engaging.

These findings so far, seem to be in line with the aesthetic principles of *Unity-in-Variety* and typicality and novelty. When you start from the fact that topology optimised designs are generally more varied and novel looking, increasing unity and typicality would result in a balance between those opposites, in turn resulting in a more aesthetically pleasing design. Applying symmetry, balance, continuous lines and simplicity all will result in more unity. Additionally, increasing simplicity will also make a design look less novel.

The last aspect that seemed to increase aesthetic appeal was logic. People who are technically educated are able to look at a design and judge whether forced are distributed in a logical way. However, people don't need to be technically educated to form an opinion on if a product looks fragile or robust. If there are elements in the design that *seem* illogical regarding the force distribution, the design was disliked. Participants referred to these designs as weird, crazy and awkward.

Participants furthermore showed consistent preferences for certain design characteristics across different product categories, indicating that aesthetic preferences may transcend specific product types. The data suggests that simplicity, symmetry, and typicality are generally favoured over complexity, asymmetry, and novelty, respectively.

Four overall preferred designs can be seen in Figure 15. The designs are relatively smooth, with flowing lines, there is balance in the material use vs empty space and the shape of the design looks logical for its function. Lastly, all designs are symmetrical.

Figure 15.Top: Bike rack design (3b) and Shelf design (3b) that were preferred by most participants.
Bottom: simple shelf design (5a) and chair design (5a).

To conclude, a generated design is aesthetically preferred when it looks fluid, not too complex, has few beams and, above all, is symmetrical. Because the technology itself is generally already novel and complicated in appearance, it is more favourable for acceptability if it is a simple shape. In addition, the design should be somewhat logical: the force distribution should follow a rational course, and there should be a sense of uniformity in the thicknesses of the beams.

Following these findings, the following guidelines are synthesised:

1. **Symmetry**: A design must strive for symmetry.
2. **Balance**: A design must strive for balance in beam thickness, and material vs void.
3. **Continuation:** A design must have continuing lines.
4. **Simplicity**: A designs appearance must choose simplicity over complexity.
5. **Logic:** A designs topology must look logical for its function.

5. Quantitative User Study

The first user study from which the guidelines emerged, had 11 participants and was meant to receive qualitative data. To test whether the guidelines contribute to an improved aesthetic experience, a second user study was setup. This second user study is a quantitative study, with the aim of gathering statistical data to verify whether the guidelines produce the desired effects. In this study, designs will be created with the newly setup guidelines, and without. They will then be placed side by side and shown to the participants.

The goal of the second user study is to verify if generated designs that where the guidelines are visible will result in more aesthetically pleasing designs than designs where the guidelines are not taken into account. The first four guidelines: Symmetry, balance, Continuation and Simplicity, will increase unity and typicality. The fifth guideline: Logic, is a new desired effect.

In this user study, it will therefore be tested whether following the guidelines will result in the effects of increased perceived unity, typicality and logic. And are therefore perceived as more aesthetically pleasing.

5.1. Abstract

Performance-driven generative design has been commonly used in engineering applications. In addition to performance metrics, aesthetics plays an important role in the acceptance of generatively designed forms. In this paper, we aim at deriving and validating design guidelines for increasing aesthetic appeal of topology optimized shapes.

These guidelines are based on the principles *Unity-in-Variety* and *Most Advanced, Yet Acceptable* (MAYA). Variety stimulates our interests, whilst unity helps us make sense of a design in its entirety. MAYA states that people want both the safety of typicality as well as the excitement from novelty. According to these principles, aesthetic appreciation is maximized when a balance in those opposing aspects is attained. Since designs from topology optimization often exhibit remarkable novelty and variety, we hypothesize that increasing unity and typicality is the key to reach a balance and thus to elevate aesthetic appreciation in topology optimization.

In our experimental setup we created designs with topology optimisation. These designs exhibit different levels of unity and typicality. A selection was made to include designs where the effects of these guidelines were visible, with the intention of increasing unity and typicality and logic, and designs where the effect of these guidelines were less/not visible.

Our user study showed that in 9 out of the 10 pairs of topology optimized designs, the design with guidelines applied are perceived as more aesthetically pleasing in relation to the opposing design, confirming our hypothesis.

These guidelines can be used as actionable recommendations for designers, engineers and architects seeking to optimize both the structural and aesthetic qualities of generatively designed products.

5.2. Introduction

Performance-driven generative design has been commonly used in engineering applications. In addition to performance metrics, aesthetics plays an important role in the acceptance of generatively designed forms. This acceptance can play a role in consumer products as well as in architecture.

One of the main challenges in the integration of aesthetics in generative design is the lack of mathematical models for predicting the aesthetics. Data-driven approaches potentially avoid the necessity of a mathematical model for describing aesthetics. It faces challenges including, (i) the creation of generatively designed products, (ii) the labelling of the aesthetic preferences, and (iii) the required quantity for a reliable data-driven approach is unclear.

The current control that users have with generative design programmes is often limited to providing a design space and a non-design space and different load cases with a safety factor. Creating different shapes requires a form of control that is currently not widely available with many generative programmes. In addition, because of the iterative process, the outcome of an optimisation is not clear in advance. This makes it a time-consuming process to achieve new visual outcomes through small adjustments. To achieve this, a computational tool is needed capable of generating diverse and aesthetically pleasing designs.

Topology optimisation is a mathematical technique that, by meeting specific criteria and minimising a pre-determined function, spatially optimises the distribution of material within a specific domain (Srivastava & Kawakami, 2023).

A process of design exploration is generative design. Design goals and characteristics such as performance or spatial requirements, materials, manufacturing processes and cost constraints are entered into generative design tools by designers or engineers. The programme explores the possible permutations of a solution and generates design alternatives. It tests and learns from each iteration what works and what doesn't (Autodesk, 2018).

For both Generative design and topology optimisation, structural optimisation is a common objective. The difference is that topology optimisation is based on material removal, while generative design is based on adding material, growing a shape like organic systems do. Due to the way these techniques work, the outcome often has a organic and novel appearance.

Earlier study has showed that, by implementing objective methodologies to understand and measure aesthetic preferences, the gap between users aesthetic preference and the designers translation of that into form can be closed. Such approaches would give designers clear guidelines to shape the development of product forms. Moreover, quantifying aesthetic preferences can serve as supporting evidence for designers when making technical and manufacturing decisions that may affect the visual appeal of the product (Orsborn, Cagan, & Boatwright, 2009).

In this light, quantified Gestalt principles have also already been used to measure aesthetics in product design (Lugo, Schmiedeler, Batill, & Carlson, 2016). However, few studies have made the step from 2D to 3D generated designs. Accurate and reliable methods for capturing and quantifying aesthetic preferences in 3D from human feedback is needed to label aesthetic preferences.

In this paper we aim to understand whether it is possible to influence the aesthetic pleasure people experience in viewing 3D generated designs by finding correlation between guidelines and their effects. We do so by applying the *unified model of aesthetics* which states that aesthetic appreciation of products is determined by conflicting needs for safety and accomplishment (Blijlevens, et al., 2017).

5.2.1. Unified Mode of Aesthetics

The unified model of aesthetics identifies five ways of interaction between a designed object and a person. This can be done perceptually, cognitively, socially, physically and as a manifestation of an intention (Berghman & Hekkert, 2017). The model predicts that in each of these ways there is a balance between two opposing forces. One of these two opposing forces is related to safety, while the other is related to accomplishment. Visible in Figure 16 are five aesthetic principles. For this study we will focus on the two principles that are linked to perception and cognition: *Unity-in-Variety (perception) and Typicality and Novelty (cognitively)*. The guidelines that will be tested are related to these two principles.

For *Unity-in-Variety*, the safety need can be described as order, control, unity. The accomplishment need is more towards variety, challenge and uniqueness. For Typicality and Novelty, the safety need can be described as typical, known, recognisable. The accomplishment need can be described as new, exiting, explorative. The model predicts that when both qualities are maximised at the same time, aesthetic pleasure is reached.

Unity-in-Variety

With a general overload of information to the senses all around, we naturally seek patterns, connections, and coherence to understand the world. *Unity-in-Variety* suggests that our sensory systems are inclined to detect order and relationships in the chaotic environment as mentioned previously.

The evolutionary idea behind this, is that it is beneficial to be able to recognise patterns and cues (a snake moving through the leaves) in order to survive. The *Unity-in-Variety* principle states that aesthetic pleasure can be increased by striking a balance between unity and variety, also referred to as a balance between order and chaos.

When looking at generated forms and comparing them to human-designed forms, we see that the level of variety is typically higher in the computer generated forms. Therefore our hypothesis is that it will be beneficial to increase unity in these forms in order to increase aesthetic pleasure. Unity can be increased by applying rules from the Gestalt principles.

Typicality and Novelty

A paper from 2003, also co-authored by Hekkert, explored the joint effects of typicality and novelty called *Most Advanced, Yet Acceptable* (MAYA) (Hekkert, Snelders, & van Wieringen, 2003). It brings together the notion that we prefer both familiarity in a product as well as something new and unfamiliar. The researchers found that people prefer products that have an optimal combination of both typicality as well as novelty. This attraction to these opposing factors is expected to also be a by-product of our evolution.

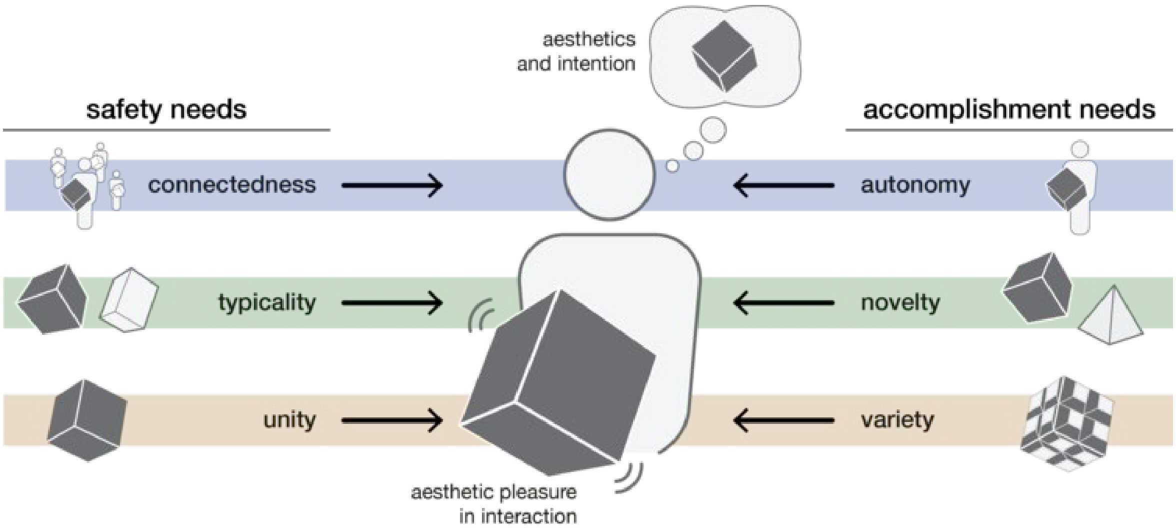


Figure 16. Unified model of Aesthetics (Berghman & Hekkert, 2017).

A previous study has investigated the *Unity-in-Variety* principle for 2D generative design, in that paper, the authors have successfully established that the principle of unity-in-variety also applies for 2D topology optimised designs (Loos, van der Wolk, de Graaf, Hekkert, & Wu, 2022).

For this paper our contributions include:
(1) the investigation of novelty vs typicality in generative design
(2) the investigation of the role of 'logic' in generative design

Furthermore, our work also confirms the unity-in-variety principle in 3D, extending previous work of the same principle on 2D.

We conduct this study by creating a set of generatively designed consumer products, and collecting and analysing aesthetic preferences. We intend to release this dataset to facilitate future work in this exciting research direction.

5.2.2. Guidelines

In a previous, unpublished study of the authors, guidelines haven been created to increase the aesthetic appeal of generated designs. In this study, participants were shown a great variety of generated designs. In an open interview, the participants were asked to explain what aspects of the designs made it more or less appealing. The analysis of these results have resulted in five guidelines to increase aesthetic appeal.

1. Symmetry: A design must strive for symmetry
2. Balance: A design must strive for balance in beam thickness and material vs void.
3. Continution: A design should have continuous lines.
4. Simplicity: A design must have minimalistic appearance
5. Logic: A designs topology must appear logical for its function.

The study showed that designs that appear to be mostly symmetrical are preferred over designs that are not. Designs where the beamlike structures of the shape are similar in thickness are preferred over designs where the thickness varies. Also, there must be a balance in material vs void spaces. This refers to designs being disliked when they appear too bulky (e.g. too little void spaces) or too thin (e.g. too much void vs material). Designs must have recognisable continuous lines. A design that is simple in topology is preferred over a design that is has much complexity.

Lastly, the perception of logic became apparent as a factor. If the topology of a design does not appear the be in line with the function of the design it is considered illogical and consequently unfavourable as a design.

5.2.3. Research aims and motivation

The aim of this study is to test whether the application of newly setup guidelines creates a more aesthetically pleasing result. The application of the guidelines should results in three effects: two are known but not yet validated for 3D generated shapes, one is new. The first two effects are that unity will be increased (unity vs variety) and that typicality will be increased (typicality vs novelty). The increase in unity and typicality would result in a balance to the *variety* that generated shapes often have and to the *novelty* of the appearance that these shapes have as this technique is not yet common in consumer goods.

The third and the newly desired effect is that increasing appearance of logic of the load-bearing structure of the design, results in a more aesthetically pleasing result.

The intended result of this study is to provide guidelines that enable designers and engineers to be more time-efficient in using generative design tools, by decreasing the number of iterations and post-processing needed in order to result in a design that is aesthetically pleasing to a user and therefore increases the user acceptance of a computer generated shape. In addition, increasing the perceived aesthetics of initial design outcomes can lower the barrier to start using this technique, making these generative tools more accessible to designers and engineers.

Currently, no data exists on consumer opinions on a variety of computer generated shapes from which these guidelines can be verified. This study aims to provide that data.

5.3. Methodology

5.3.1. Stimuli

The stimuli used in this study are 3D designs of wall-mounted shelves. This product was chosen since most people are familiar with it and it has a clear function as a load bearing mechanical component.

In total, twenty unique designs were created using Synera (version 23.08, Heroic Horus). The designs were created by supplying the program with these boundaries: fixation points, recognisable as the mounting holes in the designs, a design space, and a non-design space. The load is a distributed force on the top of the shelf, seeFigure 17. The x and y location of the fixation points and the topology of the design- and non-design space were altered in order to create varied designs. In addition, the Synera program allows for advanced input for the topology optimisation model like iteration count, safety factor, strut density, complexity and load direction. These were varied too to result in a wide variety of design.

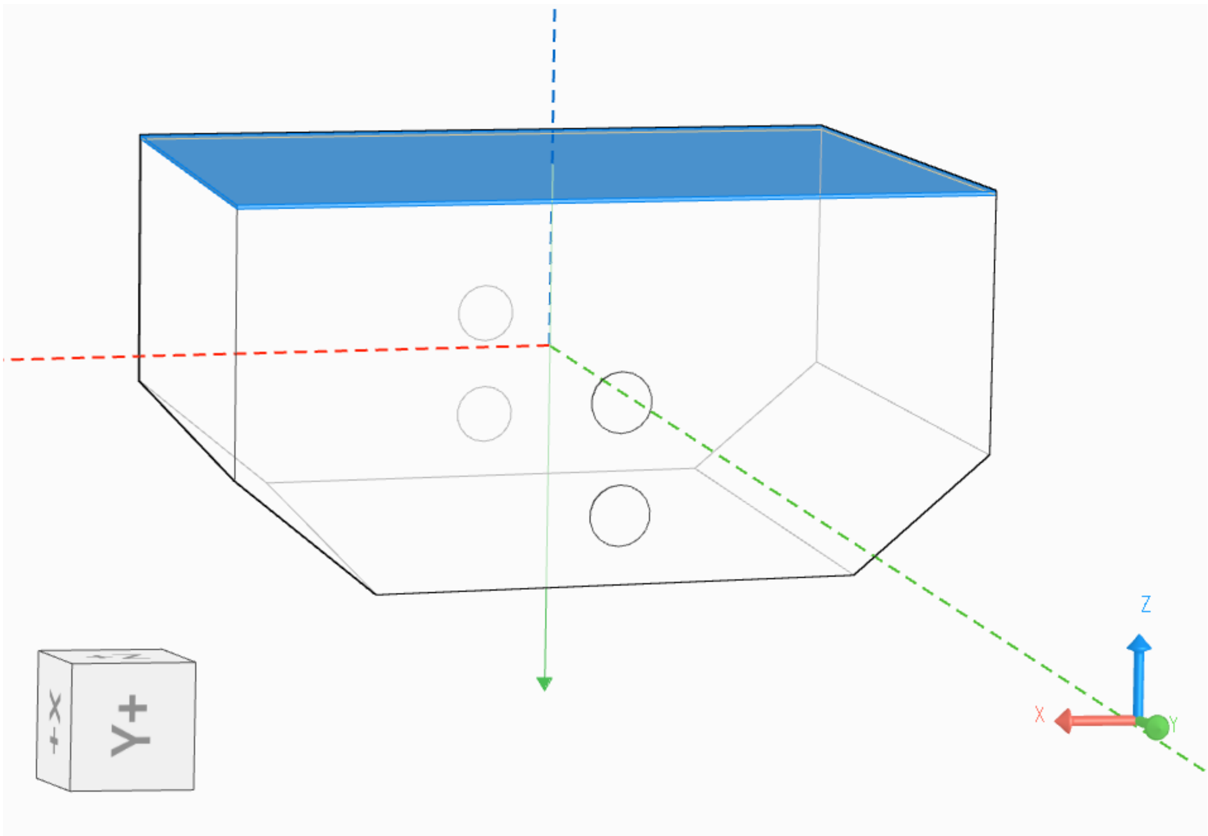


Figure 17. The design space is marked by the transparant box. Two through holes are visible where there are fixation points. The area on which the distributed downward force acts upon is marked blue.

Changing these parameters influenced multiple aspects of the shape of the generated designs. Strut density and complexity together with iteration count influenced the number of beams a design ended up having. The iteration count together with the safety factor influenced the thickness of the beams. The iteration level together with strut density influenced the smoothness of the design.

Dozens of varied designs were created. From these, 20 designs were selected and grouped into 10 pairs. Each pair contained two designs: one design that was recognisable as having most or all guidelines applied (4 or 5 guidelines out of 5) and a design where little to none of the guidelines (0 to 2 guidelines out of 5) were recognisable. For the first of the two designs, it was chosen to include designs that did not have all guidelines applied to see if the guidelines would also work if one was not applied. The rationale behind this, is that it might not always be possible for all guidelines to be applied. For instance in a design where the fixation points are not symmetrical. For the other design of the pair it was chosen to allow for at least one guideline to be applied to also allow for a comparison of two symmetric designs.

The guidelines used are: symmetry, balance, continuation, simplicity and logic. Whether a design is in line with the guidelines will be explained using two example designs shown in Figure 18. The left design has the all guidelines applied, the right design has no guidelines applied.

A design is determined as being symmetrical if it is perceived as being symmetrical over one plane. A design is determined as being balanced if the thickness of the beams is consistent as well as the ratio between material and void spaces is visually balanced. The design on the left features smooth lines, whereas the right design also contains topology that does not convey a continuous line, identifiable by horizontal topology between beams and bumpiness. Simplicity is determined by a design having little identifiable separate structures. In the examples this is defined by the amount of individual beams. Logic is determined by whether the design's topology follows the expected force distribution for the product. In this example, the variation in thickness of the beams, combined with the asymmetry of the topology compared to the symmetry of the fixation points in the right design, is deemed to be illogical for its function.

Figure 18. Example of two generated designs. The design on the left has all guidelines applied. The design on the right has no guidelines applied.

5.3.1. Procedure

The study was conducted using the Qualtrics platform. Each respondent got shown 5 design pairs and were asked 6 questions per pair and then again 6 questions asking about their top three, resulting in a total of 36 questions per respondent. The respondents were first given an introduction that briefly explained the goal of the study, the product that was used (wall-mounted shelf), what questions to expect and the time the survey would take (approximately 8 minutes). There were, however, no time constrictions for the survey. There was also no incentive provided for the respondents.

The first thing needed was to verify if following the guidelines indeed results in their intended effects of increasing unity, typicality and logic. Then, it is necessary to see whether that results in increased aesthetic appreciation.

To asses an individual shape and rate it on the amount of – for instance – variety, is difficult. Therefore, it is chosen to show designs in pairs and to ask the respondents comparison questions which are easier to answer. Each pair consists of a design where most or all guidelines are applied, and a design where some or none of the guidelines are applied. The comparison questions were about the intended effects. Respondents were asked which design they found most: beautiful, unified, varied, typical, novel, logical. The respondents chose via a 7-point Likert scale which design they found most suitable to the question (Figure 19). The specific terms used in these questions, except for logic, were derived from a previous study in the development of scales to measure aesthetic pleasure for designed artifacts with the goal of developing a reliable scale to measure aesthetic pleasure (Blijlevens, et al., 2017).

The following questions were asked about a pair of designs:

Q1 "Beauty: Which design do you find more beautiful?"

Q2 "Unity: Which design is more orderly/unified?"

Q3 "Variety: Which design conveys more variety/diversity?"

Q4 "Typicality: Which design is more typical/normal for this kind of product?"

Q5 "Novelty: Which design is more novel/original?"

Q6 "Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?"

The 7-point Likert scale indicates preferences ranging from a strong inclination towards the left (1) to a strong inclination towards the right (7). 4 indicated a neutral option.

The designs were animated in order to allow the respondent to view the design in 3D using the GIF file format. The respondents were shown the front view rotating 70 degrees to the left, then back to front view, then right 70 degrees and back again in a loop. The rotation speed was 35 degrees per second.

In total there are 10 different pairs: 20 unique designs. After a pilot test it was chosen to show each respondent 5 pairs in order to decrease the length of the survey and therefor increase the completion rate. These pairs that were shown to each respondent were chosen randomly. An exposure management feature in the survey ensured that each pair was shown to approximately the same number of respondents.

One limitation of asking questions per pair, is that it doesn't result in an understanding of the opinions between other pairs. For that reason, in the second part of the survey, the respondents were shown all 20 designs and were asked the same type questions as the comparison questions but were now asked to select three designs that they found the most: beautiful, unified, varied, etc. The designs were shown in a grid of four horizontal and five vertical designs and were each given a letter. Respondents could then select preferred designs using selection boxes with corresponding letters. The grid and order of the selection boxes matched the grid and order of the designs (Figure 20). This approach complemented the pairwise comparison questions by offering a more holistic view of respondent perceptions and preferences.

5.3.2. Participants

The survey was distributed across platforms including LinkedIn and internal communications at Delft University of Technology, to ensure a broad reach. The survey remained active for a duration of two weeks.

Out of the 147 individuals who responded to the survey, 90 completed it in its entirety. Incomplete responses were excluded from the analysis. The 90 respondents who completed the survey represented a diverse age range, spanning from 18 to 65+. Among them, 31 participants reported having an educational or professional background in (product) design, while 59 did not.

Each respondent was tasked with assessing 5 out of 10 pairs of 3D generated designs, resulting in an average of 45 respondents evaluating each pair. The distribution ranged from a minimum of 37 to a maximum of 49 respondents per pair. Additionally, all 90 respondents completed the 'top three' questions, where they were asked to select their preferred designs from the full overview of 20 designs.

The minimum required sample size to detect a large effect size of f = 0.40 with a statistical power of 80% and α set to 0.05 was calculated (Faul, Erdfelder, Lang, & Buchner, 2007). This analysis determined a minimum sample size of 41 participants. Previous studies have demonstrated large effect sizes in explaining visual aesthetic appreciation, including for *Unity-in-Variety* (Post, Blijlevens, & Hekkert, 2016).

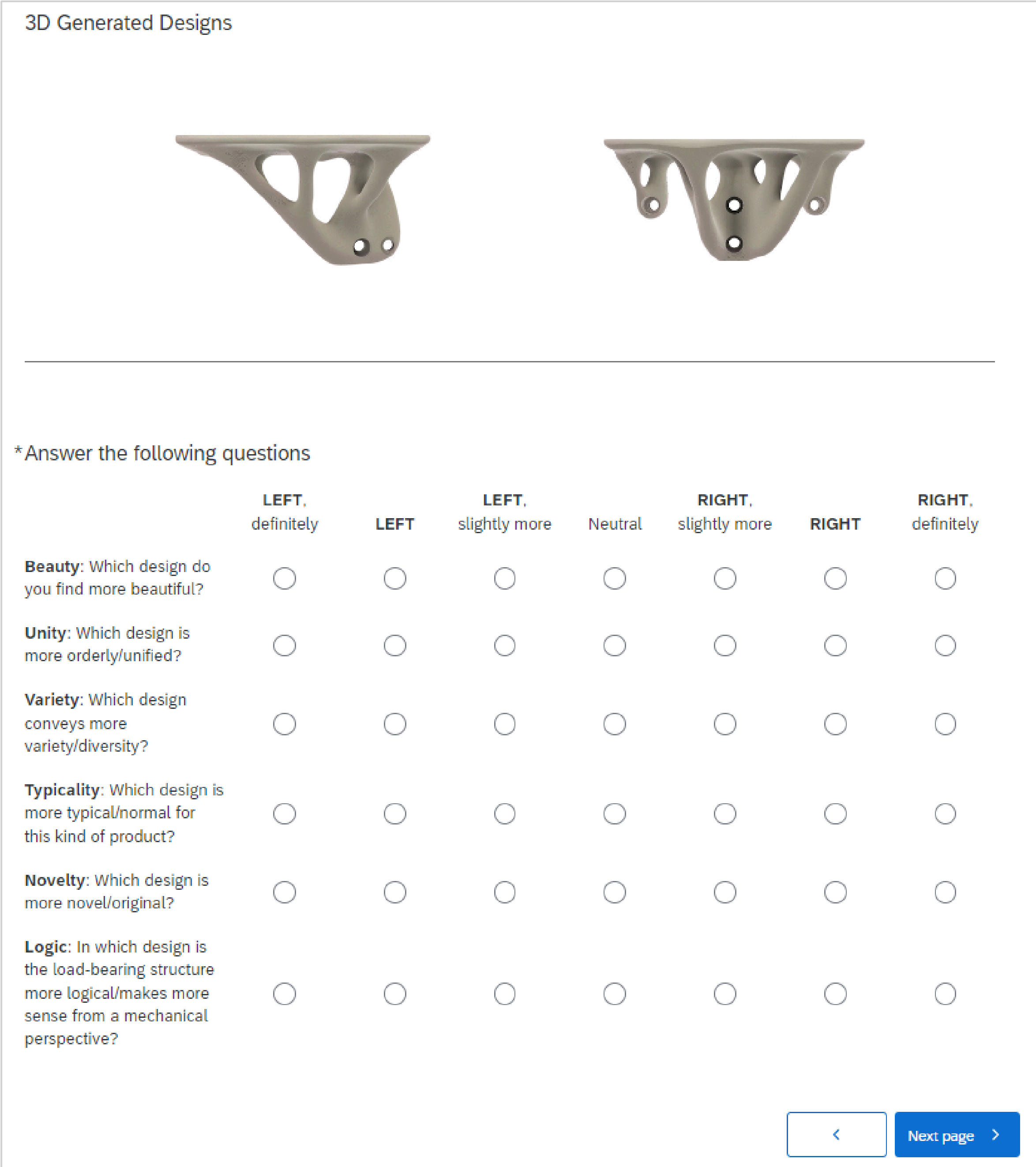
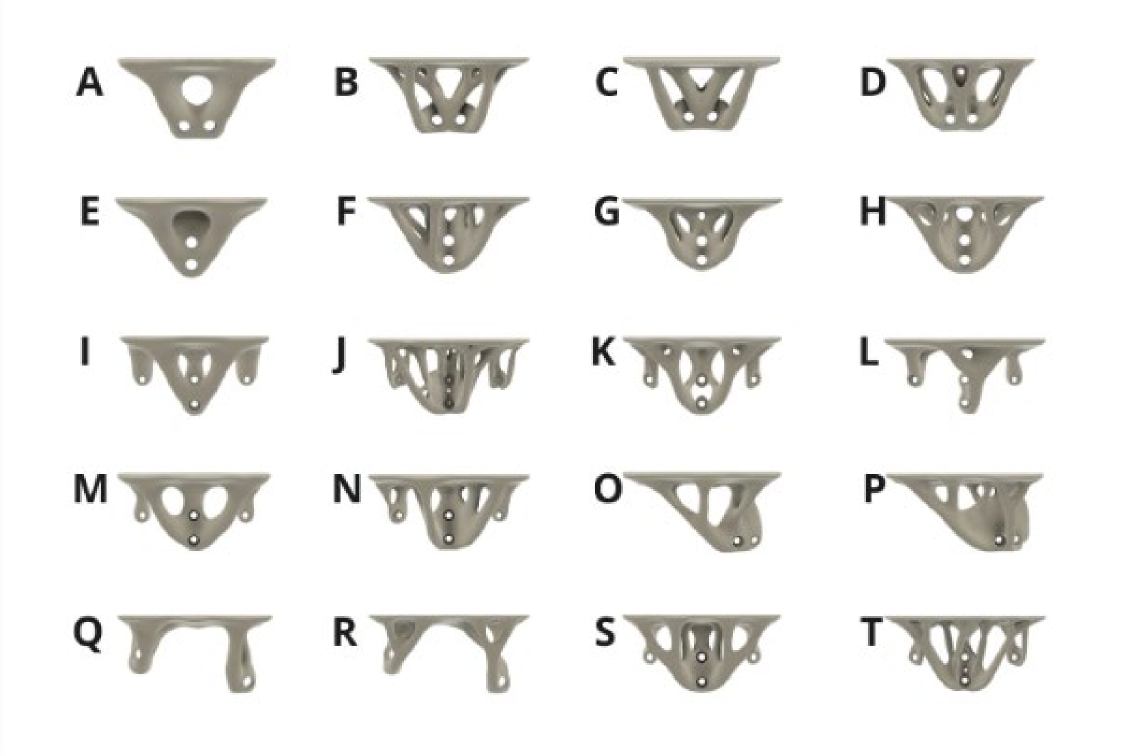


Figure 19. Screenshot of a comparison question in the survey. The designs were animated, rotating left and right on the vertical axis.

Choose top 3 most novel/original designs.



*Choose top 3 most novel/original designs.

☐ A	☐ B	☐ C	☐ D
☐ E	☐ F	☐ G	☐ H
☐ I	☐ J	☐ K	☐ L
☐ M	☐ N	☐ O	☐ P
☐ Q	☐ R	☐ S	☐ T

Figure 20. Example of one of the 'top three' questions.

5.4. Results and Discussion

5.4.1. Comparative results

We first look at the results from the comparative questions that were asked about the pairs to validate whether applying the guidelines resulted in the intended effects. The intended effects, with guidelines applied are that the design is perceived to be more unified, typical and logical.

The results of the comparative questions are visualised and split into two figures. Figure 22 shows the results from the pairs AB to IJ and Figure 23 shows the results from the pairs KL to ST. The results are shown in a horizontal bar chart that shows the average score and the standard deviation. Next to the charts are the corresponding designs. The left side of the chart corresponds with the left design of the pair, this is the design where guidelines are visible. The right side of the chart with the right designs of the pair, this is the design that has no/less guidelines visible than their counterpart. For the analysis of the survey results, the responses from the 7-point Likert questions were converted to numbers ranging from -3 to +3. Where *LEFT, definitely* equals -3, *Neutral* equals 0 and *RIGHT, definitely* equals 3. This results in a negative value meaning a preference for the left design and a positive value meaning a preference for the right design. This results in a horizontal bar chart with a left and right side. From top to bottom, each pair is compared in their results from: Beauty, Unity, Variety, Typicality, Novelty and Logic.

At 8 out of the 10 pairs, the design with guidelines was perceived as more unified. With a clear average of all pairs on -1.14. The two pairs where the other design was found more unified were KL and OP. The magnitude of unity in these two cases was with 0.10 and 0.13 respectively, smaller than the average magnitude of unity towards the designs with guidelines (-1.46). This indicates a less pronounced difference in unity among the two designs in the pair.

Also for typicality, 8 of 10 of the designs with guidelines were found to be more typical. The average of all 10 pairs was -0.89. The two pairs where the other design was found more unified were, again, KL and OP. Their average was 0.27 and 0.65 respectively.

For logic 7 out of 10 designs with guidelines were found more logical with a mean average of -0.23. Among the pairs KL, OP and GH, the opposing design was found to be more logical. These findings validate the hypothesis that the application of the newly setup guidelines reaches the desired effect of a topology optimised design being perceived as more unified, typical and logical.

The second hypothesis is that through these effects, the design will be perceived as more aesthetically pleasing. Overall, when looking at the aesthetic preference within the pairs, the designs with guidelines applied was found to be more aesthetically pleasing in nine out of ten cases, with a mean average of -0.68. Only in pair AB was the other design preferred, with an average of 0.60.

Pearson correlations

Pearson correlations were performed to investigate how the different effects relate to each other. The variable beauty was examined in relation to Unity, Typicality and Logic. All average correlations are visible in Figure 21. An overview of all individual correlations are added in the appendix.

Pearson correlations between beauty and unity show a positive correlation at all pairs. Ranging from r_{AB} = 0.16, p = 0,299 to r_{CD} = 0.63, p = 0.000. With an average of r_{AVG} = 0,45, p< = 0.05 this was the strongest correlation.

Between beauty and typicality, Pearson correlations also showed a positive correlation at nine out of ten pairs. The correlations ranged from r_{AB} = -0.33, p = 0,029 to r_{IJ} = 0.64, p = 0.000. With an average of r_{AVG} = 0,24, p = 0.205.

Also for beauty and logic there was a positive correlation for all pairs, ranging from r_{MN} = 0.04, p = 0,825 to r_{OP} = 0.45, p = 0.001. With an average of r_{AVG} = 0,26, p = 0.168.

Negative correlations

Negative correlation were found between the opposing aspects of unity and variety and for typicality and novelty. This supports the principles that state that maximising the opposing forces contributes to aesthetic appeal. The average correlations were $r_{U\text{-}V}$ = -0.14, p = 0,324 and $r_{T\text{-}N}$ = -0.17, p = 0.295.

Partial correlations

The negative correlation between unity and variety and between typicality and novelty could however indicate that the correlation between unity and beauty was suppressed by the effect of variety and that the correlation between typicality and beaty was suppressed by novelty. Partial correlations confirmed these expectations as controlling for each other's influence increased the correlations with beauty for unity and typicality. The correlations were respectively $r_{P\_U\text{-}V}$ = 0.47, p = 0,020 and $r_{P\_T\text{-}N}$ = 0.29, p = 0.162.

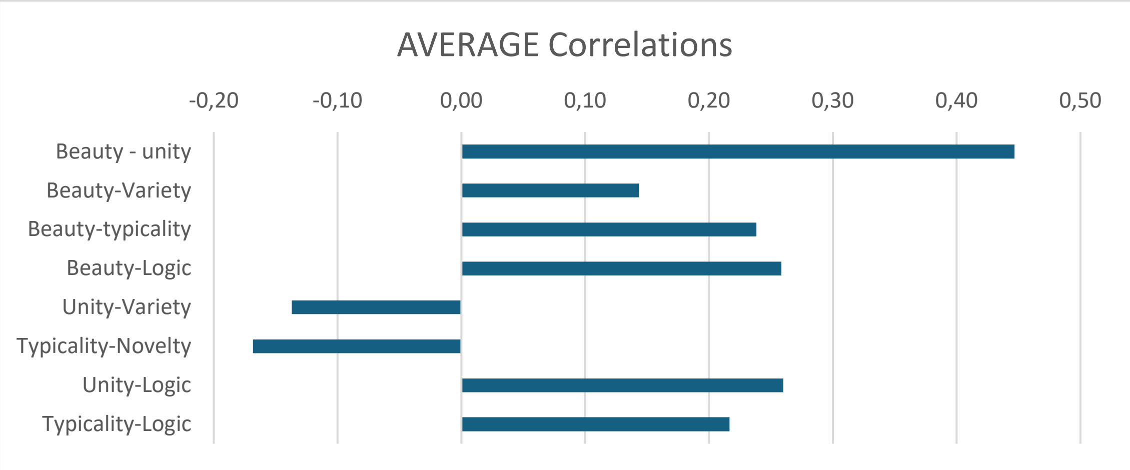


Figure 21. Pearson correlations, average of all 10 pairs.

These correlations support the second hypothesis further that the increased effects of unity, typicality and logic increases the aesthetic appeal of the design.

The results in pair AB is least consistent with the second hypothesis and the rest of the results. Although the unity, typicality and logic are all significantly more noticeable for design A, and variety and novelty for design B, B is still chosen as more beautiful. A possible explanation for this can be that design A is *too* unified, typical and logical. The guidelines were setup to make topology optimised designs more unified, typical and logical to counteract the unbalance because these designs are typically perceived as more varied and novel than everyday products. This would create more of a balance between unity and variety and typicality and novelty. With the appearance of design A leaning too much towards unity and typicality, the unbalance is shifted too far. The results from the top 3 questions supports this, where design *A* was the most chosen design for both unity, typicality and logic, while ranking only third in most beautiful.

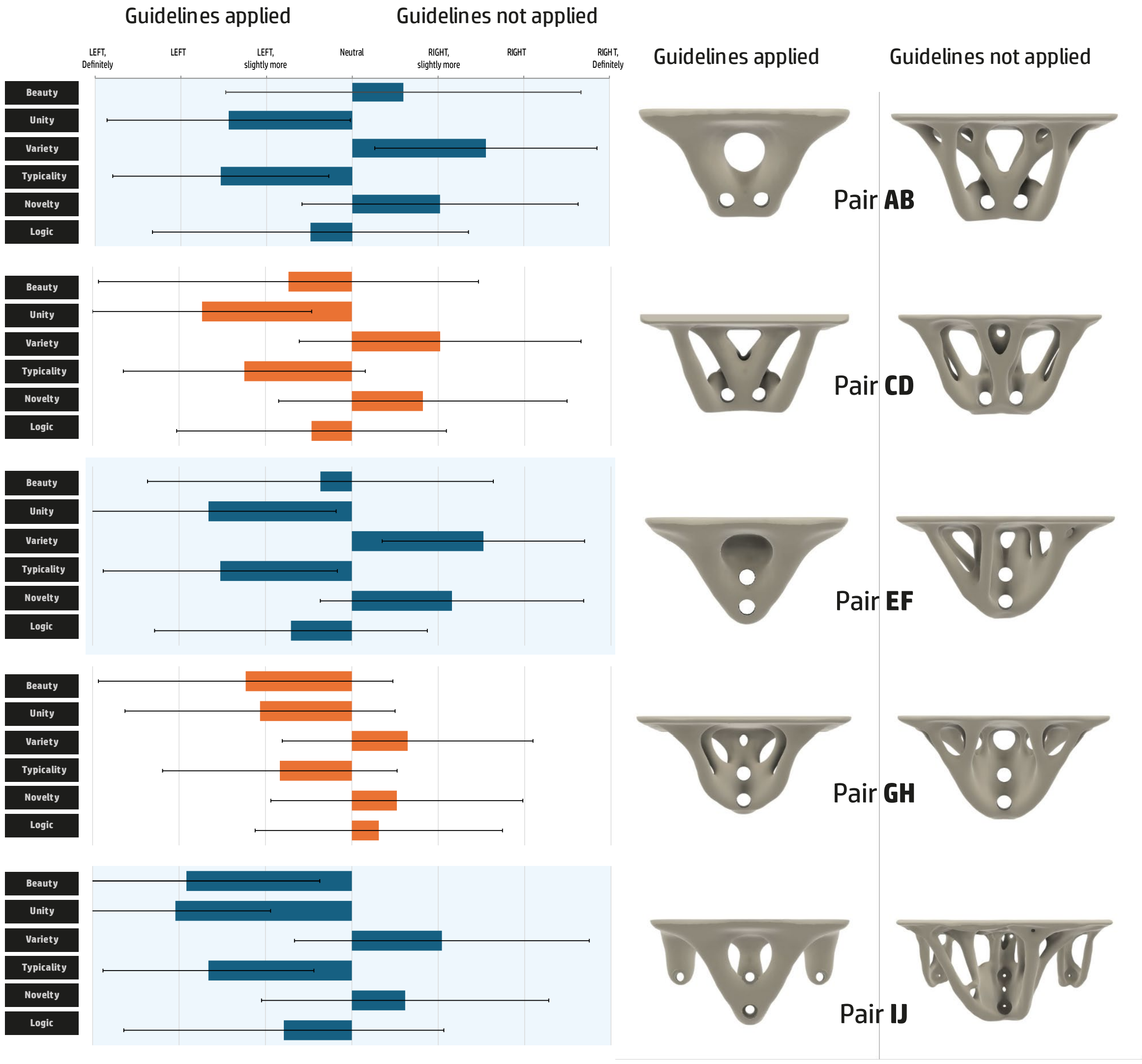


Figure 22. Comparative results AB to IJ

The data displays a notable standard deviation. This can be attributed in part to the format of the survey questions. A tendency for responses to cluster towards opposite ends when respondents are prompt to compare two designs. This tendency in a comparative rating system often results in a wider standard deviation. Also, in aesthetics research, large standard deviations are not uncommon (Berghman & Hekkert, 2017).

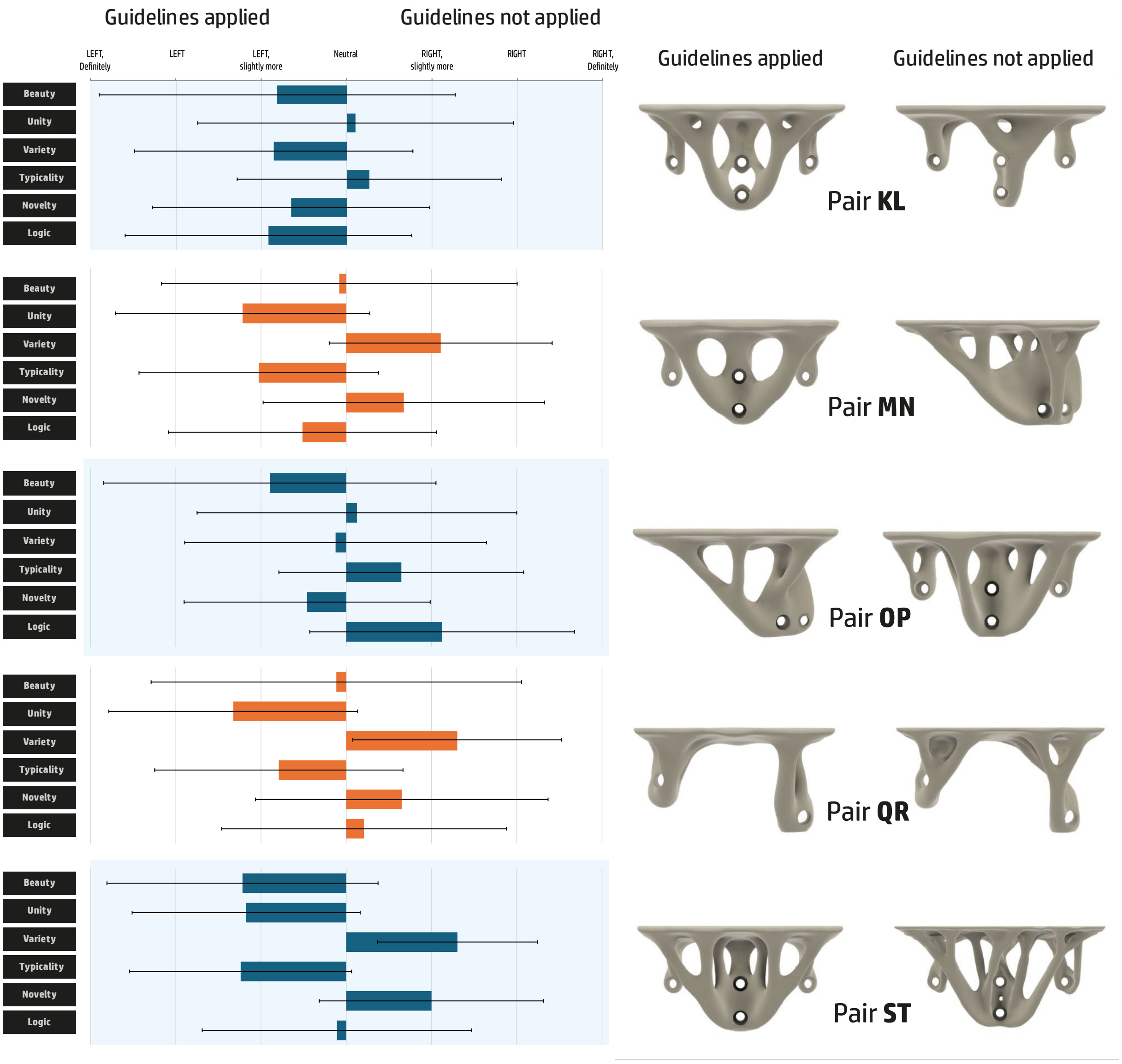


Figure 23. Comparative results KL to ST

5.4.2. Top 3 results

The results from the top-3 questions are visualised in six separate column charts in Figure 24. The results are organised so that all designs *with* guidelines are on the left side in the chart, the designs with no or little guidelines are on the right side. Additionally, the charts coloured orange indicate the data that was expected to be more favourable towards the designs with guidelines applied (beauty, unity, typicality, logic). The other two charts, coloured blue, were expected to be more favourable towards the designs with no/less guidelines applied (variety, novelty), as seen in the previous data. Additionally, the three most chosen designs can be seen on the right in the charts in order of 1st most chosen (left) to 3rd most chosen (right).

Figure 24. Top 3 results. The results from the designs are organised so that the designs with guidelines applied are on the left side in the chart. The three most frequent chosen designs are shown right of the charts.

The top 3 most beautiful designs were C, B, A. Respectively 44%, 32%, 28% of respondents put these designs in their top 3.

Looking at both novelty and variety we see that design J and T both score high. This was expected as the topology of the designs is varied, unbalanced and unsymmetrical.

It is noticeable to see that among the three intended effects of unity, typicality and logic, the same top three emerged in the same order: A, E, C. With A being the most chosen in the top three among respondents. This indicates a possible correlation between these aspects.

But although A is the most chosen designs in those cases, design C is chosen most as being most beautiful. Also looking at design E, which was consistently ranked second among unity, typicality and logic, only ranked eighth among the most beautiful designs.

As mentioned before this might indicate that there is a limit in increasing unity, typicality and novelty in topology optimised designs, after which there again is an unbalance. Bringing it back to the applied guidelines, A and E can be perceived as being unbalanced in their material vs void ratio, leaning towards being bulky.

Opposing Aspects Balanced

According to the principles, optimal beauty is reached when both opposing aspects are maximised. An analysis was done on designs that score similar values on the opposing aspects unity and variety. This was done the same for typicality and novelty from the MAYA principle. The balance is calculated by the difference between the opposing aspects, divided by the maximum value of the two and then calculated by subtracting that value of a hundred percent.

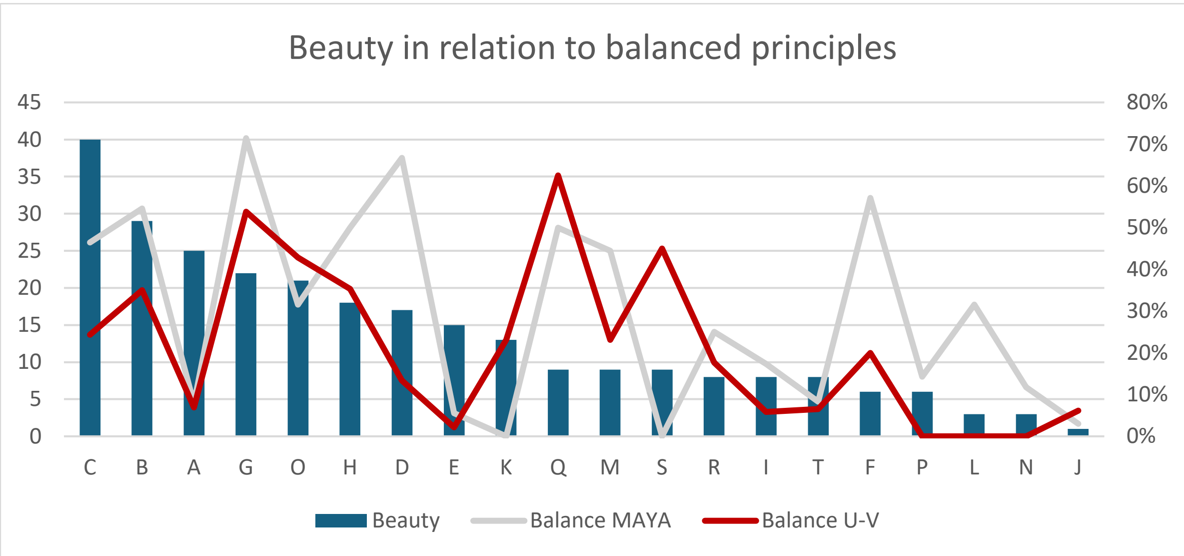


Figure 25. Results of beauty in relation to balanced aspects of unity/variety and typicality/novelty. In order of most beautiful to least. The left vertical axis displays the number of times a designs has been chosen in the top-3 of most beautiful designs. The right vertical axis displays the balance of the opposing forces of unity and variety (U-V) and typicality novelty (MAYA).

Although difficult to see in the graph (Figure 25), Pearson correlations did show that there in fact is a positive correlation between Beauty and the Balance between unity and variety as well as between Beauty and the balance between typicality an novelty ($r_{U\text{-}V} = 0.35$, p = 0,129 .0; $r_{T\text{-}N} = 0.39$, p = 0.087). However, both P-Values were both above the significance level of 0.05, it therefore cannot be said that this correlation in the study was significant.

A possible limitation of this study was the organisation of the designs in the survey. Each participant was shown five pairs, which were randomized, as was the order in which they were presented. This was also the case for the order of the top-3 questions. However, the position of the designs with guidelines compared to those without guidelines was consistent across all pairs. This consistency might have influenced the results.

5.5. Conclusion

The results of the study has shown that the guidelines result in the effect of a design being perceived as more unified, typical and logical and ultimately more beautiful. At the same time the designs where no guidelines were applied were being perceived as more varied and novel.

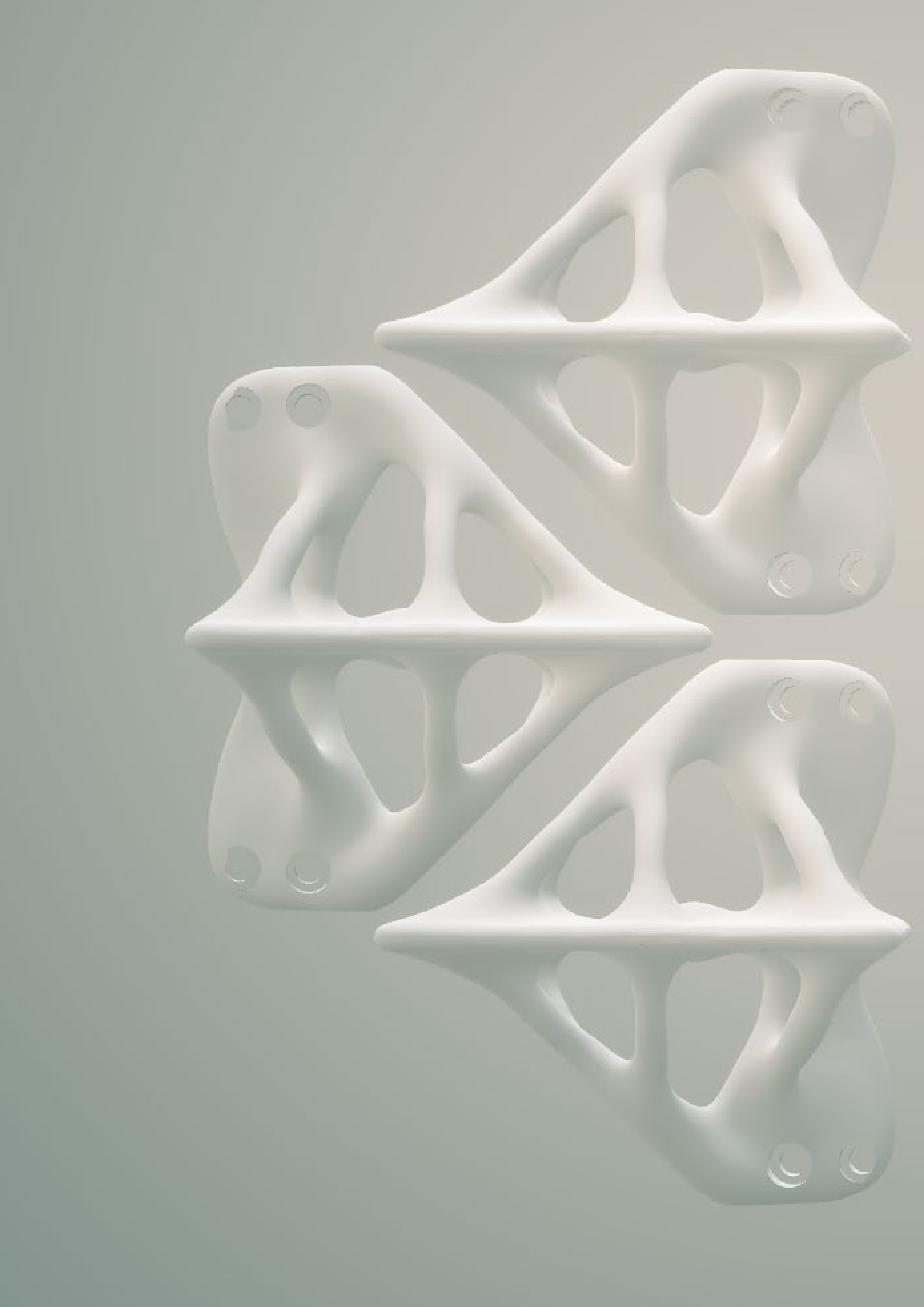
We began with the notion that the appearance of generated forms generally have an unbalance between *unity and variety* and *typicality and novelty*, where these designs generally lean more towards variety and novelty. By creating and selecting designs in which the guidelines reflected, we tempt to have designs that are perceived as more unified and typical. This then creates a balance between these opposing forces and therefor increase the aesthetic experience.

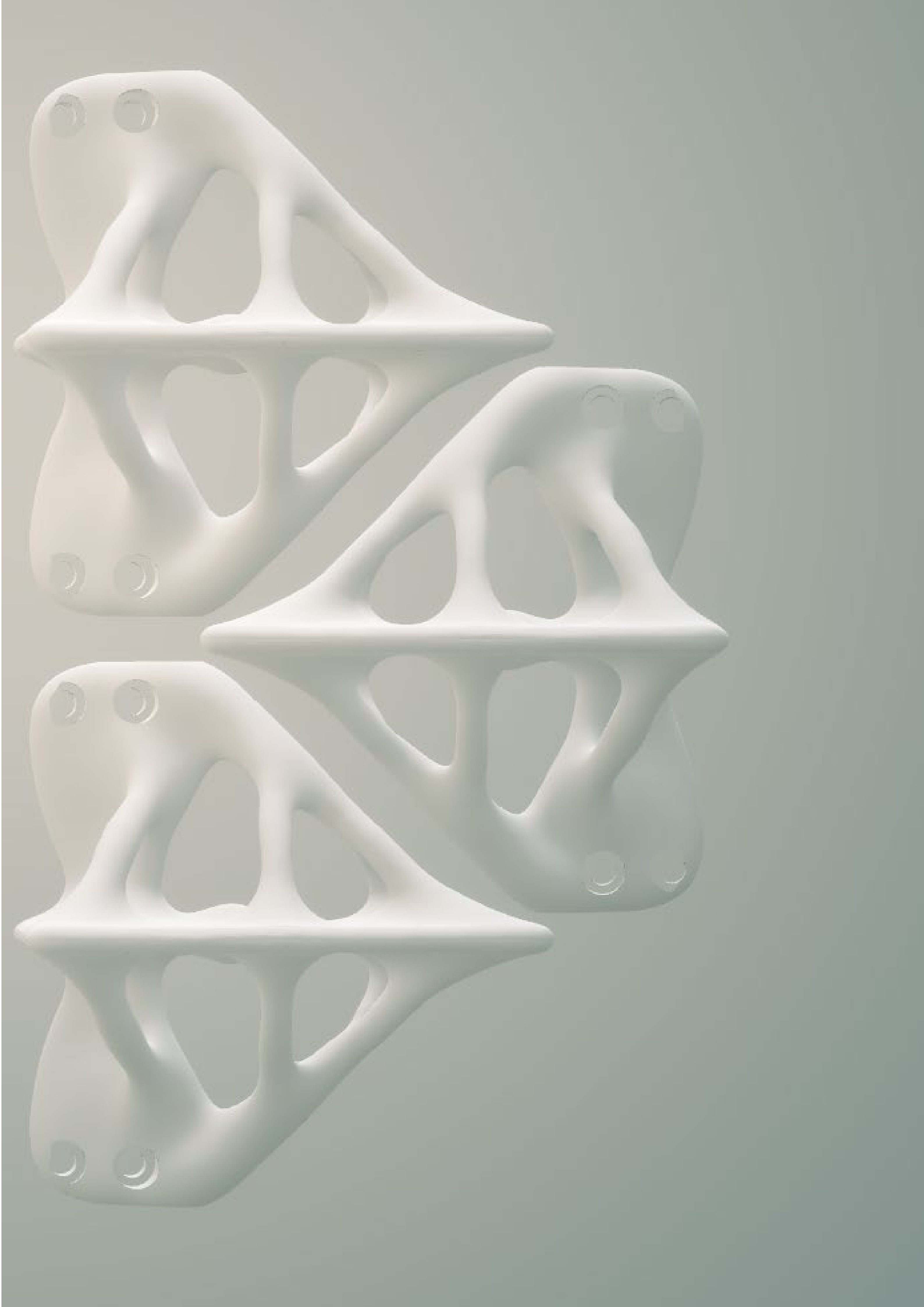
When creating or selecting designs using these guidelines however, it is possibility to make the designs *too* unified and typical which in turn can result in an unbalance towards the other direction. The authors therefor ask designers and engineers who want to use these guidelines in the selection of their generated designs, or when these guidelines are integrated into generative software, to be aware of this risk.

In the case of typicality and novelty, people should be aware that over time, people's perception towards what is typical and novel will change. When generative designs like these become more common, the novelty will decrease. It is therefor always a balancing act that the designer must be aware of.

5.6. Acknowledgements

The authors would like to thank all participants who kindly undertook the survey. No funding was used for this research.





6. Conclusions and Recommendations

This graduation project was aimed at answering the question whether it is possible to identify aspects of 3D generated designs that contributes to a more aesthetically pleasing result. And by doing so, opening the door to the possibility of increasing intentional aesthetics in 3D generative design.

By analysing existing principles on aesthetics in design hypotheses were synthesised as a starting point for a starting user study.

These hypotheses were then tested in the first user study through comparative questions and open questions on what aspects, according to the participants, contributed to a design being perceived as aesthetically pleasing or not.

The user study revealed key factors influencing the aesthetic appeal of 3D generated designs. Symmetry emerged as a prominent aspect, with participants consistently favouring symmetric designs. Additionally, balance between void and solid, smoothness, simplicity, and logical force distribution were identified as contributing to aesthetic preference. While simplicity was generally preferred, complexity was favoured when the design aimed to serve as a statement piece. These findings align with aesthetic principles of *Unity-in-Variety* and typicality versus novelty. Subsequently, these findings were synthesised into five guidelines aimed at making a design more aesthetically pleasing:

Symmetry: A design must strive for symmetry,

Balance: A design must strive for balance in beam thickness, and material vs void,

Continuation: A design must be have continuing lines,

Simplicity: A design must have a minimalistic appearance,

Logic: A designs topology must look logical for its function.

A second used study was then set up in order to verify whether the guidelines indeed result in the desired effects. Comparative questions were used to validate whether the guidelines enhanced the perception of unity, typicality, and logic in the designs. Results demonstrated that designs with guidelines applied were consistently perceived as more unified, typical, and logical compared to their counterparts. Correlation analysis revealed a positive relationship between these effects and aesthetic preference. However, the results from one pair of designs deviated from our expectations, suggesting a potential limit to increasing unity and typicality.

Top three results further reinforced the importance of unity, typicality, and logic in aesthetic preference. Despite consistency in the top-ranked designs across intended effects, design E was an exception, ranking lower in aesthetic appeal.

This study has shown that implementing the guidelines improves the aesthetic appeal of designs by achieving a balance between opposing forces. However, designers should take into account that perceptions of typicality and novelty are always evolving.

The guidelines can currently be used as actionable recommendations for designers, engineers and architects seeking to optimize both the structural and aesthetic qualities of generatively designed products.

This thesis project should be viewed as stepping stone to further research into this subject. The research from Shannon Loos from 2022 on increasing unity in 2D topology optimised forms was a stepping stone for this thesis. This thesis should in turn be the beginning of further research into developing the use of generative design.

The guidelines have proven that it is possible to identify aspects of 3D shapes that will increase the aesthetic appreciation. Further research can involve more aspects of a product such as colour, texture.

Ultimately it would be the goal of being implement these guidelines, either as settings that engineers and designers can tweak before or during generation of shapes, or to fully implement them in the software like earlier proposed by Perez Mata (Perez Mata, Ahmed-Kristensen, & Shea, 2018). This could decrease barrier for other designers and engineer to use this technology. It could decrease the time needed to produce and develop products. Furthermore, generative design, in combination with manufacturing methods like additive manufacturing, can result in products that use less materials, less diversity of materials in the same products with less separate parts. Which in turn could benefit environment and society.

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8. Appendices

8.1. Appendix A – Project Brief

Personal Project Brief – IDE Master Graduation Project

Name student Jesse Hols **Student number** 5,441,145

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Aesthetic design principles for generative Design

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The domain of the project is in design aesthetics and in generative design with a focus on 3D topology optimised forms. Generative design is a computer-aided technique that uses algorithms to generate a designs based on specific constraints. Topology optimisations is a subset of generative design where the designer provides constraints, loads and an initial geometry. The computer then uses algorithms to remove material where it is not necessary for the given constraints, resulting in a lighter part (Figure 1). This usually results in shapes that have a organic appearance, like the `Bone chair' (Figure 2).

The organic geometry are often challenging to produce with traditional manufacturing methods, resulting in a lot of manual post altering of the design. 3D-printing makes it possible to produce these parts with little alterations. Topology optimisation together with 3D printing result in lighter parts, using less material and can be manufactured with fewer individual parts, as well as reduced material diversity, which can offer sustainability benefits. However, the unique appearance of these components could potentially have a negative impact on the acceptance of this technology in consumer products.

The goal is the create a set of aesthetic design principles that can be applied during the process of generating a design as a way to ensure the human-informed aspect of design in these processes.

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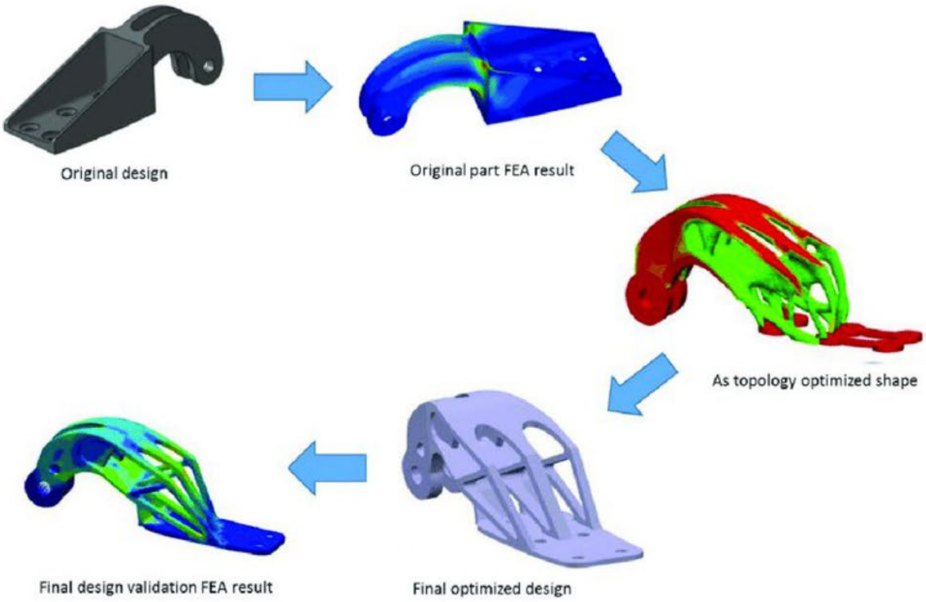

image / figure 1 Topology optimisation process (FormLabs.com)

image / figure 2 The bone chair by Joris Laarman

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Generative designs are optimised for their mechanical functionality while their appearance varies. Aesthetics are not considered in the current workflow of generative design that focusses purely on functionality. Aesthetic pleasure is important in consumer products, therefor in order to increase the acceptance of these designs for consumer products, aesthetics must be taken into the equation.

With the creating of validated design principles on aesthetics of a 3D form, I want to ensure the designer input and control on the aesthetic outcome of the generated part. With these principles, a designer should be able to work together with the computer to design/generate a form which is aesthetically pleasing.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Create design guidelines for increasing aesthetic in generative design.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The first step is to generate a variety of designs within a product group. Then, these designs are rated on their aesthetic appeal. Aspects that make a form more aesthetically pleasing are determined using a framework of opposites. From these aspects, design principles are created. These principles will then be validated in a new user study. Here, non-altered generated designs will be compared to designs that are altered using the new design principles.
In the beginning of the project, the history of design aesthetics and design tools will be examined.
Then, a variety of designs will be generated within a product group using a software with topology optimisation abilities, like Fusion 360 or Synera.
The user studies should be done in such a way that the designs can be well distinguished. This could be done using physical 3D printed models, with the use of VR, or by using step- or stl-files in an online survey. The validation of the user studies and the conceptualisation of the design principles will be done with using the Model of aesthetic preference (Hekkert 2014).

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	30 okt 2023
Mid-term evaluation	11 jan 2024
Green light meeting	7 mrt 2024
Graduation ceremony	4 apr 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✔
For how many project weeks	5
Number of project days per week	4,0

Comments:
First five weeks 4days a week to finish read a book elective.
Total of 2 week vacation around christmas

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I have been interested in Topology optimisation since I first came into contact with it. I liked idea of form follows function. However, by generating my own designs I have seen that it requires a lot of iterations to end up with a part that is aesthetically pleasing. Previously I have focussed more on the technical aspects of product design and less on the aesthetics of it. In this project I want to develop my technical competences as well as learning the principles of aesthetics in design.

A personal learning ambition is to become more acquainted with CAD software using a form of parametric `visual programming' like grasshopper and Synera.

8.2. Appendix B – Consent Form English/Dutch

Esthetisch genoegen van gegenereerde vormen

Dit onderzoek wordt uitgevoerd als onderdeel van de MSc opleiding Industrieel Ontwerpen aan de TU Delft.

Student: Jesse Hols

Contactpersoon: Jesse Hols – 5441145 – [redacted]

Toestemmingsverklaring participant

Je bent uitgenodigd om deel te nemen aan een onderzoeksproject genaamd *visuele esthetiek van computer gegenereerde vormen.*

Dit onderzoek wordt uitgevoerd door Jesse Hols van de Technische Universiteit Delft. Het doel van dit onderzoek is om informatie te verzamelen over de meningen van mensen over de visuele esthetiek van computer gegenereerde vormen met als uiteindelijk doel het opstellen van ontwerpregels die de esthetiek van computer gegenereerde vormen kan bevorderen.

Het onderzoek zal ongeveer 25 minuten duren.

De gegevens worden gebruikt voor een afstudeerproject van de master Integrated Product Design aan de TU Delft. Aan het begin van het onderzoek worden de volgende persoonlijke gegevens gevraagd: Leeftijdsgroep, geslacht, ervaring omtrent esthetiek.

Vervolgens wordt u gevraagd om uw mening te geven over een aantal computer gegenereerde voorwerpen in de vorm van een interview. Uw zult deze vormen waarnemen door middel van een Virtual Reality bril terwijl u stil zit op een stoel. U kunt de vormen roteren met gebruik van een controller. Tijdens het interview zal de onderzoeker notities maken van uw antwoorden.

Zoals bij elk onderzoek bestaat er een risico op gegevensinbreuk. We doen ons best om uw antwoorden vertrouwelijk te houden door de gegevens anoniem te verzamelen en op te slaan op een betrouwbare locatie waartoe alleen de onderzoekers toegang hebben.

Uw deelname aan dit onderzoek is volledig vrijwillig en u kunt zich op elk moment zonder opgaaf van reden terugtrekken. Het staat u vrij om vragen niet te beantwoorden.

Contactgegevens uitvoerende onderzoeker:

Jesse Hols
[redacted]

Contactgegevens van afstudeercommissie:
Jun Wu
[redacted]

Paul Hekkert
[redacted]

TU Delft

Vink de hokjes die voor u van toepassing zijn aan	Ja	Nee
A: ALGEMENE OVEREENSTEMMING – ONDERZOEKSDOELEN, TAKEN VAN DEELNEMERS EN VRIJWILLIGE DEELNAME		
1. Ik heb de informatie over het onderzoek gelezen - of deze is aan mij voorgelezen- en begrepen. Ik heb de mogelijkheid gehad om vragen te stellen over het onderzoek en mijn vragen zijn naar tevredenheid beantwoord.	☐	☐
2. Ik doe vrijwillig mee aan dit onderzoek, en ik begrijp dat ik kan weigeren vragen te beantwoorden en mij op elk moment kan terugtrekken uit de studie, zonder een reden op te hoeven geven.	☐	☐
3. Ik begrijp dat mijn deelname aan het onderzoek de volgende punten betekent - dat ik op een stoel zit met een VR-bril op waarmee ik vormen ga beoordelen. - geschreven notities gedurende het interview	☐	☐
B: MOGELIJKE RISICO'S VAN DEELNAME (INCLUSIEF GEGEVENSBESCHERMING)		
5. Ik begrijp dat mijn deelname het risico met zich meebrengt dat ik me oncomfortabel kan gaan voelen in de virtuele omgeving. Ik begrijp dat deze risico's worden geminimaliseerd doordat ik op elk moment kan stoppen met de test.	☐	☐
6. Ik begrijp dat mijn deelname betekent dat er persoonlijke informatie (leeftijdsgroep, gender en ervaring op basis van esthetiek) en onderzoeksdata worden verzameld.	☐	☐
7. Ik begrijp dat de volgende stappen worden ondernomen om het risico van een databreuk te minimaliseren, en dat mijn identiteit op de volgende manieren wordt beschermd in het geval van een databreuk: de data is anoniem, de data wordt veilig opgeslagen, de data is alleen beschikbaar voor de betrokken onderzoekers.	☐	☐
C: PUBLICATIE, VERSPREIDING EN TOEPASSING VAN ONDERZOEK		
8. Ik begrijp dat na het onderzoek de geanonimiseerde informatie gebruikt zal worden voor een afstudeeropdracht en mogelijk een onderzoekspublicatie. In deze publicatie zullen alleen statistische uitkomsten van de data vermeld staan op een manier dat ze niet meer naar u te herleiden zijn.	☐	☐
D: (LANGDURIGE) OPSLAG, TOEGANG EN HERGEBRUIK VAN GEGEVENS		
9. Ik geef toestemming om de geanonimiseerde data over meningen van de verschillende computer gegenereerde vormen te archiveren in de TU Delft repository zodat deze gebruikt kunnen worden voor toekomstig onderzoek en onderwijs.	☐	☐
10. Ik begrijp dat de toegang tot deze repository openbaar is.	☐	☐

TU Delft

Handtekeningen

______________ ______________ ________________

Naam deelnemer Handtekening Datum

Ik, **de onderzoeker**, verklaar dat ik de informatie en het instemmingsformulier correct aan de potentiële deelnemer ter informatie heb gegeven en, naar het beste van mijn vermogen, heb verzekerd dat de deelnemer begrijpt waar hij/zij vrijwillig mee instemt.

___Jesse Hols_______________ ________________ _______________

Naam onderzoeker Handtekening Datum

Contactgegevens van de onderzoeker voor verdere informatie:

Jesse Hols

[redacted]

TU Delft

Aesthetic pleasure of generated forms

This research is conducted as part of the MSc programme in Industrial Design at TU Delft.
Student: Jesse Hols
Contact person: Jesse Hols – 5441145 – [redacted]

Participant consent form

You are invited to participate in a research project called *visual aesthetics of computer-generated forms*.

This research is being conducted by Jesse Hols from the Delft University of Technology. The aim of this research is to gather information about people's opinions on the visual aesthetics of computer-generated shapes with the ultimate goal of establishing design principles that can promote the aesthetics of computer-generated shapes.

The survey will take about 25 minutes.

The data will be used for a graduation project of the Integrated Product Design master's programme at the TU Delft. At the beginning of the survey, the following personal data will be requested: your age group, gender and experience in aesthetics.

You will then be asked to give your opinion on a number of computer-generated objects in the form of an interview. You will perceive these shapes through Virtual Reality glasses while sitting still on a chair. You can rotate the virtual shapes using a controller. During the interview, the researcher will take notes of your answers.

As with any research, there is a risk of data breach. We do our best to keep your responses confidential by collecting and storing the data anonymously in a trusted location to which only the researchers have access.

Your participation in this study is completely voluntary and you can withdraw at any time without giving any reason. You are free to not answer questions.

Executive researcher contact details:
Jesse Hols
[redacted]

Contact details of graduation committee:
Jun Wu, [redacted]

Paul Hekkert
[redacted]

TU Delft

Tick the boxes that apply to you	Yes	No
A: GENERAL AGREEMENT - RESEARCH OBJECTIVES, TASKS OF PARTICIPANTS AND VOLUNTARY PARTICIPATION		
1 I have read - or been read to me - and understood the information about the study. I had the opportunity to ask questions about the survey and my questions were answered to my satisfaction.	☐	☐
2. I am voluntarily participating in this study, and I understand that I can refuse to answer questions and withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that my participation in the study entails the following points: - Me, sitting in a chair with VR glasses on with which I am going to assess shapes. - written notes during the interview	☐	☐
B: POTENTIAL RISKS OF PARTICIPATION (INCLUDING DATA PROTECTION)		
5. I understand that my participation carries the risk that I may feel uncomfortable in the virtual environment. I understand that these risks are minimised by the fact that I can quit the test at any time.	☐	☐
6. I understand that my participation means that personal information (age group, gender, educational background) and research data will be collected.	☐	☐
7. I understand that the following steps are taken to minimise the risk of a data breach, and that my identity is protected in the event of a data breach in the following ways: the data is anonymous, the data is stored securely, the data is only available to the researcher and supervisors.	☐	☐
C: PUBLICATION, DISSEMINATION AND APPLICATION OF RESEARCH		
8. I understand that after the research, the anonymised information will be used for a thesis and possibly a research publication. This publication will only include statistical outcomes of the data in a way that they cannot be traced back to you.	☐	☐
D: (LONG-TERM) STORAGE, ACCESS AND RE-USE OF DATA		
9. I give permission to archive the anonymised data on opinions of the various computer-generated forms in the TU Delft repository so that they can be used for future research and teaching.	☐	☐
10. I understand that access to this repository is restricted to TU Delft students and employees.	☐	☐

Signatures

____________________ ________________ _______________

Name of participant Signature Date

I, **the researcher**, declare to have correctly given the information and the consent form to the potential participant for information and, to the best of my ability, assured that the participant understands what he/she is voluntarily consenting to.

__Jesse Hols_________ _________________ _______________

Researcher name Signature Date

Study contact details for further information:

Jesse Hols
[redacted]

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8.3. Appendix C – Results User study 1

Participant		1	2		3	4	5	6
Chair 1	a	-Ugly -wierd -tree-like	-scary		+interesting structure +cool +symetry			-no structure -balance void/solid -nonsymetry -ugly transition
	b	+beautiful +logical +clean +good	+stable +comfortable		+backside cool +flow			+connected lines
	c	-Bulkier +soft	+stable -Heavy -boorish		-fat, -friendly, -too much material -unecessary -looks like organs			+hind leg +continuous lines +doesnt show all at once;intriguig +symetry
Chair 2	a	-wierd	-sharp		+more typical -unsymetric			-continuos lines
	b	+more beautiful	+symetric +refined +balance void/solid		+interesting +legs starting from middle +new/novel +cool			
Chair 3	a		+symetric, +elegant, +roundings		+symetric side profile, -clunky			-rough -holes
	b	+backrest connection +balance in thickness			+cooler, +connection backrest			+cross on hind leg looks like it has function of handle +continuing lines
Chair 4	a	+symerty	+sexier		-different thicknesses, +Dinosaurus skull, +back architecture			+continuous line +organic
		-spiderweb-like -thin	-backside is ugly, -elephant like		+base architecture, + more calculated			-small feet -less organic
Chair 5		-spider on legs -fragile -less comfortable	+most normal +typical	typical	-gross, out of proportion			+clean +repeting legs +minimlistic +more attention to chair function, less showy
	b	+elegant		mid	+balance void/solid			-wierd
	c	-bulky	-novel	novel	-too blocky			+more connected
Chair 6	a	-connection to backrest	+ bit of free form but stays true to typical chair design classic GISPEN, +sympathetic, less showy		-no balance, -match up between new and old			
	b	better	-crazy					
Chair 7		6 or 7	1 or 4		1 (like the symetry of side profile)			5e

7	8	9	10	11			Favorite	out of
-flimsy -fragile -plates with holes -hind leg	+hind leg	+hind leg +organic +balance holes material			Chair 1	a	1	14%
+organic +sturdy +flowing	+simpel -asymetric	-nonsymetric +classic sitting				b	4	57%
-bulky -heavy +fatboy achtig +heeft wel wat	-volume -too big	-full -blob				c	2	29%
		-branches			Chair 2	a	2	29%
	+symetric +sleek	+legs start from middle				b	5	71%
+continuous lines +organic	-blunt	+large hole behind -not sleek			Chair 3	a	3	43%
+symetric +leaner -large plate	-blunt +sleeker	-elephant association -angry eyes +flowing line				b	4	57%
-elephant trunk association -mixed thick and thin beams	-fat legs	-nonsymetric +organic			Chair 4	a	4	57%
+order in structure +uniform +coherant	+order +thin legs +hind legs simpeler	-trunk association -pumpkinmouth (grill)				b	3	43%
+classic chair +typical	+simple +small	-bit boring +beautiful +simpel +typical -not strong +thin +easy to store			Chair 5	a	5	71%
+light weight +balance	-busy -chaotic -complex	-creepy +uneven				b	2	29%
-bulky -solid -clay blob	-fat -blunt -too much material -not efficient	-ugly -angry elephant assiciation -fat				c	0	0%
					Chair 6	a	4	57%
+looks like nek vertibray -plates -connection						b	3	43%
6	4	4			Chair 7			

Participant		1		2		3	4		5	6
Bikerack 1	a	-fragil -weak					+elegant, +less material, +round beams		-fragile	
	b	-fat		+clean, +modern, +solid			+balance		+curvy +organic	
	c	+very beautiful +the flat look		-showy			-flat beams		-bulky -heavy -too much material	
Bikerack 2	a						+balance void, +symetry		+beautiful +clean +elegant -non symetric	
	b	-too much material -ugly		-too crazy -not logical -not symetric -too much material			-plane with holes.		-too much matterial -unefficient -nonsymetric -no repeting elements -messy	
Bikerack 3	a			-unnecessary hole			+less material		+straight lines +composition beams	
	b	+nice +flat +cool/tough		+cleaner			-busy, -more complex			
Bikerack 4	a								-messy	
	b	-straight beams + V-shape is cleaner		-less logical force distribution - less exciting			+simpler, +parralel lines		+order +right angles +repeting elements	
Bikerack 5	a	+chique	mid	+Looks right	typical		+typicallity, +clean, +balance void/solid		-not stable -spaghetti	
	b	more normal	typical		novel		+balance void/solid	mid	+stable +clay like	
	c	+graceful -but ugly	novel	+right side -left side -nonsymetric	mid		+funny, +cool, +organic tree like, +balance void/solid	novel	+novel (different) +futuristic +new +efficient matial use	
Bikerack 6		-Looks like tree					+symetry, +balance, +less complex		+sturdy	
	b	+Flat beams +Looks less like tree		+stronger			-too much material, +solid		+sturdy -organic	
Bikerack 7		8th		9			3		11	

7	8		9		10	11				
	+simple +efficient matterial use		+sleek +minimalistic +typical		-fragile	-outdated	Bikerack 1	a	3	38%
	-fat				+elegant +balance solid/weight +organic	+sturdy +rbust +flowing lines +tree branches		b	4	50%
	-fat -extra beams (inefficient use)		-wierd -nonsymetric		-too heavy	-flat		c	1	13%
	+symetry		+symetric +diagonal line		+recognisable as bike rack +organic +balance void/solid	+symetric	Bikerack 2	a	7	88%
	organic -plates -nonuniform sides -nonsymetric		+panther stripes -nonsymetric +music note association		-heavy +organic -no balance void/solid	-failed -too much redundant material -non symetric -unlogical -bumpy		b	1	13%
			-fragil -small holes -unbalanced void/solid +continuing line				Bikerack 3	a	2	25%
	+symetric		+symery +flowing line +continuing line		+symetry	+symetric= visually nice and logical force distribution wise		b	6	75%
	-nonsymetric +better designed +stronger				+more naturelike +combination straigt and diagonal		Bikerack 4	a	5	63%
	-parralel beams		+straighter +sleeker		-boring	-form language inconsistent (organic+squares) -squares makes it look		b	3	38%
	+simple	typical	+thin +simpel +sleek		-boring	-too thin -fragile -unsymetric	Bikerack 5	a	4	50%
			-organic -busy		+interesting to look at +crossing lines +more interaction between beams			b	2	25%
	+unique +simpel +few beams		+music note association +tall +sleek +nonsymetric +uniform thickness		+treelike -less balance -not recognisable as bike rack +treelike doesnt fit the function	-wierd connection		c	2	25%
	+simpel +uniform thickness		+simpler +balance thickness beams		+lighter construction +right amount of material (not too little not too much)	+balance	Bikerack 6	a	5	63%
	-inefficient material use +non uniform thickness		+jungle +jaguar -small hole			-chewinggum -flat -messy -oddly distributed compartements -variation in		b	3	38%
	3		3		5 or 9	7 of 2	Bikerack 7			

Participant		1	2	3	4	5
Bookshelf 1	a	+lean		-thin, -akward, -tentacles	+thin, +symetry	-lean
	b	+more balance -too busy		+solid, +efficient, +high tech ingineering	+symetry	-lumpy
	c	-ugly -bulky -coarse	+most novel +could be made by nature	-big, -tree	-dik	-messy -lumpy
Bookshelf 2		-tree-like -chaotic	+calmer		+organic	+sturdy
	b	+more symetric	-'grill' at front bothers me	-eyes, delicate, +sharper profile	-skelet, -engig	+grill +symetric +nack legs in order
Bookshelf 3	a			+edges better		
	b	+balance +softer +rounder +leaner beams	+smoother +symetric +'pelvis of woman'	+overall body	+symetric, +slicker	+symetric +leaner +sturdy +sharper
Bookshelf 4	a		+least ugly -nonsymetric +stable	-alien like, -organic	-bone like	+elegant +lightweight +sturdy
	b	+ Symetric +clear shape +more to the point +more unity	-grill	+looks like engine block, +looks like something you screw bolts into, +engineerd	+symetry, +unity	-boorish -too much material -plates (platte vlakken)
				(a= grown, vs b=engineerd)		
Bookshelf 5	a	+calm +flowing +typical	typical +'I want to handle the shape, it is inviting to handle'.	-ice cave	+symetry, +simpel, smooth, easier to understand	+less beams +round
	b		mid - heavy -boring	+least worse	-back legs are different	+thickness of beams +round
	c		novel + also interesting -fragile	-bumby, - asymetric	-not smooth	-no order -messy
				hate them all'		
Bookshelf 6		-looks like fingers -bone-like -horror movie	-fragile	-fragile, -low quality	+more simpel, -bare/hollow	-unlogical thichness
	b	+balanced	+more interesting +more too see	+complex, + more too look at, interesting, +superior	+fuller, +balance void/solid	+order +symetry +complex
Bookshelf 7		6	6	2-4-5		6

6	7	8	9	10	11				
-scary -earie	+flowing -simple +balance	-skinny -fragile	+thin +logical +functinal	-nonsymetric -eerie -restless	-thin +maybe elegant if it is strong enough -feels fragile -not in proportion	Bookshelf 1	a	3	27%
-scary -earie -individual small beams	+blance -right angle	+volume +body +interesting		-nonsymetric -restless +thickness is good			b	4	36%
+least scary +more unity	+flowing +wavelike -too busy	-solid whole	-organic -fat	+more symetric +recognisable shape(tree) -restless -chaotic -solid block	+logical flow +tree roots +expected shape for function +familiar form (tree roots)		c	4	36%
			like star wars	*voldemort vibe*	*Alien vibes*				
-shit "both shit"	+flowing +calm +organic	+volume	+flowing table -organic	+balance +organic +grows gradually to all corners	-shape/function connection unclearer	Bookshelf 2	a	6	55%
-shit -starwars -'spaceship from plant planet -engineblock -	+automotive +grill/manifold +engineering +order +human+computer	+volume but lean +symetric	+minimalistic +symetric +hides mounting holes +half a circel +rounding	-concentrated mass	+form follows function		b	5	45%
		+looks engineerd							
-non symetric	-symetry				-wiry(pezig)	Bookshelf 3	a	0	0%
+nice branching +symetry +clean	+flowing +symetry	+symetry	+sleeker +symetric +logical	+symetric	+smooth		b	11	100%
-no symetry -less order -proportion	-wierd -nonsymetric	+organic -nonsymetric	+thinner +minimalistic +less matterial	+tree branches +could look hours at it +non symetric +negative space in combination	-unlogical(form/function)	Bookshelf 4	a	3	27%
+symetric +proportions	+funky	+symetric	+symetric +sturdy +recurring order +combination organic and sleek design	+symetry -less organic -restless -solid block	+symetric +form/function more logical		b	8	73%
+symetric +no wierd corners +smooth	+solid +flowing +smooth +organic +'young'	"young" +simpel +uniform thickness +organic +peacefull +slightly asymetric	-alien -ugly	-uninteresting	+unexpectedly beautiful +smooth +simpel	Bookshelf 5	a	9	82%
-non symetric	+nice	+mostly symetric		-uninteresting	-extra(unnescesary)divergance		b	1	9%
-non symetric +thick branches +continuing line +refined +tought through	-unpleasant -old -wrinkly -bones-like *Likes organic when it is more smooth flowing rather than bone-like and*	"old" -asymetric -wierd -nonuniform thickness		-monster +most interesting	-bumpy		c	1	9%
-non symetric	-unpleasant -no coherance	+simpel -nonsymetric	+fewer sprites +simpler	-eerie -ugly	-not nice -restless -bumpy	Bookshelf 6	a	1	9%
+symetric +sophisticated +bracing	+swamplike(funny) -unpleasant -too much beams -busy +coherance	-too many branchin -chaotic +body +volume	-too much -busy -treelike +clean +eerie	+intersting -eerie +dark forrest	-not nice +smoother -too many branches		b	10	91%
both not nice				i'd like it als an art object, intersting too look at object'					
6	6	6	3	Laatste *I find some of these things interesting, but more a an art piece"*	6 for simplicity, 5 for function *Alien vibes*	Bookshelf 7			

8.4. Appendix D – Results User study 2

2

AB - Answer the following questions (AB)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	4.53	2.06	4.25	43	195.00
Unity: Which design is more orderly/unified?	1.00	6.00	2.56	1.40	1.97	43	110.00
Variety: Which design conveys more variety/diversity?	2.00	7.00	5.56	1.28	1.64	43	239.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	7.00	2.47	1.25	1.55	43	106.00
Novelty: Which design is more novel/original?	1.00	7.00	5.02	1.59	2.53	43	216.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	3.51	1.82	3.32	43	151.00

CD - Answer the following questions (CD)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.27	2.17	4.73	45	147.00
Unity: Which design is more orderly/unified?	1.00	6.00	2.27	1.25	1.57	45	102.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	5.02	1.61	2.60	45	226.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	6.00	2.76	1.38	1.92	45	124.00
Novelty: Which design is more novel/original?	1.00	7.00	4.82	1.65	2.72	45	217.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	3.53	1.54	2.38	45	159.00

EF - Answer the following questions (EF)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.64	1.98	3.91	44	160.00
Unity: Which design is more orderly/unified?	1.00	7.00	2.34	1.46	2.13	44	103.00
Variety: Which design conveys more variety/diversity?	2.00	7.00	5.52	1.16	1.34	44	243.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	7.00	2.48	1.34	1.79	44	109.00
Novelty: Which design is more novel/original?	1.00	7.00	5.16	1.51	2.27	44	227.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	6.00	3.30	1.56	2.44	44	145.00

GH - Answer the following questions (GH)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	2.77	1.69	2.84	48	133.00
Unity: Which design is more orderly/unified?	1.00	6.00	2.94	1.55	2.39	48	141.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	4.65	1.44	2.06	48	223.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	6.00	3.17	1.34	1.81	48	152.00
Novelty: Which design is more novel/original?	1.00	7.00	4.52	1.44	2.08	48	217.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	2.00	7.00	4.31	1.42	2.01	48	207.00

IJ - Answer the following questions (IJ)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	6.00	2.09	1.53	2.33	47	98.00
Unity: Which design is more orderly/unified?	1.00	6.00	1.96	1.09	1.19	47	92.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	5.04	1.69	2.85	47	237.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	6.00	2.34	1.21	1.46	47	110.00
Novelty: Which design is more novel/original?	1.00	7.00	4.62	1.64	2.70	47	217.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	3.21	1.83	3.36	47	151.00

KL - Answer the following questions (KL)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.18	2.07	4.27	49	156.00
Unity: Which design is more orderly/unified?	1.00	7.00	4.10	1.83	3.36	49	201.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	3.14	1.62	2.61	49	154.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	7.00	4.27	1.54	2.36	49	209.00
Novelty: Which design is more novel/original?	1.00	6.00	3.35	1.61	2.59	49	164.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	6.00	3.08	1.66	2.77	49	151.00

MN - Answer the following questions (MN)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.92	2.06	4.24	37	145.00
Unity: Which design is more orderly/unified?	1.00	6.00	2.78	1.47	2.17	37	103.00
Variety: Which design conveys more variety/diversity?	2.00	7.00	5.11	1.29	1.66	37	189.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	6.00	2.97	1.38	1.92	37	110.00
Novelty: Which design is more novel/original?	1.00	7.00	4.68	1.63	2.65	37	173.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	3.49	1.55	2.41	37	129.00

OP - Answer the following questions (OP)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.10	1.93	3.72	48	149.00
Unity: Which design is more orderly/unified?	1.00	7.00	4.13	1.86	3.44	48	198.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	3.88	1.75	3.07	48	186.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	7.00	4.65	1.42	2.02	48	223.00
Novelty: Which design is more novel/original?	1.00	6.00	3.54	1.43	2.04	48	170.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	2.00	7.00	5.13	1.54	2.36	48	246.00

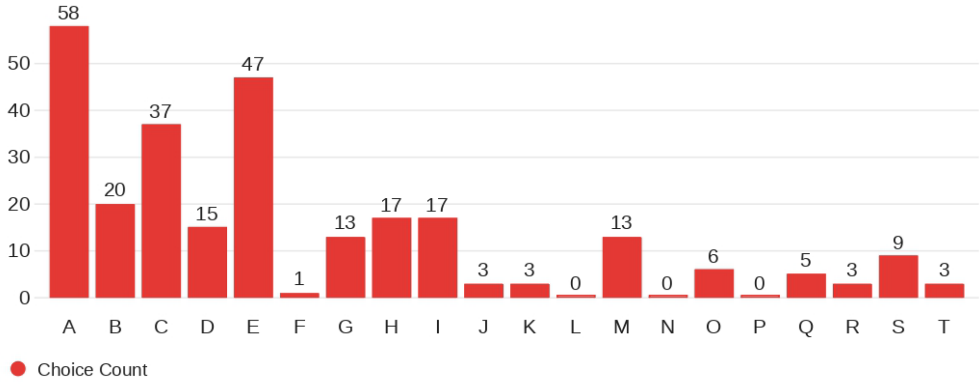
QR - Answer the following questions (QR)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	7.00	3.88	2.15	4.61	43	167.00
Unity: Which design is more orderly/unified?	1.00	7.00	2.67	1.44	2.08	43	115.00
Variety: Which design conveys more variety/diversity?	1.00	7.00	5.30	1.21	1.47	43	228.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	7.00	3.21	1.44	2.07	43	138.00
Novelty: Which design is more novel/original?	1.00	7.00	4.65	1.70	2.88	43	200.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	4.21	1.65	2.72	43	181.00

ST - Answer the following questions (ST)

Field	Min	Max	Mean	Standard Deviation	Variance	Responses	Sum
Beauty: Which design do you find more beautiful?	1.00	6.00	2.78	1.57	2.47	46	128.00
Unity: Which design is more orderly/unified?	1.00	6.00	2.83	1.32	1.75	46	130.00
Variety: Which design conveys more variety/diversity?	4.00	7.00	5.30	0.93	0.86	46	244.00
Typicality: Which design is more typical/normal for this kind of product?	1.00	6.00	2.76	1.29	1.66	46	127.00
Novelty: Which design is more novel/original?	2.00	7.00	5.00	1.30	1.70	46	230.00
Logic: In which design is the load-bearing structure more logical/makes more sense from a mechanical perspective?	1.00	7.00	3.89	1.56	2.44	46	179.00

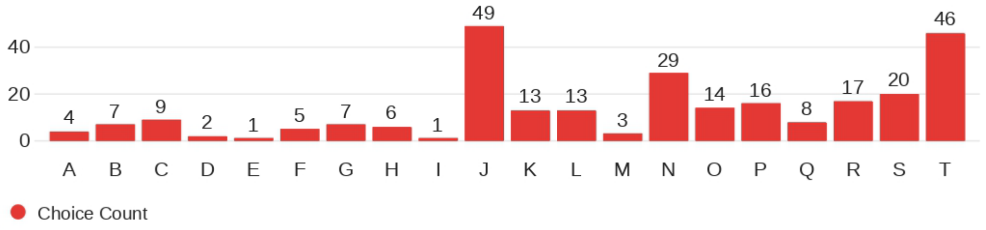
Prefered unity answe - Choose top 3 most unified/orderly designs.



Prefered unity com - Room for additional comments

Room for additional comments
I don't really know what is meant by orderly or unified, but I interpreted it as having a pattern of some sort.
symmetrical
Symmetry
No intricate shapes to distract you, the simple design would give more of an structured and easy to look at shelf holder
Not much is going on in these designs. Therefore more unified
simple one form or symmetrical properties

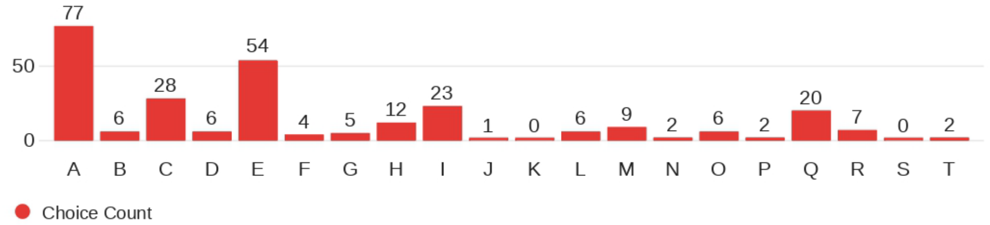
prefered variety ans - Choose top 3 most varied/diverse designs.



prefered variety com - Room for additional comments

Room for additional comments
Asymmetry helps with being novel, however it may suggest weakness to a consumer. Though the design of the slim arms remind me of a living organism like tree roots or myselium
You should have given a definition for diverse before starting the questionaire
More legs, more diverse, also asymmetric is more diverse I think
A lot of smaller sections instead of a sturdy one look more diverse
Irregular shape, irregular load bearing or amount of beams determine varied/diverse designs for me
This answer is very hard to give without context or a baseline So disregard my input here

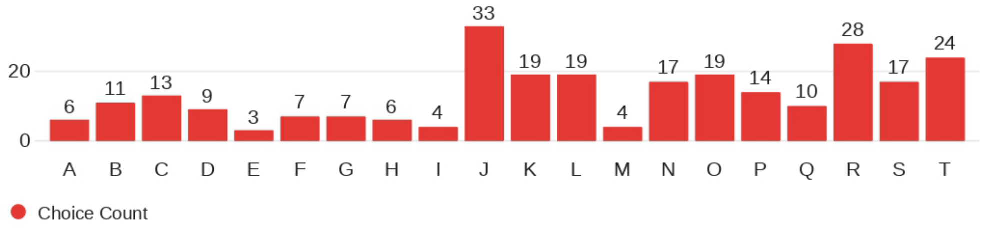
Typicality ans - Choose top 3 most typical/normal designs.



Typicality com - Room for additional comments

Room for additional comments
Anything robust and symmetric feels more normal, particularly with mounting in the center
looks most like typical shelf
None
Hoi Jesse! Gr. Sef!
Simple shapes and thick arms and no holes suggest to my simplicity compared to the contenders. You could convince me that A and E are already available in the Ikea for sale
They're all quite atypical
Sturdy and symmetric sounds more typical
symmetrical shape, relatively inorganic shapes
Same as the statement on the diverse/novel question
Hard to answer without a baseline
Most simple

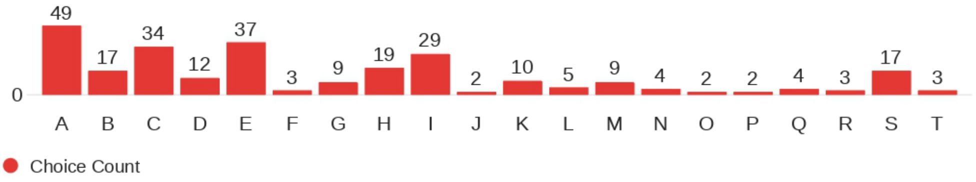
novelty ans - Choose top 3 most novel/original designs.



novelty com - Room for additional comments

Room for additional comments
Q and R are effectively identical to me in this aspect
very diverse
Interesting new shapes that I would consider to use, O specifically would go great with a shelf that holds some plants. Although the asymmetry of O would be great if sold in a mirrored pair so the shelf itself would still enjoy symmetry
They are all very similar
I like how the legs have different heights, like a tree
Asymmetric designs are in my opinion more uncommon and therefore original

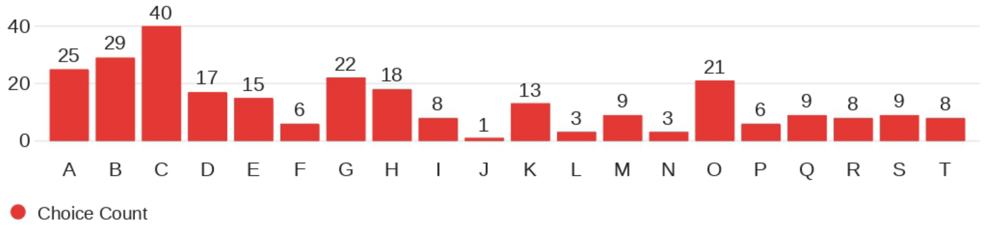
preferred logic ans - Choose top 3 most logical designs from a mechanical perspective



preferred logic com - Room for additional comments

Room for additional comments
I don't have a mechanical background, so I can't answer this question.
Ik heb de eerste pagina niet gezien. Maar volgens mij moet het een boekenplank zijn. Doordat er is gekozen voor een witte kleur in de 3D objecten, Ipv bijvoorbeeld de plank een bepaalde kleur en het ophangmechanisme in een andere kleur, vond ik het erg lijken op een soort skeletachtig object. Waardoor ik geneigd was vrijwel alle objecten niet aantrekkelijk/mooi te vinden. Succes met de opdracht!
simple use of the triangles with not too much pezaz
It looks structurally sound and without intricate structures that would "divert" from the objective of holding a shelf.
The bending moment from the shelfload, results in compressive forces in the bottom. A wider bottom with more bolts and area is therefore considered more stable. You need 2 bolts to reduce torsion. Asymmetric designs are definitely worse.
I find that my replies on aesthetic quality mainly rely on symmetry.
amount and placement of screw holes

aesthetics ans - Choose 3 aesthetically preferred designs.



aesthetics com - Room for additional comments

Room for additional comments
I quite enjoy O and P, reminiscent of mushrooms growing on trees in nature
L and Q are almost art like objects, what makes it aesthetically interesting.
A would be greatly preferred in a office setting where I'd enjoy an easy and orderly setting. However B and O would be preferred in a more homely setting where distractions and interesting shapes are more in place
The asymmetry makes it more playful. Also not too bulky like A or E and not too chaotic like K and T
Symmetry is the way to go in my opinion

Select a Source

8.5. Appendix E – Pearson Correlations User study 2

Pair:		AB		CD		EF		GH		IJ	
		r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
Pearson	Beauty - unity	0,16	0,299	0,63	0,000	0,59	0,000	0,47	0,001	0,63	0,000
	Beauty-Variety	0,42	0,007	0,14	0,345	0,10	0,512	0,12	0,433	0,20	0,172
	Beauty-typicality	-0,33	0,029	0,59	0,000	0,39	0,009	0,16	0,265	0,64	0,000
	Beauty-Logic	0,30	0,047	0,26	0,090	0,23	0,127	0,31	0,033	0,27	0,062
	Unity-Variety	-0,10	0,552	0,11	0,484	0,02	0,921	-0,13	0,393	0,19	0,216
	Typicality-Novelty	-0,45	0,003	0,07	0,663	-0,03	0,870	0,08	0,592	0,17	0,262
	Unity-Logic	0,14	0,372	0,31	0,041	0,12	0,461	0,31	0,038	0,30	0,041
	Typicality-Logic	0,15	0,333	0,27	0,074	0,18	0,236	-0,04	0,796	0,29	0,045
Partial	Beauty-Unity(Variety)	0,22	0,161	0,63	0,000	0,60	0,000	0,50	0,001	0,61	0,000
	Beauty-Typicality(Novelty)	-0,21	0,204	0,59	0,000	0,41	0,008	0,15	0,350	0,63	0,000

Pair:		KL		MN		OP		QR		ST	
		r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
Pearson	Beauty - unity	0,37	0,008	0,25	0,131	0,41	0,004	0,42	0,006	0,52	0,000
	Beauty-Variety	0,02	0,914	0,15	0,389	-0,13	0,388	0,37	0,017	0,05	0,773
	Beauty-typicality	0,17	0,240	0,07	0,700	0,14	0,333	0,11	0,470	0,44	0,002
	Beauty-Logic	0,26	0,075	0,04	0,825	0,45	0,001	0,13	0,401	0,34	0,023
	Unity-Variety	-0,32	0,035	-0,60	0,000	-0,64	0,000	0,22	0,175	-0,12	0,459
	Typicality-Novelty	-0,28	0,061	-0,39	0,020	-0,12	0,440	-0,39	0,013	-0,35	0,025
	Unity-Logic	-0,02	0,916	0,33	0,046	0,45	0,002	0,31	0,047	0,35	0,022
	Typicality-Logic	0,01	0,959	0,31	0,064	0,46	0,001	0,38	0,011	0,15	0,323
Partial	Beauty-Unity(Variety)	0,40	0,007	0,43	0,008	0,43	0,004	0,37	0,017	0,53	0,000
	Beauty-Typicality(Novelty)	0,24	0,122	0,11	0,527	0,14	0,354	0,31	0,056	0,49	0,001

	Correlation	AVERAGE	P-value avg
	Beauty - unity	0,45	0,045
	Beauty-Variety	0,14	0,395
	Beauty-typicality	0,24	0,205
	Beauty-Logic	0,26	0,168
	Unity-Variety	-0,14	0,324
	Typicality-Novelty	-0,17	0,295
	Unity-Logic	0,26	0,199
	Typicality-Logic	0,22	0,284
Partial	Beauty-Unity(Variety)	0,47	0,020
	Beauty-Typicality(Novelty)	0,29	0,162