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Departamento de Comunicação e Arte e
Departamento de Engenharia Mecânica

Phelipe Calado de Souza Costa

Use of Topology Optimisation in Product Design and Development

Uso da Otimização Topológica no Design e Desenvolvimento de Produto

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia e Design de Produtos, realizada sob a orientação científica do Doutor João Alexandre Dias de Oliveira, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro, e do doutor João Nunes Sampaio, Professor Auxiliar Convidado do Departamento de Comunicação e Arte da Universidade de Aveiro,

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palavras-chave

Otimização Topológica, Metodologias de Design de Produtos, Biomimética, CAE.

resumo

A forma de se projetar produtos tem ganhado uma nova dimensão com o amadurecimento de conceitos e tecnologias como o Design Generativo e Otimização Topológica, Cloud Computing, Inteligência Artificial e Fabrico Aditivo. Este avanço, tem aberto espaço para se criar melhores e mais sofisticados produtos, que face a competitividade entre organizações, pode vir a ser num futuro próximo um critério competitivo quase que obrigatório.

Considerando esta janela de oportunidade para explorar o novo e levá-lo para a rotina no desenvolvimento de produtos, este trabalho de dissertação tem como objetivo, através de um estudo abrangente, explorar uma metodologia que possa servir como guia a profissionais de Design e/ou Engenharia que queiram entender como usar melhor ferramentas de otimização de produtos focada em otimização topológica através de métodos computacionais, de forma a compreender seus princípios básicos e como realizar um processamento de dados fiável. Um exemplo aplicado a um caso, assim como dificuldades e aprendizados obtidos. E por fim, uma análise crítica quanto as vantagens e desvantagens de se utilizar tais ferramentas.

Portanto, o foco neste estudo é explorar a Otimização Topológica em conjunto com a Biomimética e fornecer uma base de como estes conceitos podem ser aplicados no desenvolvimento de um produto.

keywords

Topology Optimisation, Product Design Methodologies, Biomimicry, CAE.

abstract

The way to design products has won a new dimension with ripening of concepts such as Generative Design and Topology Optimisation, Cloud Computing, Artificial Intelligence and Additive Manufacturing. This development has opened space for new ways to create better and more sophisticated products that, in the organisations' competitiveness, it can be in the near future a nearly mandatory competitive standard.

Whereas this opportunity window aims to explore the new and lead it to a product development routine, this dissertation has as goal, through a wide study, to explore a methodology that ought to serve as a guide for design and/or engineering professionals who would like to understand how to better use these concepts as a tool for products optimisation by computational methods. In order to understand its basic principles and how to perform a reliable data processing, an applied example for a case will also be shown as well as its difficulties and learnings obtained and, finally, a critical analysis of the advantages and disadvantages of using these tools.

Therefore, this study will have as focus to explore the Topology Optimisation along with Biomimicry and provide a basis on how to apply these concepts in the product development.

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CHAPTER 1

Introduction

1.

1.1. Introduction and Objectives

This dissertation has the aim to explore the concepts of Topology Optimisation (TO) and its application on product design and development, facing the current demand for optimised products. This exploration will focus on structural design. Since the TO will influence in the form of the product, the core question of this work is how to merge the design constraints and requirements with the TO results. Consequently, a new methodology will be presented and tested as a result of such exploration, and the conclusion discussed at the end as well as advantages and disadvantages found.

In short, the aims of this work are:

- Explore Topology Optimisation concepts and applications;
- Explore Biomimicry concepts and applications;
- Explore product design development methodologies;
- Create a new methodology to incorporate the Topology Optimisation as a drive of design process;
- Test the methodology with practical case;

1.2. Methods

First, information about the current state of TO will be collected and its constraints, challenges and opportunities identified. After, a more in-depth exploration of TO and biomimicry concepts will be presented in two chapters. Finally, current principles for design and development of product shapes will be analysed by both its constraints and its requirements. So, a new methodology of application of TO on product design processes will be presented. To test this new methodology, a practical case will be performed and validated, by having a critical analysis of main challenges (Figure 1).

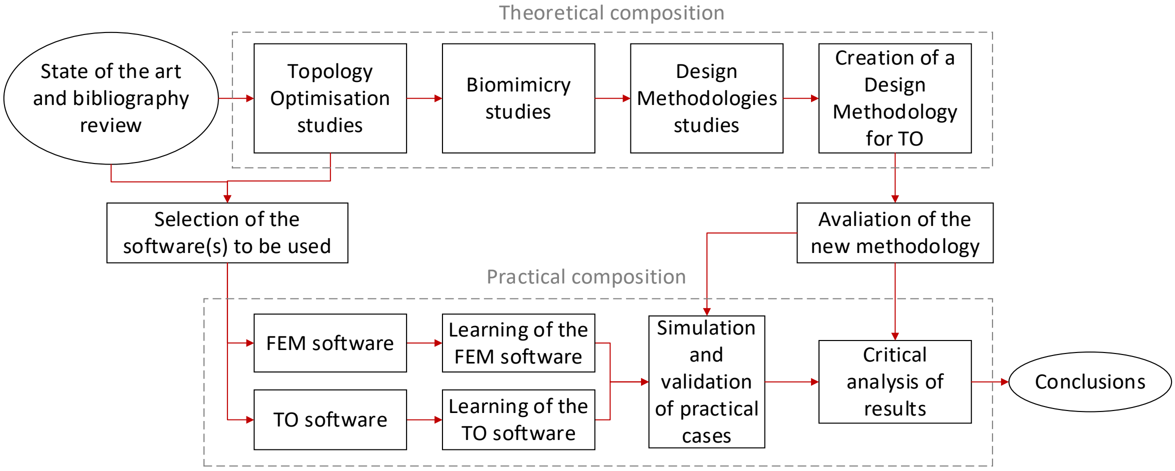

Figure 1 - Dissertation planning.

1.3. A New Frontier to Design and Develop Products

1.3.1. Definitions and General Concepts

1.3.1.1. Design

Design as science (or art), has a wide definition that can be understood by different means. This word comes from Latin *designare*, that means to define, to describe, or to mark out (Erlhoff & Marshall, 2008). Some authors and institutions have their own design definition: “Design is what links creativity and innovation. It shapes ideas to become practical and attractive propositions for users or customers. Design may be described as creativity deployed to a specific end” – Sir George Cox

(McLoughlin & Sabir, 2017, p.175). “Design is the method of putting form and content together. Design, just as art, has multiple definitions; there is no single definition. Design can be art. Design can be aesthetics. Design is so simple, that's why it is so complicated” – Paul Rand (Maeda, 1996). “A plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made” (oxforddictionaries, n.d.).

In this dissertation, the concept of Design will be applied in the product creation field, where the meaning will be: the entire process necessary to create a tangible product to the market, involving all requirements for the adequate human use and respecting natural sciences constraints.

It means that the creation of a product is a multidisciplinary task, involving art, sociology, history, economy, psychology, marketing, engineering, biology, chemist, physics and others.

1.3.1.2. Generative Design and Topology Optimisation

Generative design is a method in which the concept is getting from a computational algorithm, in which constrains data are inputted (manually or automated). The algorithms will explore several possible results which can better satisfy the requirements of the projects. Some iterations could be done from previous selection, and new results will be created until the final concept is reached. Some advantages of using generative design are the massive number of possibilities created quickly (in comparison with the capacity of human creation) and to obtain complex and disruptive forms, difficult to be imagined before. Topology optimisation aims to create an optimal material distribution adding or removing material into a geometrical domain, satisficing input constraints (more about TO will be discussed in Chapter 2).

1.3.1.3. Computer Aided Engineering and Finite Elements Method

Computer Aided Engineering (CAE) is the use of computational programs for engineering analysis and simulation. Finite Elements Method (FEM) is one of the tools used at CAE domain, in which forms are transformed in a mesh composed of nodes and elements, in a finite quantity. Each node and element have its behaviour well defined from physical principles and calculated through differential equations.

1.3.2. Biomimicry

Biomimicry is the imitation, inspiration or learning from natural biological designs or processes to find solutions to human problems and necessities, considering that the solutions created by nature are sustainable, optimised and reliable due to the gradual evolution and natural selection (more about Biomimicry will be discussed in chapter 3).

1.3.3. Current Context

A while ago, designers and engineers started using the computer to product design as a passive tool, in which solution options were limited by generation capacity of these professionals. However, a new way to work is arising through the 4.0 Industry, in a way that the computing starts to have active participation with the designer in solutions searching through several possibilities created by software algorithms combined with boundary condition constraints, created by the designer. This range of possible options allows finding optimal solutions that would be impossible to be deduced without these tools (Canaltech, 2016).

In recent TED essay (Conti, 2017), it is also defended that the way to work is entering in a new era, called of Augmented Era, in which artificial intelligence algorithms will start to work together with engineering and designers in an active way in searching for complex solutions, until then humanly impossible to be obtained. Such increase will enable the emergence of forms theretofore never imagined, as well as optimised for structure and performance, without penalising the form and semantic of product associated with the user. The generative design and topology optimisation are two examples that will be inserted into product development routine.

CAE design simulations, in which the main base is on FEM process, have been used by industries from decades ago, significantly supporting to obtain more reliable and efficient design with cost and time reduction. However, it has been mostly a passive tool that with the incorporation of new algorithms such as Topology Optimisation and Generative Design made possible due to the improvement of mathematical approaches, artificial intelligence, computing processing and cloud, will act now as an active tool to search optimised solutions, together with designers and engineers.

Therefore, the role of designers and engineers is now to be able to achieve better knowledge of computational tools available by acting through data introduction to boundary conditions and premises, either by physical or mathematical models or by data collection from sensors or Big Data, joining with the processing criteria, for later reading them after the presentation of multiple possible solutions that are given by software. In this situation, this will be the central human role - to read and select the relevance and applicability of the solution chosen. According to study disclosed by (World Economic Forum, 2016), the next five to ten years will be critical for the transition to the new production paradigm. Companies and countries that will not be able to adapt, have the risk of being left behind and have serious economic consequences. As a consequence and in order to get better results, in both design reliability and in economic resources, product development offices must include computational optimisation methods as well as more sophisticated in product design and engineering to stay competitive facing this new demand from the 4.0 industry.

1.4. Optimisation

1.4.1. Definition and Applications

Optimisation is a wide concept, which most people understand intuitively but cannot explain so easily. To define what optimisation is and how to get it, this dissertation will restrict this concept only for design and engineering of tangible products aimed to be launched in the market.

In this universe, there are several metrics to be considered, where these are chosen at initial steps of the product development, coming from various strategies such as Design Thinking, Double Diamond, Product Design Specification, Total Design Methodology etc. In this step are defined which of the metrics have more importance or weight, according to of the design targets chosen. Most of the metrics exist because the real world has restrictions such as cost, energy, material, time, environment etc. In a competitive market, continuous endeavour to make better and cheaper products is the only way to survive through the time. Another advantage of optimising products is that less material and energy are used to make or use them (less weight or less maintenance for instance), and this is good for the environment by the time that a change in production paradigm with reduction of resources is coming (Capra, 1982). In order to create improved, competitive and eco-friendly products, it is necessary to look for an optimised design.

To briefly summarise, in this case, optimisation can be understood as the best solution possible to satisfy all metrics selected for making a specific product design respecting the priority of these metrics.

1.4.2. Problem Optimisation Approach

Once the parameters to be considered for the product design are known (more about design parameters will be discussed in chapter 4), the second step is how to equate it to find the best region to work. This step is not an easy task on the case in which there are several variables in the project. Traditional methods like attempts and errors or trust on the designer's/engineer's experience, supported by empiric or parametric processes, is not enough to solve complex problems, which means several amounts of time and resources could be lost. The ideal approach should equate the problem in an analytical function, but in most engineering problems, it is not possible to be described, being necessary a numerical approach supported by a computerised routine and software (Paredes & ESSS, 2016). This condition, in which several quantities of variables and iterations are required, forces to look for computational algorithms as a tool for supporting in the search for the best solution in less time and resources. Numerous outputs values can be generated for each alteration in input values, creating a conjunct of possible solutions to be analysed. To support the search for the solution, it is essential to convert the problem into mathematical language. The formal description of an optimisation problem is to Maximise (or Minimise) desired functions and minimise (or Maximise) objective functions.

Examples of an objective functions are efficiency, cost, thermal exchange, friction, stress, natural frequency and others. Decision variables are all parameters that we have the freedom to change from objective function, for instance: materials, dimensions and form, operations conditions and another. Examples of constraints are standards, manufacturing, mass or volume, displacement, Tensile Yield Strength and another.

In a multi-objective optimisation problem, each function has an objective and in general, there is not only one solution that is optimum for all goals, once usually objectives are conflicting. In this case, increase the resolution of a function will necessarily decrease the resolution of other function (Pareto´s Optimal Boundary). Most of real-life problems are MOOP and to solve it, there is a conjunct of possible solutions.

In literature, there are several techniques to solve single and multi-objective optimisation problems. However, is not the goal of this dissertation discussing in depth some of the most commons methods.

Some commons solutions methods of optimisation problems are:

- Ant Colony Optimisation
- Direct-Search
- Elitist Non-Dominated Sorting Genetic Algorithms
- Genetic or Evolutionary Algorithm
- Gradient Methods
- Heuristics
- Interactive Optimisation
- Lagrangian Relaxation
- Mono/Multi-objective Particle Swarm Optimisation
- Neural Networks
- Pareto Optimal Boundary
- Swarm Intelligence

1.4.3. Structural Optimisation

Currently, it is common to divide structural optimisation into four types: Parametric or Dimensional Optimisation, Shape Optimisation, Topology Optimisation and Topographic Optimisation.

Parametric or Sizing Optimisation: Do not change the structural form, but only its dimensions (*Figure 2*)

Shape Optimisation: The external shape is altered. More possibilities can be generated in comparison to the parametric optimisation (Figure 3).

Topology Optimisation: The material is distributed for each domain point, changing internal and boundary geometry. This method is the one which can remove more material and make more possibilities (Figure 4).

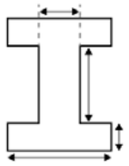

Figure 2 - Illustration of sizing optimisation.

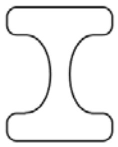

Figure 3 - Illustration of shape optimisation.

Figure 4 - Illustration of topology optimisation.

Topographic Optimisation: Applied to shell structures. It works mixing the concepts of parametric and topology optimisation (Figure 5).

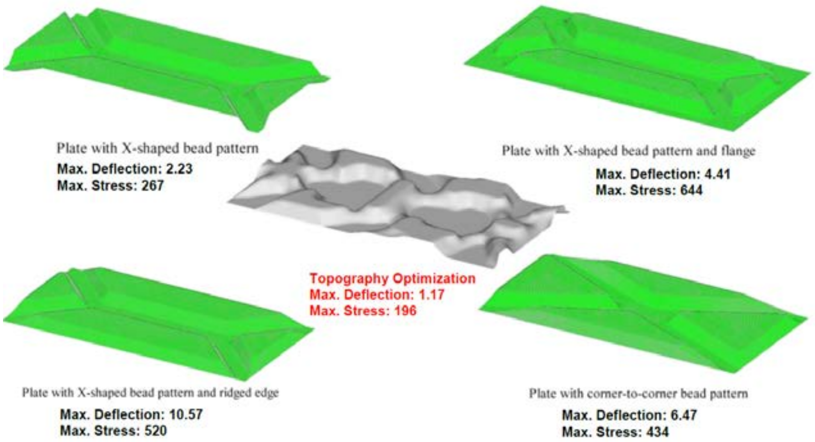

Figure 5 - Example of topography optimisation (Source: Altair).

1.5. Applications of the Topology Optimisation

A very clear statement of applications of the Topology Optimisation (TO) is cited next by two of the nowadays major specialists in TO:

> "Topology optimization gives answers to the fundamental engineering question: how to place material within a prescribed design domain in order to obtain the best structural performance? The concept was initiated for mechanical design problems but has spread to a wide range of other physical disciplines, including fluids, acoustics, electromagnetics, optics and combinations thereof. The method builds on repeated analysis and design update steps, mostly guided by gradient computation" (Sigmund & Maute, 2013, p. 1031)

Nowadays, it is possible to apply and potentially use the TO for instance in exploratory design (Figure 6), structural mechanics (Figure 7), medical (Figure 8), architecture (Figure 9), thermal (Figure 10), electromagnetism (Figure 11) and fluid dynamics (Figure 12). The TO applied is rather new, and some barriers are still on the way of this method's potential that is yet in development. Nevertheless, some market applications can already be found and these will keep increasing through the next years.

Figure 6 - Use of Topology Optimisation in exploratory design (Source: Marco Hemmerling).

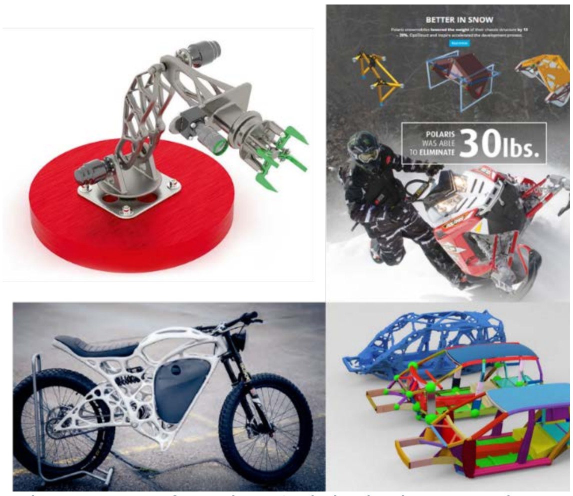

Figure 7 - Use of Topology Optimisation in structural mechanics (Source: Altair).

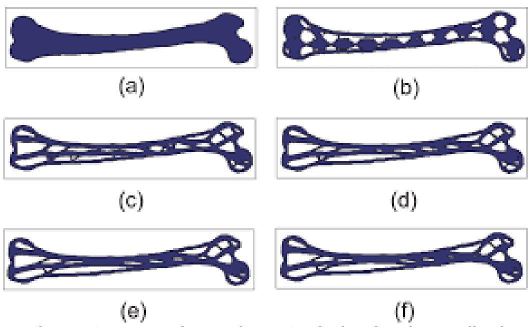

Figure 8 - Use of Topology Optimisation in medical (Source: ASME).

Figure 9 - Use of Topology Optimisation in architecture (Source: Altair).

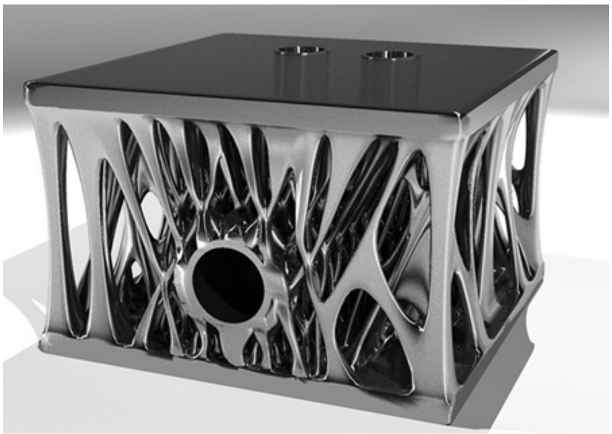

Figure 10 - Use of Topology Optimisation in thermal (Source: Autodesk).

Figure 11 - Use of Topology Optimisation in electromagnetism (Source: Autodesk).

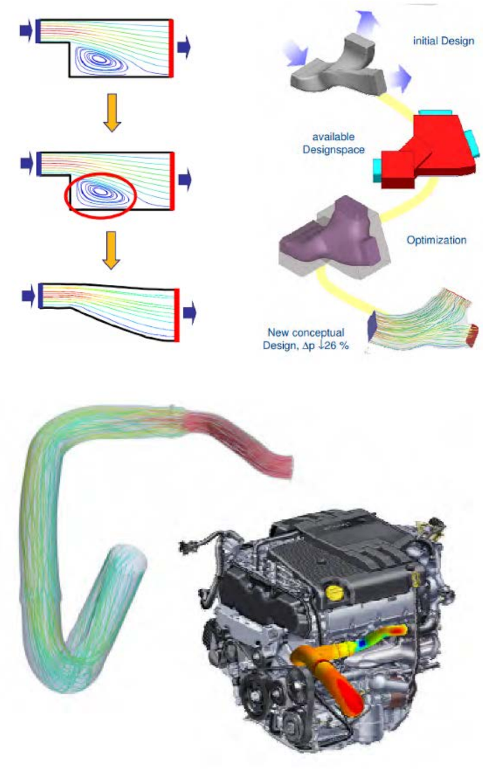

Figure 12 - Use of Topology Optimisation in fluid dynamics (Source: Tosca).

1.6. The Evolution of Topology Optimisation

In the 16th and 17th century, in his book *Discorsi e Dimonstrazioni Matematich,* Galileo Galilei introduced the first concepts about optimal forms of structural elements. He started to investigate a brittle fracture process, where the body's forms were designed considering local strengths (Figure 13).

Figure 13 - Galileo Galilei optimal forms studies. (Galilei, 1638)

Gottfried Wilhelm Leibniz´s (1646-1716) works introduced the basis of analytic procedure, and Leonard Euler´s (1707-1783) works, with the theory of extremes, could provide the basis for the calculus of variations development. Following Euler´s work contributions, Lagrange (1736-1813) and Hamilton (1805-1865) contributed in completing the variational calculus, which becomes the basis of several optimisations problems, once the theory of topology optimisation combines mechanics, variational calculus and mathematical programming (Johnsen, 2013).

Maxwell in 1870 (Maxwell, 1870), focused on civil engineering problems, proposed to design bridges with as little material as possible using the elasticity theory to find the ideal material distribution through principal stress field, towards the main stress. Since there is only normal stress, without shear, the optimal structure could be made of frame elements aligned with these stress directions. In 1904 Michell (Michell, 1904) continued Maxwell´ studies, to create optimal structures (Figure 14). In that time, Michell´ structures were considered very difficult to manufacture, and these become only a reference for academic studies. Currently, these structures can be used as an analytical benchmark for bi-dimensional topology optimisation problems when volume tends to zero (Rozvany, 1998).

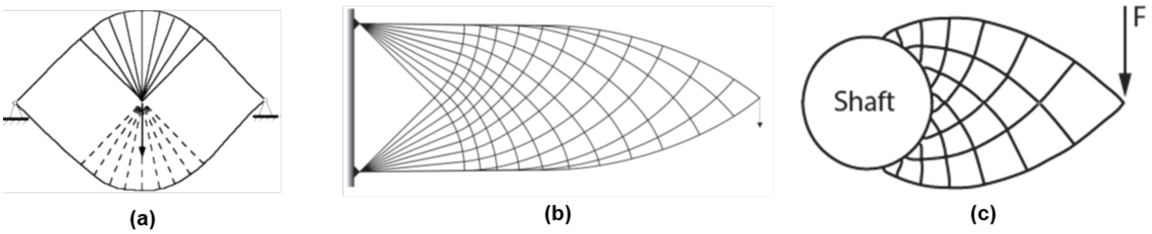

Figure 14 - (a), (b) Michell frame bridge structures. (c) Michell optimal crank structure. (Michell, 1904)

Some 70 years later, Rozvany and his research group, published papers extending Michell´s theory to beam systems (Rozvany, 1972a, 1972b). Based on these papers, Prager and Rozvany formulated the first general theory of topology optimisation, termed "optimal layout theory" (Prager & Rozvany, 1977).

In 1988, Bendsøe and Kikuchi proposed the homogenization method (Bendsøe & Kikuchi, 1988) that is considered a landmark for TO. Since this paper, this field attracted wide industrial and academic interest due to its massive potential in engineering applications and its intrinsic mathematical challenges. Several developments were made and many different mathematical methods and practical approaches have been observed: Density (Bendsøe, 1989; Mlejnek, 1992; Zhou & Rozvany, 1991) later renamed the base method to Solid Isotropic Microstructure with Penalization (Rozvany, Zhou, & Birker, 1992) and followed by Solid Isotropic Material with Penalization (SIMP) (Bendsøe & Sigmund, 2003). This method gained popularity and has received extensive research. Today SIMP is the standard approach method of the most of commercial TO software. One of the reasons for the success of this approach is the possibility of integration of manufacturing restrictions (Fiebig & Axmann, 2013). The Soft Kill Option (SKO) method (Baumgartner, Harzheim, & Mattheck, 1992), which, as a consequence, was inspired on biological growth rules of trees and bones, wherein highly stressed regions the material is added and in less stressed regions material is removed. Evolutionary approaches are another prominent example of structural optimisation methods (Xie & Steven, 1993). The Evolutionary Structural Optimization (ESO) is focused on removing unnecessary material from too conservatively designed parts. For ESO, it is only possible to remove material. Querin introduced the Additive Evolutionary Structural Optimization method (AESO) (Querin, Steven, & Xie, 2000). AESO adds material to areas in order to improve the structure. The combination of ESO and AESO leads to the Bidirectional Evolutionary Structural Optimization (BESO) method. The main idea behind ESO, AESO and BESO is to remove lowly stressed elements and add material to higher stressed regions (Fiebig & Axmann, 2013). Other approaches are topological derivative (Sokołowski & Zochowski, 1999), Level Set (Allaire, Jouve, & Toader, 2002, 2004; Wang, Wang, & Guo, 2003), Phase Field (Bourdin & Chambolle, 2003). Hybrid approaches have appeared, such as Level Set Method (LSM) which can use Shape Derivatives for design updates or Iso-Geometric Analysis (IGA) (Qian, 2013). Also, Filtered Density Fields used in recent projection techniques (Sigmund & Maute, 2013). In special, the IGA is a recent emerging technology. This method uses B-Splines and Non-Uniform B-Splines (NURBS) to describe the geometry, more common in CAD approaches, allowing to eliminate the gap between CAD and FEM to define the geometry (CAD and FEM describe the same geometry differently). With IGA, the CAD geometry is precisely and efficiently represented (different from FEM mesh, that is an approximation, most based on Lagrange polynomial) (Figure 15), allowing to simplify the analysis with a better approximation of properties and accuracy of solution, integration of design in CAD system (it is possible to use the same CAD models for structural analysis and optimization) and a faster refinement process, cutting short the time demanded for meshing the geometry at FEM. The combining of TO and IGA has the potential to generate an algorithm with faster convergence rate in comparison with the other hybrid approaches (Roodsarabi, Khatibinia, & Sarafrazi, 2016).

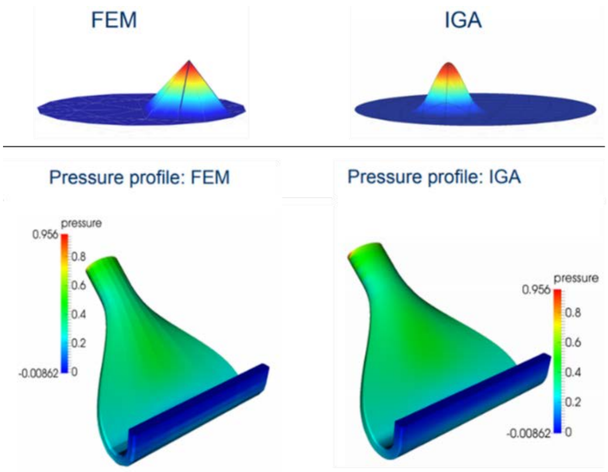

Figure 15 - Representation of differences between FEM and IGA. In IGA, the geometry is more smooth and accurate. Source: Terrific.

In recent years, with the progressive advances and maturing of methods and mathematical approaches, as well as the accessibility of computer processing power, the TO has been increasingly introduced in the industry, Industries including automotive, aerospace, heavy industry, energy, etc., can now take advantage of the successful development and promotion of topology optimisation packages from FEA commercial software providers, within CAD/CAE frameworks such as Optistruct-Hyperworks (Altair), Ansys, Simula-Abaqus (Dassault), Simula-Tosca (Dassault), Fusion 360 (Autodesk), Genesis (VR&D), Inspire (Solidthinking), MSC Nastran (MSCsoftware), Generate-NX (Frustum-Siemens), TopShape, VirtualPyxis, ToOptix-Blender (open Source), TopOpt (open Source), Z88Arion (freeware) and several others (Topology Optimization Guide, n.d.), or as its incorporation in several other CAD software SolidEdge (Siemens), Inventor (Autodesk), Nastran (Autodesk), SolidWorks (Dassault), Catia (Dassault) and several others.

1.7. Topology Optimisation Limitations and Future Expectations

Due to the free and organic forms that can be created by TO (Figure 16), some are often difficult to manufacture through traditional subtractive or formative manufacturing techniques. Thus an integration with manufacturing constraints must be considered for the feasibility of the geometry production. As an alternative to overcome this limitation, additive manufacturing[1] is a promising alternative.

According to Zhao, Li & Liu (2017):

> "…On the other hand, rapidly developing additive manufacturing technologies have the promise to overcome the barrier between the potentiality that the topology optimization approaches can provide and the limitations that traditional manufacturing technologies can

[1] The additive manufacturing is a process in which the material is deposited following some coordinate system, usually controlled by computer and typically layer by layer. It is also popularly called of 3d printing.

fabricate. In reality, additive manufacturing is a natural counterpart to topology optimization in that they have very versatile capability to quickly generate and realize new components not existing before… (p.1)

However, it is important to consider that the additive manufacturing has its limitations, such as the necessity of supporting material or anisotropic mechanical behaviour, depending on the technology used. Therefore, new constraints on algorithm must be applied to additive manufacturing seeing the good practices of DfAM[2]."

Figure 16 - Example of a complex structure to be manufactured, created by Topology Optimisation. Source: ARUP

Other limitations of the most commercial software are about the conversion of the final optimised results into useful continuous CAD geometries. When designers must create and smooth the resulting structure, it demands time (and cost), and features from optimised results may get lost, extra weight added, or even lose performance. When the software has smoothing algorithms, such as Laplace iterative smoothing, marching cube algorithm and the smoothing algorithm proposed by Wang and Wu, that it is a field still in improvement, some information from the optimised geometry could also get lost and mechanical behaviour influenced (Fiebig et al., 2015).

The benefits of adopting the TO in design process must be analysed in contrast to how much it is possible to save with weight/mass reduction or gain in performance and how much it is necessary to spend/invest to make feasible the solution found through CAD post-treatment and manufacturing process. But, if it would be necessary to compare all current limitations, make the geometry viable to manufacture is one of the most apropos.

As defended in recent years by Gu (2013):

"The manufacturing challenge prompts further thoughts on the use of Additive Manufacturing (AM) in order to retain much, if not all, of the original organic yet complex optimal topology. This emerging area of combining TO and AM is very promising for designing better… (p.2).

[2] DfAM means Design for Additive Manufacture. It is a conjunct of good practices to consider during designing some object with aim to achieve the best performance possible to additive manufacturing. DfAM is part of the DfX (Design for Excellence) methodologies.

…the integration of TO into the structural design process will be an area for continuous developments in the future (p.4).

…TO needs further integration with the manufacturing process in order to be able to fabricate the highest performing topology at reasonable cost (p.5).

Recent years have witnessed an increased variety of applicable conventional manufacturing constraints implemented in the commercial software, such as Member Size Control, Draw Directions, Extrusion Constraints, Pattern Repetition, Pattern Grouping implemented in OPTISTRUCT. However, these manufacturing constraints are still limited. They are also constrained by the simplified TO model that usually does not have finer meshes to count on small manufacturing features. To address this challenge, the commercial TO tools will keep improving and adding its manufacturing constraint capability (p.5).

… design and manufacturing, using modern information technology, would be integrated into one step, consistent with the modern trend of employing unitized structures" (p.6).

Despite the evolution of the mathematical formulation of TO over the last decade, there are still limitations on achieving practical solutions for most of the real-life engineering problems. Most of the commercials software do not have complete solutions to perform optimisation of nonlinearities, dynamics, crash, sheet structures, multi-physics interaction, fatigue, multi-scale and hybrid parts or material (Fiebig et al., 2015; Gu, 2013; Larsson, 2016). In these cases, it can be useful to combine the TO with other tools like Shape Optimisation, FEM, to get closer to the optimum solution for the problem. Moreover, with several mathematical approaches and methods in development, the unification and standardisation of methods and approach is a necessity. As defended by Sigmund & Maute (2013): "… the topology optimization community should reunite, get together in joint ventures in the search for the "optimal optimization approach" and in this process use standard benchmarks as well as insightful and expert-based comparisons between methods" (p.1050).

Since 2013, Rozvany has defended that, for industrial applications, the dominant preferences for the TO tools are: low CPU time, the generality of applicability, the simplicity of implementation, reliability and the simplicity of obtained topologies. These recommendations became the preference for methods and software development and state of the art for the main commercial tools (Gu, 2013).

For industry purposes, convergence to an integration of TO in CAD and CAE environments is a reality. The reasons for this are due to some benefits: all the functionalities and features within proved and reliable CAE solvers should also be accessible for the TO; the optimisation can utilise existing investments in hardware and software; make use of knowledge of the staff responsible for developing CAD and CAE. With these, the TO becomes an add-on module of commercial CAD and CAE solvers, as predicted in 2006 (Bendsøe, Olhof, & Sigmund, 2006).

Finally, in the product design engineering environment, to find the optimum balance between the form provided by TO and the form requirements from design, most of them intangibles and qualitative are still a challenge for designers and engineers and no softwares are provided with these constraints at all.

1.8. Topology Optimisation in Industrial Design and Hiatus

Currently, there is a continuous increase of demand on product design and development to reduce costs, energy into manufacturing and using, material to manufacture and disposed, and time to market; in other words, to optimise products. For product development and manufacture companies, optimise them projects is mandatory to survive in the market in long-term.

Traditional methods to find the optimum between cost and performance are not so efficient in general, such as attempt and error, designers and engineers experience, and gradual evolution of products on the market and benchmark. The problem of these approach methods is that numerous iterations are necessary to find the optimum solution, requiring a long time and higher cost to do it, and there is no guarantee that the solution found in fact is the best possible. Therefore, at this moment the TO is being acclaimed as the best alternative to do it (Brennan, 2014; Larsson, 2016; Sigmund & Maute, 2013). On the other hand, biomimicry has been an excellent alternative to find inspiration of concept (Figure 17, Figure 18, Figure 19, Figure 20). The evolutionary process of nature by natural selection had optimised along millions of years the design of living species. This evolution is what some TO algorithms do; they mimic the natural evolution, but only spending a couple of minutes to do it. It is not a coincidence that most of the forms generated by TO are organic and look like bones or other natural structures. Although biomimicry can give directions in the concept, the final form is far from optimal before several iterations, and it leaves us again to looking for TO. In chapters 2 and 3 TO algorithm and Biomimicry will be discussed respectively.

Figure 17 - Design created by Engineer Eiji Nakatsu inspired on a kingfisher bird to prevent the sonic boom of Japan´s 200-mph bullet train when emerging from a tunnel. Source: ASME.

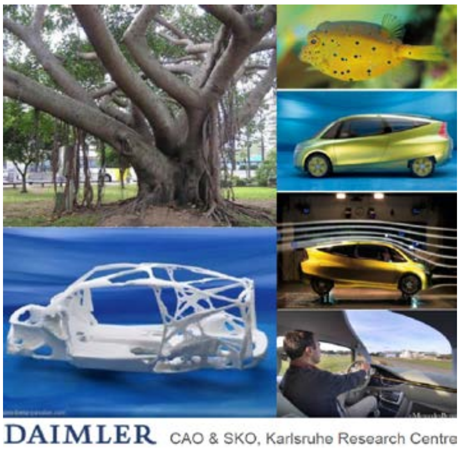

Figure 18 - The Bionic Car. Its aerodynamic was inspired by the boxfish, and its structure has been optimised by Soft Kill Option (SKO) method, which mimics the structure of trees and bones. Source: Daimler.

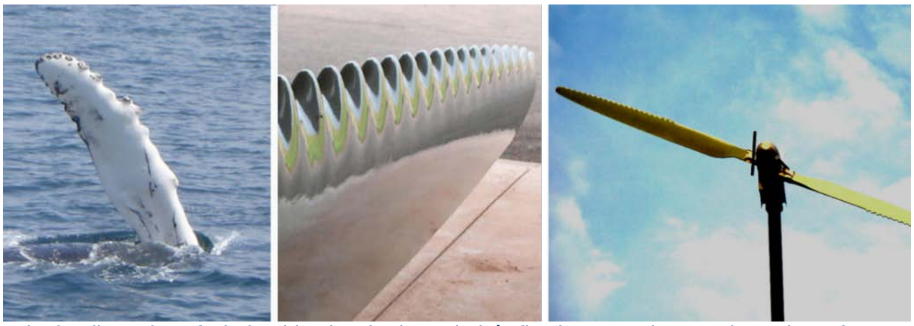

Figure 19 - The leading edge of wind turbine inspired on whale´s fins increase the aerodynamic performance. Source: WhalePower Corporation.

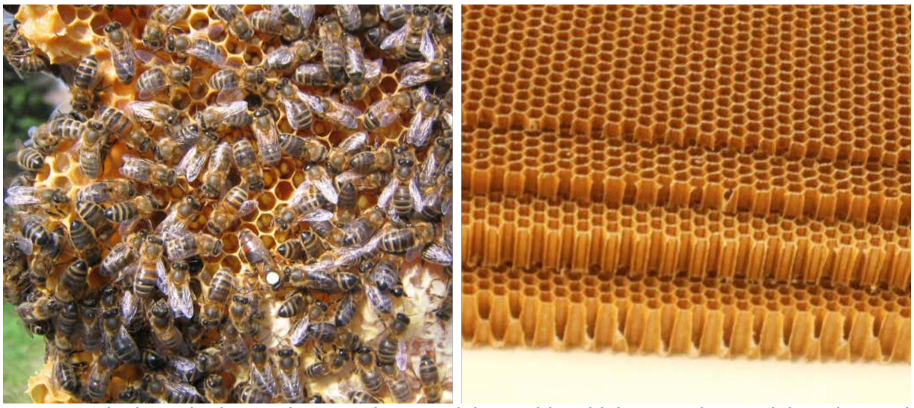

Figure 20 - Honeycomb shaped advanced composite materials provide a high strength-to-weight ratio. Inspired on bees nest cells that support heavyweights. Source: Asknature.

Another highlight is that the TO and additive manufacturing are opening a new way of products form and design when complex and organic forms with high performance will become easier and more feasible to produce. There is a strong possibility that in the next years, the dominant form and design concept around us will be made by organic forms created by TO or Generative Design. As the history of product design shown, the advances of manufacture, material and technologies are some of the main forces that drive how products look like (Figure 21).

Figure 21 - N-14 Thonet´s chair, launched in 1859 with the creation of steam-bending technology. This process allowed a mass and cheap production (composed of only six elements). Until 1930 more than 50 million of units have been sold and it has influenced profoundly chairs concepts (Thonet GmbH, 2015).

The TO is an active tool to find the best form; different from the FEM analysis that is more passive due to the fact that it needs a form preconceived, the TO is capable of leading the design process since the beginning of development. As defended by (Brennan, 2014): “It effectively puts the ‘function’ in front of the ‘form’ in the ‘form/function’ equation” In other words, adopting the TO makes it possible to merge engineering and design simultaneously in the process, as long as the function find the form. Moreover, many of the forms found are equally efficient among themselves, where it is necessary to pick only the one which is adequate for the design requirements (Figure 22). Another benefit of putting the TO in the beginning of the design process is the capacity of saving time and reduce cost avoiding concept changes due to the test phase of the design. However, these potential benefits are not so direct and certain, once the best-found form for application performance is not so easy to be manufactured, a post-treatment in CADit is required, increasing time and cost of development.

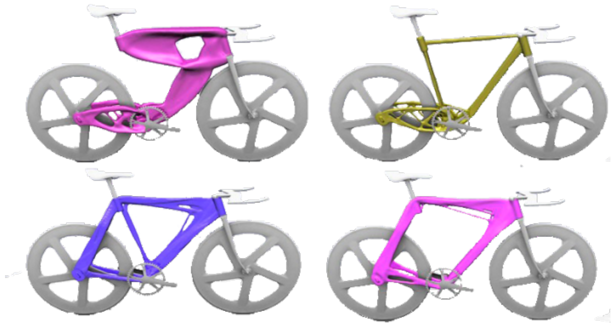

Figure 22 - Example of bicycle frames created by Topology Optimisation. All of them are structurally optimised, but the design requirements can eliminate some proposals. Source: Autodesk.

Gu (2013) discusses an attempt to compare and measure the gains with and without the use of TO (Figure 23). In the traditional process (a), the optimisation only comes in as a plus to add values. The physical test is the core of development to validate the simulation. Each arrow represents a manual step done by the engineers and designers. In the process with TO and shape/sizing (b), the box of TO intends to replace the box of concept proposal based on prior experience. If necessary, the step shape/sizing could be done autonomously. TO solves the problem from the most extensive possible design space and may generate a near-optimal concept to start designing with. This method avoids suboptimal concept that may be proposed based on prior experience. Subsequently avoids long and tedious design iterations and possible excessive weight/cost upon completion (Gu, 2013).

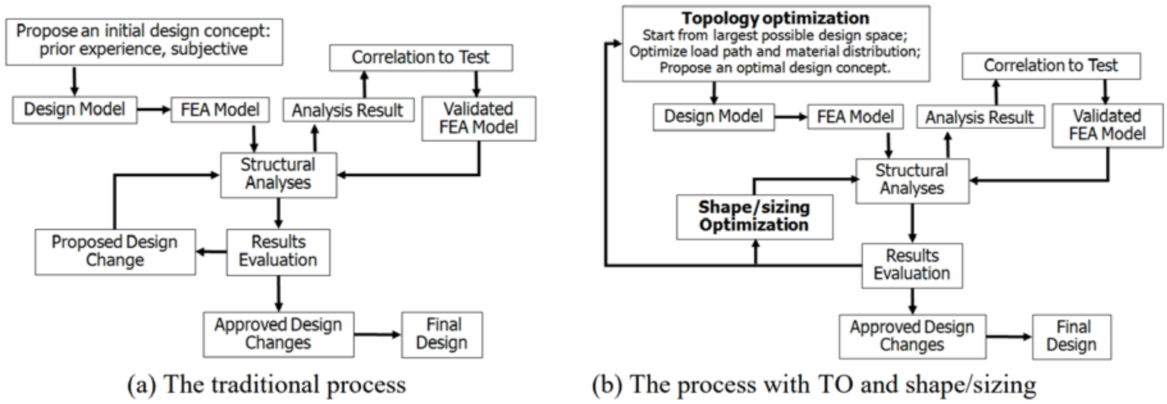

Figure 23 - Workflow using not the Topology Optimisation in the initial phase of development (a) and including the Topology Optimisation in the initial stage (b). (Gu, 2013).

However, in every company, in order to decide to replace an old method for a new one, it is necessary to somehow measure how much is gained if the old method is replaced. If on the one hand the adoption of TO in initial steps to concept design can save time and investments, on the other hand, the concept found could become a bottleneck for the analysis and process of the manufacturing, voiding all the savings obtained before. This dilemma is stronger when an unprecedented product will be designed, in which no data for comparison is available. Estimating the gains and penalties with TO until the design has been validated is still a hard task. As defended by Gu (2013), many publications of TO industrial application demonstrate the effectiveness of one TO concept but often lack of a systematic sensitivity study that can measure the real gains in comparison with traditional methods of designing. It is estimated that these studies will become a standard task to validate the TO concepts.

Finding the best form of a product is not only a matter of performance and cost to manufacture. The product design and development universe has many other variables. Many of these are intangible and not possible to incorporate into software as quantitative constraints. An evaluation of all constraints and an attempt to develop a methodology to merge all these with the use of the TO for product design and development is the main purpose and the challenge of this dissertation.

CHAPTER 2

Practical Aspects of Structural Topology Optimisation

"*The art of structure is where to put the holes"*
Robert Le Ricolais, 1894-1977

2.

2.1. Definition and Principles

2.1.1. Topology

Topology is the mathematical study of the properties of an unaltered geometry given by changes in the size or shape of geometric s under elastic deformations, as bending or stretching (Dictionary.com, n.d.; Oxford Dictionaries, n.d.), often called *rubber-sheet geometry* (Mohammed, 2004). In topology, a donut and a coffee cup with a handle are equivalent shapes, because each has a single hole (The American Heritage® Science Dictionary, n.d.) (Figure 24).

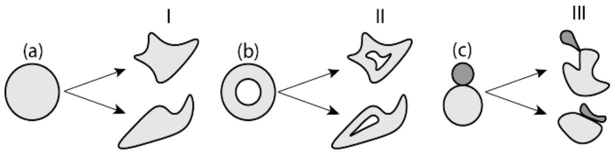

Figure 24 - The geometries (a), (b) and (c) have different topology. But, the geometries (I) created by (a), have the same topology. The same between (b) and (II), and the same between (c) and (III).

2.1.2. Topology Optimisation

Topology Optimisation (TO) is a technique with the purpose of generating a material distribution to better answer to an optimisation objective under some initial geometry boundaries and a set of constraints, being most of them, physical constraints. Different from Finit Elements Methods (FEM), that can be seen as a passive simulation tool, in which a previous geometry must be generated to perform the analysis, TO is an active tool, in the sense of it will create a geometry according to the design conditions so it can be analysed afterwards. The material is placed following the forces flow into the design space, allowing designers and engineers to identify the load paths in the part.

Basically, TO problems can be treated by shape optimisation (using Lagrangian with boundary following mesh) or as a density approach (using Eulerian with fixed mesh) (Sigmund & Maute, 2013). There is a large number of mathematical schemes to solve these problems. However, some of the most popular and well known approaches in literature and software will be discussed in the next paragraphs. In density approach, the TO solves a structural problem in which the design domain is initially discretised in *n* elements (defined as a discrete problem). The aim is to have the TO algorithm interactively decide, based on gradient information, where to place material and where to remove it in each cell created by the discretisation, to satisfy the objectives functions and to respect all constraints. During iterations, the solver searches for low-stress regions and place into that, elements with a lower equivalent density, to then analyse the behaviour of the remained structure. This discretisation is performed by FEM (Figure 25).

Approaches based on the idea of discretisation and selection of cells with or without material are called Element Based Methods (Dunning, Brampton, & Kim, 2015). This problem is mathematically formulated as a non-linear mixed 0-1 problem. Each element can have the material density 1 (material) or 0 (void). However, discrete problems are difficult and inefficient to solve and to contour this inconvenience, it is relaxed in which the amount of material in each element can continuously vary from 0 to 1 density, in which the intermediate density represents fictitious material. Being this the reason why this formulation is called for Density Approach. The material stiffness is considered as linearly dependent of the density (Altair University, 2015). Nevertheless, one problem with the Density Approach is that the solution at convergence often exhibits several grey-scale elements (intermediate density). Unless an advanced manufacturing process is used, such as Additive Manufacturing, capable of making infills volume with different fractions, the grey elements are not desirable to the most of common manufacturing processes that need a uniform density, such as moulding (Nobel-Jørgensen & Bærentzen, 2016). In order to have an approximate behaviour to the discrete problem and to reduce the occurrence of intermediate density elements, density values are induced to become 1 or 0. This is called Penalisation, and a value of penalisation factor is used to move these intermediate densities to the extremes (0 or 1). One of the most used methods is the Simplified Isotropic Material with Penalization (SIMP). SIMP can have variants, with an implementation of filters, bringing additional benefits, such as the elimination of checkerboard patterns for instance (Figure 26).

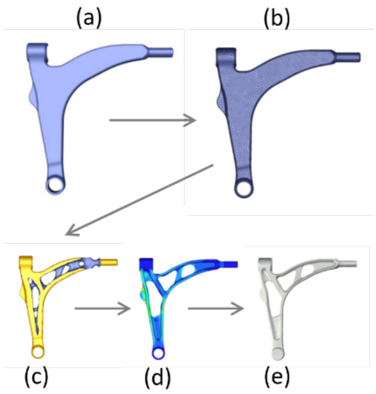

Figure 25 - Topology optimisation workflow. (a) first geometry boundary, (b) discretisation, (c) geometry generated by TO, (d) geometry treatment and FEM validation, (e) final part. Source: Dassault Systems.

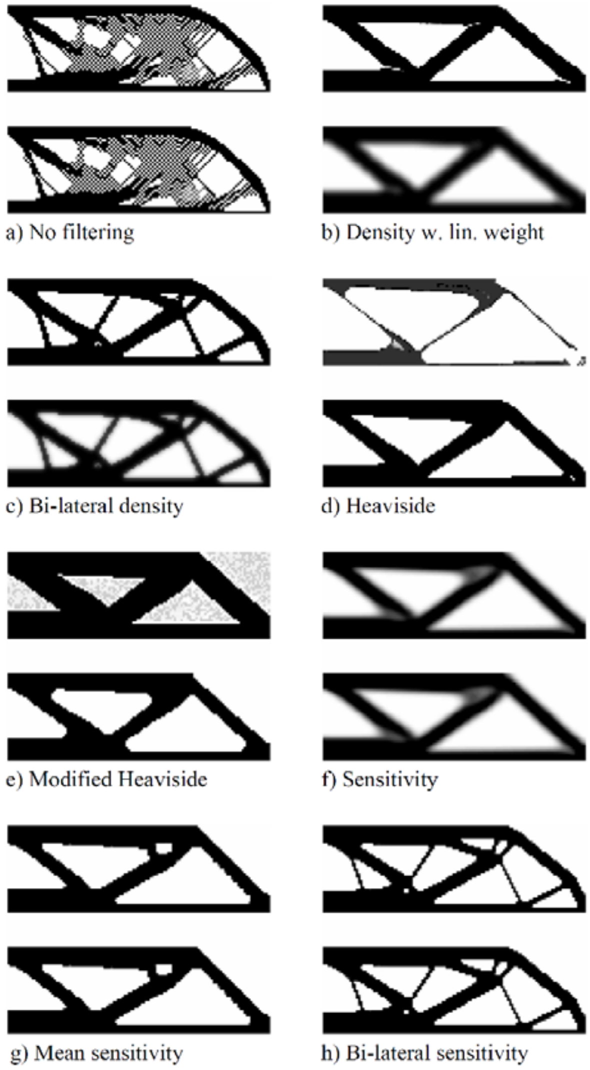

Figure 26 - Example of filters implementations in SIMP method. In (a) it is possible to verify a dominant presence of checkerboards. Source: (Sigmund, 2007).

Another alternatives method to SIMP has been developed, such as Rational Approximation of Material Properties (RAMP) and methods based on homogenisation of microstructures. Another element based method that does not use penalisation, working directly with 0 or 1 densities is the Bidirectional Evolutionary Structural Optimisation, that uses heuristic criteria to remove or add material (Dunning et al., 2015)

Element based methods have demanded improvement to avoid numerical issues such as mesh dependent solutions, checkerboard patterns, rough surfaces etc., most of them leading to the need for post-treatment of geometries. Some of the inconveniences of this post-treatment are the time spent to perform the corrections, and the risk of losing the benefits gained in the optimised geometry., Boundary Based Methods have been developed as an alternative to avoid these issues (Dunning et al., 2015).

2.2. Problem Formulation of Structural Optimisation

An optimisation process is a sequence of changes of design variables to find the maximum or minimum of the objective function, satisfying all the design constraints.

2.2.1. Design Variables

These are all inputs parameters that are likely to be changed while searching for the best solution. Normally these are geometry, material and operations conditions. Design variables can be continuous, discrete or mixed variables.

Some of the discrete variables could come from commercial and manufacturing limitations or standards, such as materials, beams dimensions, sheet thickness etc. Solving an optimisation problem with discrete variables is usually much more difficult that solving it with continuous variables (Haftka & Gürdal, 2012). Therefore, for complex discrete variables problems, it is common to first solve it with continuous variables and after that, adjust the value to the nearest discrete value available. This strategy could be satisfactory when there are not too spaced values between the solutions, and this difference can be disregarded. However, with the variables spaced too far apart, the optimised solution could be lost when taking the nearest discrete value available.

To solve TO problems, the software still needs designations of design region (or design space) and exclusion region (or non-design space). Design region is all the volume allowed to remove material through TO iterations. Exclusion region(s) is all the volume not allowed to remove material, usually, loading support, connectors and standard parts Figure 27).

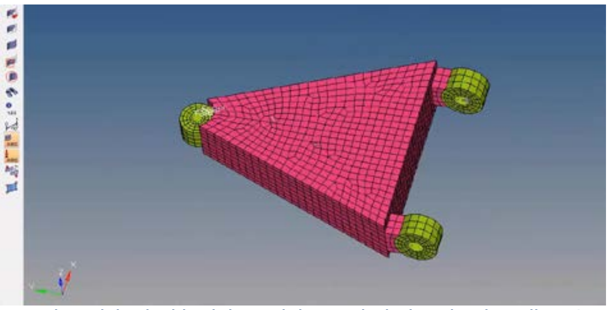

Figure 27 - The design region picked with pink, and the excluded region in yellow Source: Altair University.

2.2.2. Constraints

Responses are the result of design variables and are all output characteristics that can be measured in the system.

For a feasible solution, constraints for responses and design variables are necessary. The constraints will limit a range or set a value that the solution must respect. The constraints are specified by guidelines or standards, or from several project requirements. Usual constraints in structural optimisation are related to constraints such as mass, volume, global and local von-Mises stress, displacement, centre of gravity, moments of inertia, reaction force and natural frequency.

For the TO problem, it is essential to apply geometric constraints (or manufacturing constraints) to achieve a design feasible to be produced by traditional methods (Figure 28). For some advanced techniques such as additive manufacturing, usually, no particular geometry constraints are required.

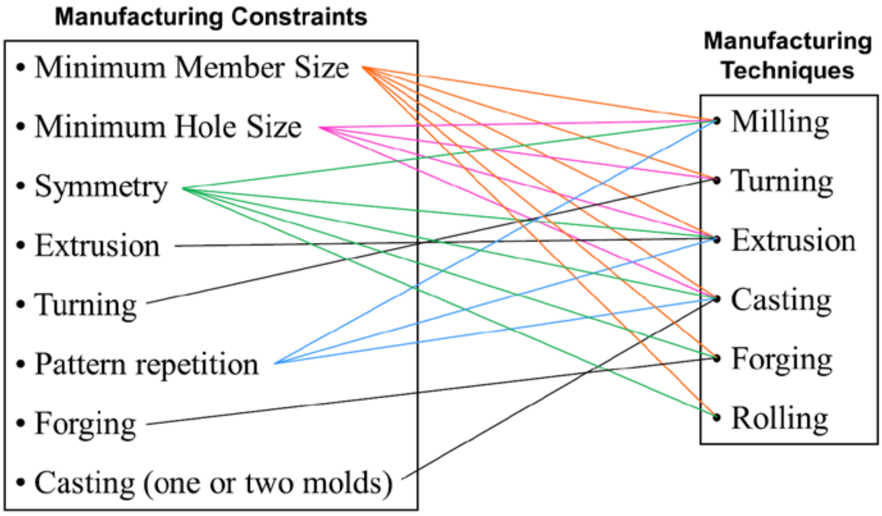

Figure 28 - Relationship between the most common manufacturing constraints with common manufacturing techniques Source: (Vatanabe, Lippi, Lima, Paulino, & Silva, 2016).

2.2.3. Objective Functions

The objective function sets the target to minimise or maximise, and is represented by a continuous function that can be linear, non-linear, implicit or explicit. Some of the usual objectives in problems of structural optimisation are: minimising compliance (or maximise stiffness), minimising mass, minimising volume, maximising vibrations frequency, maximising buckling loads and minimising cost.

If there are two or more objective functions, the problem is multi-objective (or multicriteria optimisation). In multi-objective problems, some functions have more importance than others, and for this case weights for each one must be applied to balance priorities in the solution. Multi-objective problems in structural optimisation are not easy to be solved, and these are usually solved by a systematic approach, such as Edgeworth-Pareto (or Pareto´s frontier) optimisation (Haftka & Gürdal, 2012).

2.3. Topology Optimisation Workflow

A general workflow is presented in this section to perform a TO for linear structural context. Depending on each TO software, the sequence of some steps can change, but in general, all of them should be considered to perform the TO simulation properly.

2.3.1. Geometry Selection

A solid or surface that bounds the region where the solution must be into. It can be all the model, some of the body or some region of the body (Figure 29).

Figure 29 - Possible geometry selections: (a) solid model, (b) surface model, (c) part of an assembly, (d) region of a part.

2.3.2. Generation of the Mesh

It is necessary to generate the mesh of geometry (Figure 30). The influence of the mesh parameters will be discussed in the section 2.4.

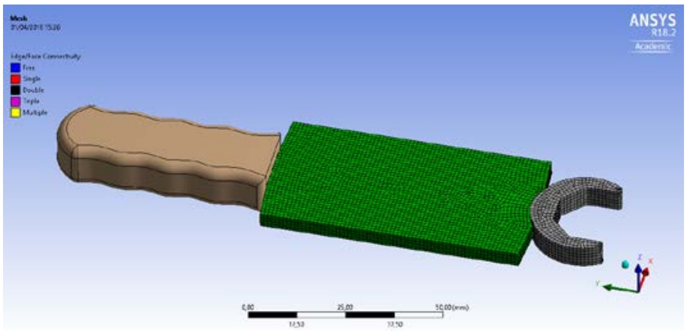

Figure 30 - Mesh of volume boundary. A wide volume was created (green) to allow more freedom to the software and to check how different the new geometry could be.

2.3.3. Regions Definitions

Definition of design region and exclusion region (Figure 31).

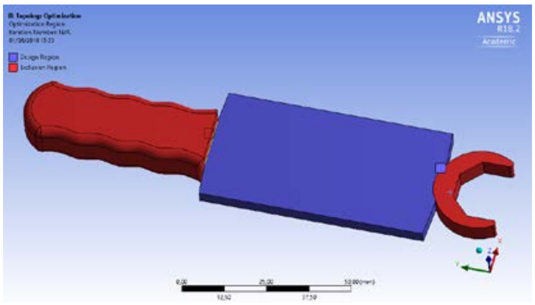

Figure 31 - Marked with blue, the design region that allows removing material.

2.3.4. Boundary Conditions

In (Figure 32) is shown the setting of loadings (A, arrows in red in two moments) and support (purple, into of the wrench).

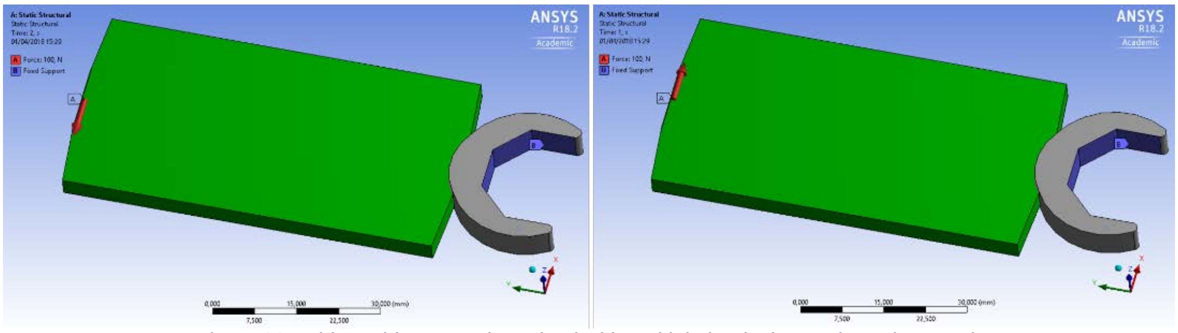

Figure 32 - This problem must be solved with multiple loads, in two times (or steps).

2.3.5. Objectives

One or more objectives (multiple-objectives) are defined in this step, different level of weight of importance can be set if necessary. The most common objectives of the TO for linear structural are:

- Minimizing compliance (simple or multiples loadings)
- Minimizing mass
- Minimizing volume
- Maximizing natural frequencies (one or multiples)
- Maximising buckling loads

2.3.6. Responses Constraints

One or more constraints can be defined in this step, setting a range of values or fixing a value. The most common constraints of the TO for linear structural are:

- Mass
- Volume
- Global von-Mises stress
- Local von-Mises stress
- Displacement
- Reaction force
- Natural frequency

Typical formulation of Topology Optimisation Problems (Altair University, 2015):

- Minimise compliance with constrained mass/volume
- Minimise mass/volume with constrained displacements
- Maximise frequency with constrained mass/volume
- Minimise mass/volume with constrained frequencies
- Minimise combined compliance and frequencies with constrained mass/volume
- Minimise mass/volume with stress constraints

2.3.7. Solving

Set the analysis parameters such as the number of iterations, convergence accuracy, minimum density, the type of solver[3] etc. It is important to know the solvers available in the software, and its best applications and limitations. Most softwares allow (watching the iterations of the solution process followed by a graphic or geometry evolution (Figure 33, Figure 34, Figure 35).

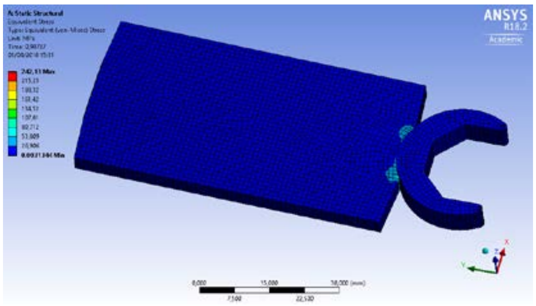

Figure 33 – Pre-FEM analysis of equivalent Von-Mises stress., required to perform the TO next.

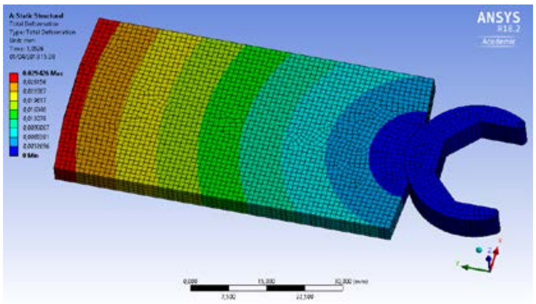

Figure 34 - Pre-FEM analysis of deformation, required to perform the TO next.

[3] The solver (known as black box) is the module of FEM software that contains all algorithms that will decompose all data from pre-processing, process it and output the results to post-processing.

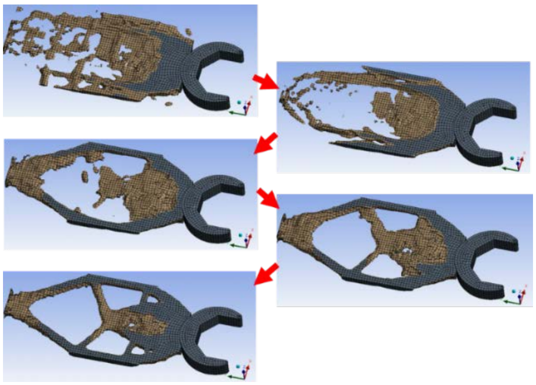

Figure 35 - The geometry iterations evolutions.

2.3.8. Post-treatment

The material can be added or removed through a range of elements density. The evaluation of the remaining structure obtained through density adjusts requires in part, an intuitive judgement of designer and engineers. The more refined the mesh is, the smaller is the impact of this density setting (Figures 36, 37, 38 and 39).

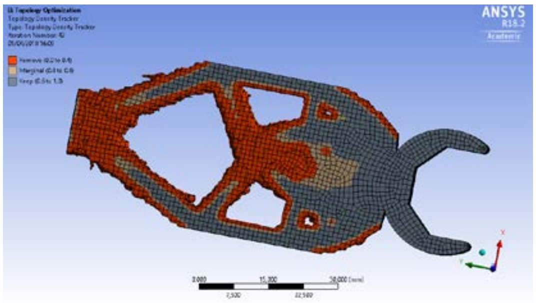

Figure 36 - All elements density (0 to 1) are shown.

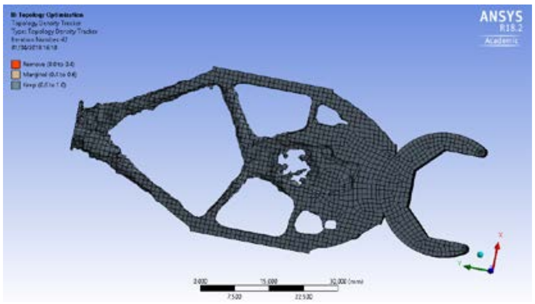

Figure 38 - Only elements with density above than 0,7 are shown.

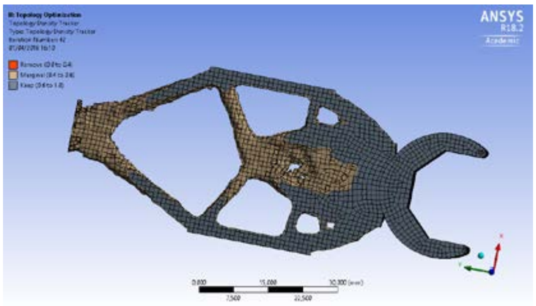

Figure 37 - Only elements with density above 0,5 are shown.

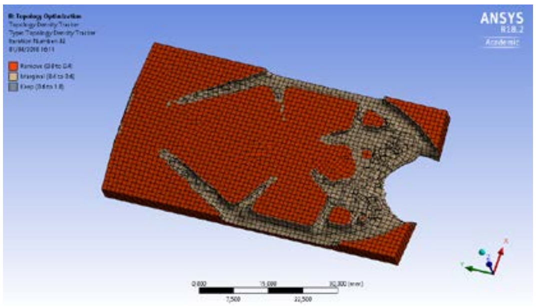

Figure 39 - Representation of all material removed from the original volume.

2.3.9. CAD post-treatment

Geometries created by TO iterations usually are coarse (Figure 40), and for these cases, CAD post-treatment is required to smooth the geometry faces and to produce a practicable body for FEM simulation. This post-treatment can be done with automatic tools available in some software or manually (Figure 41).

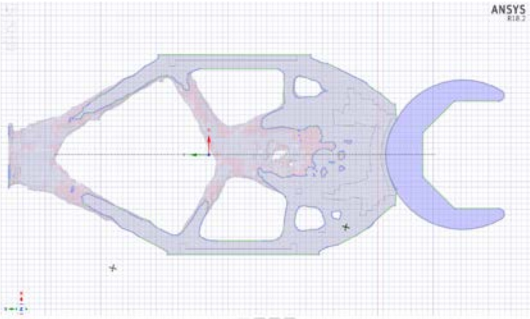

Figure 40 - The original geometry before treatment.

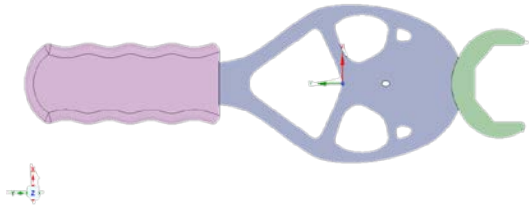

Figure 41 - The final geometry after manual treatment in CAD environment.

2.3.10. FEM Validation

The final CAD geometry has to be validated. In order to avoid extra costs of the project with prototypes and reviews, it is recommended to first perform a FEM validation (Figure 42).

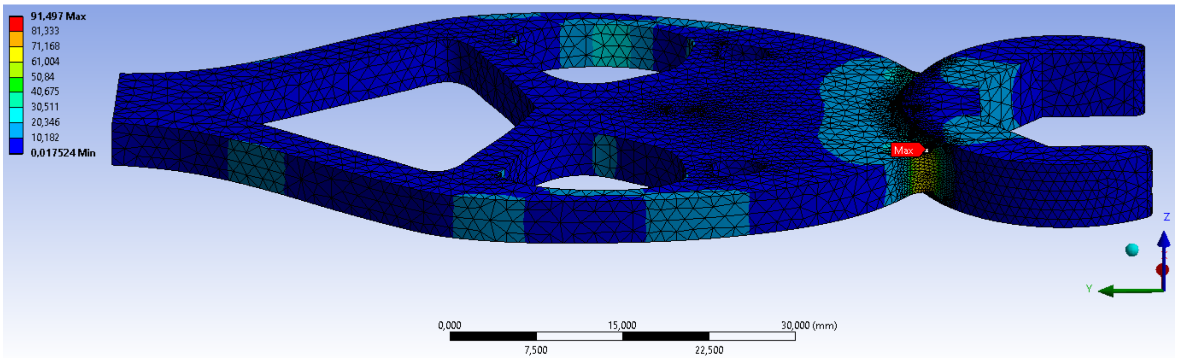

Figure 42 - FEM validation of the geometry, using convergence test (local refinement).

2.3.11. Results Analysis

The final decision of TO process is if the final geometry satisfies the project requirements such as cost, manufacturability, reliability, performance, visual appeal and others tangible and intangible aspects of the design. The solution found can be reproved, and the search process will go back to new iterations or approved and go ahead to next steps to make feasible the commercial production.

2.4. Influences of Parameters Change

Considering various settings that are available to perform a TO, a wide variety of possible results can be found. In fact, they are all optimised for criteria established. The TO interaction can demand time and computing power, adding the fact that the engineers and designers are not able to imagine precisely what geometry the software will create, consecutive refinement of the result could be necessary, spending more reSources. Knowing how all parameters will influence the final result is an initial step to avoid spending a long time on the final geometry research.

A practical experiment will be executed to understand parameters influence and the results discussed as follows. The analysis will be based on MBB problem (Bendsøe & Sigmund, 2003; Rozvany, 1998). This problem originated from the Messerschmidt-Bälkow-Blohm company and it is about an Airbus commercial plane part. The MBB problem has the objective of minimising compliance. Results of this problem are widely explored in the literature (Oliveira, 2013). The MBB is a two-dimensional problem (Figure 43). However, a three-dimensional problem will be adapted to expand the results possibilities in two types A and B (Figure 44). Next, the experiments were performed with the specific software ANSYS Workbench 18.2, it is possible to assume that some different results may occur to different software.

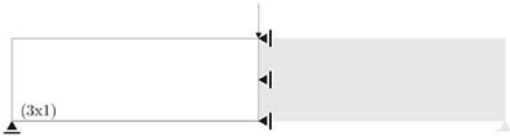

Figure 43 - Representation of MBB problem with symmetry boundary conditions (Oliveira, 2013).

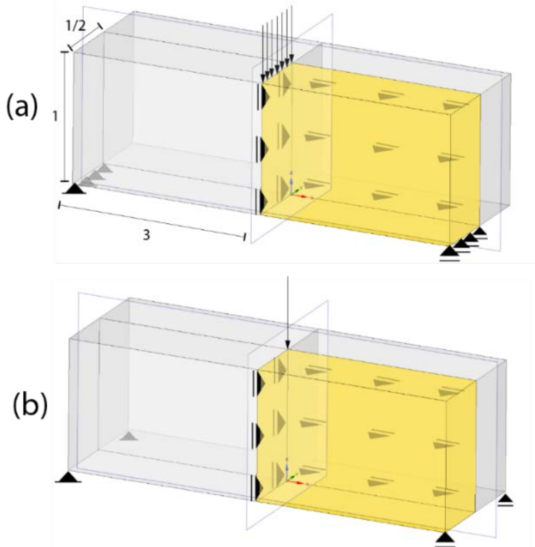

Figure 44 - Three-dimensional MBB problemadaptation with one-quarter symmetry. (a) Problem type A with loading and supporting linear, (b) Problem type B with load and supports punctuaMesh Influence

Considering a regular volume boundary (cube, parallelepiped, sphere, cylinder, prism, pyramid etc) as the design region, the mesh tends to be homogeneous, and no mesh control will be considered for the experiments. Only elements size and order will be evaluated as the main parameters of influence in a TO. For initial iterations, the objective will be to minimise compliance and reduce the mass to 50% as response constraint.

2.4.1.1. Element Size

The analysis will consider three sizes of elements. The edge of the element is based in a proportion defined in relation to the the total height of the part:

Fine mesh: 2D - Element edge = 0,010 x height (Figure 45).
3D - Element edge = 0,025 x height (Figures 46 and 47).

Medium mesh: Element edge = 0,050 x height (Figures 48, 49 and 50).

Coarse mesh: Element edge = 0,100 x height (Figures 51, 52 and 53).

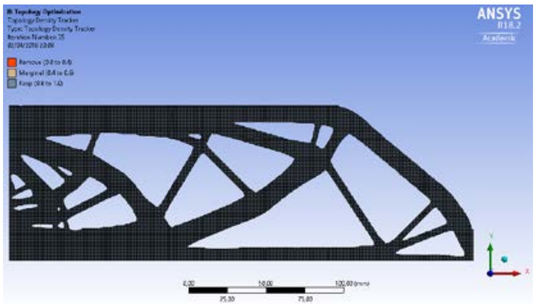

Figure 45 - MBB two-dimensional result with fine mesh.

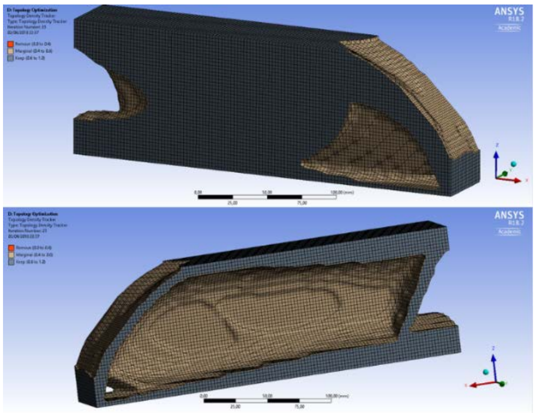

Figure 46 - Three-dimensional problem type A result with fine mesh.

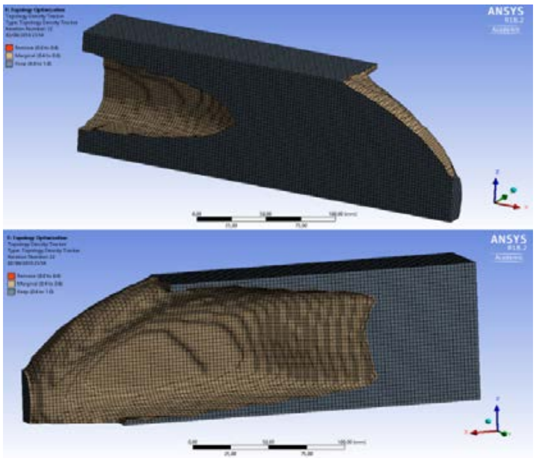

Figure 47 - Three-dimensional problem type B result with fine mesh.

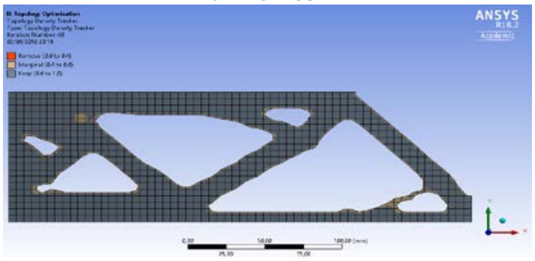

Figure 48 - MBB two-dimensional result with medium mesh.

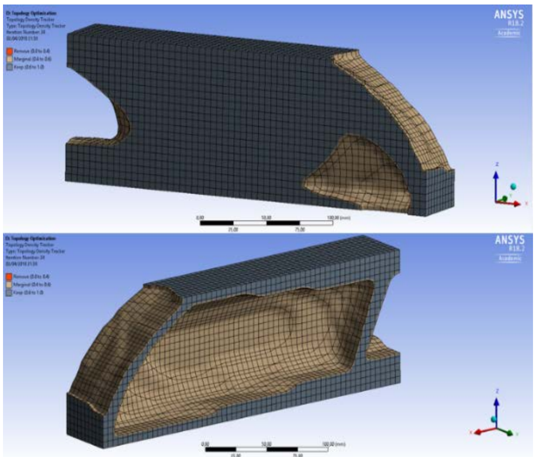

Figure 49 - Three-dimensional problem type A result with medium mesh.

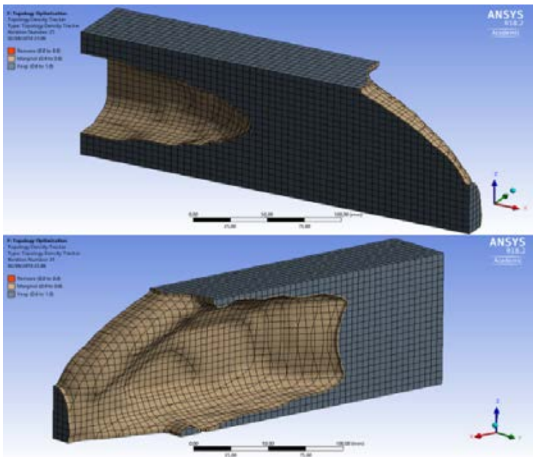

Figure 50 - Three-dimensional problem type B result with medium mesh.

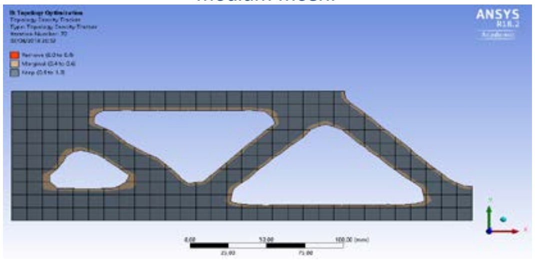

Figure 51 - MBB two-dimensional result with coarse mesh.

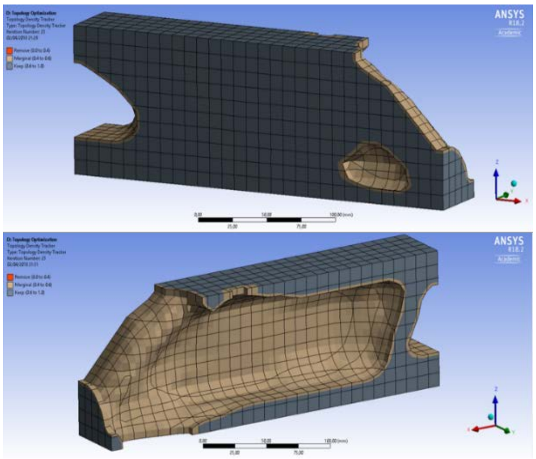

Figure 52 - Three-dimensional problem type A result with coarse mesh.

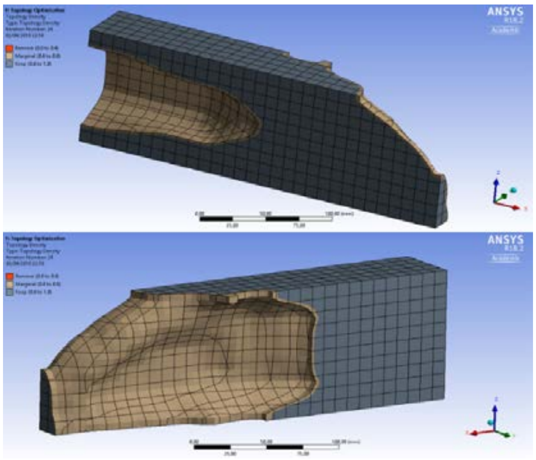

Figure 53 - Three-dimensional problem type B result with coarse mesh.

It is possible to note that by decreasing the element size, the solving time increases considerably (Table 1).

Table 1- Spreadsheet with performance results of the elements size influence.

2D - Element size influence				
Mesh	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Fine	35	3m 31s	527	1,16
Medium	40	1m 11s	268	0,061
Coarse	70	1m 55s	91	0,025
3D - Element size influence				
Problem (a)				
Mesh	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Fine	23	19m 35s	2422,9	4,5
Medium	24	2min 35s	358	0,623
Coarse	23	57s	112	0,095
Problem (b)				
Mesh	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Fine	22	16m 35s	2416	4,6
Medium	25	2m 41s	355	0,623
Coarse	24	50s	111	0,095
Objective: Minimize complain				
Response constraint: 50% mass				

2.4.1.2. Element Type

The analysis will consider fine mesh; the objective function is to minimise compliance and as response constraint reduce the mass to 50%. Two types of elements will be considered:

Triangles/Tetrahedrons: For two-dimensional and three-dimensional respectively (Figures 54 and 55).

Quadrilaterals/Hexahedrons: For two-dimensional and three-dimensional respectively. The results are the same found in section 2.4.1.1.

Performance data: Shown on (Table 2)

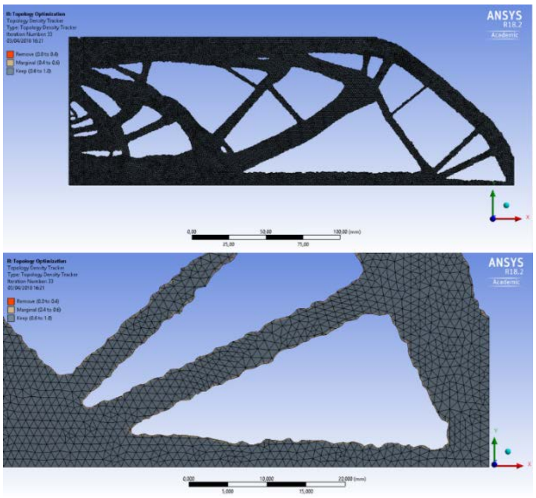

Figure 54- Using triangles elements the contour geometry has a ripple aspect.

Table 2 - Spreadsheet with performance results of the elements type influence

2D - Element tipe influence				
Type	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Triangle	33	5m 14s	684	1,9
Quadrilateral	35	3m 31s	527	1,16
3D - Element size influence				
Problem (a)				
Type	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Tetrahedrons	23	16m 24s	1814,5	6,4
Hexahedrons	23	19m 35s	2422,9	4,5
Mesh: Fine				
Objective: Minimize complain				
Response constraint: 50% mass				

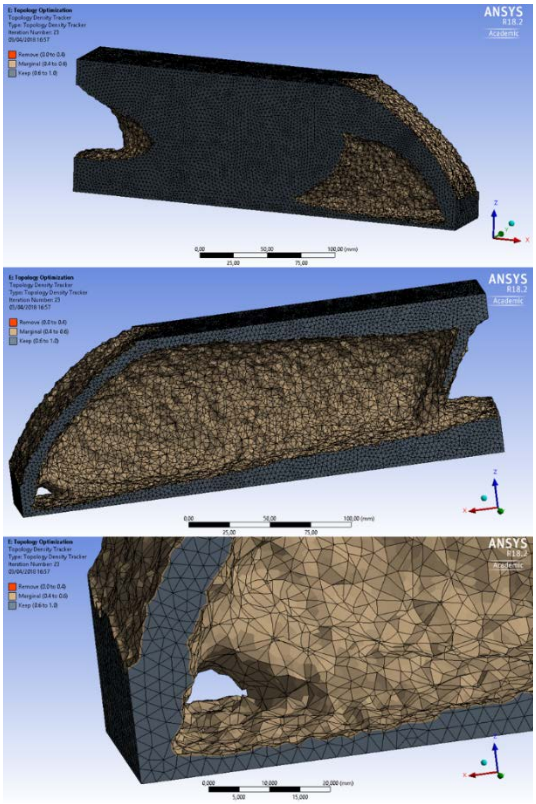

Figure 55 - Using tetrahedral elements the contour geometry has a ripple aspect.

2.4.1.3. Element Order

For two-dimensional, the analysis will consider fine and medium mesh; for three-dimensional, fine mesh only. The objective function is to minimise the compliance and as response constraint reduce the mass to 50%.

Linear: In FEM it means less result accuracy, but the computer solves the problem faster (Figures 56, 57 and 58)

Quadratic: In FEM it means more result accuracy, but it is harder and slower for the computer to solve the problem (Figures 59, 60 and 61).

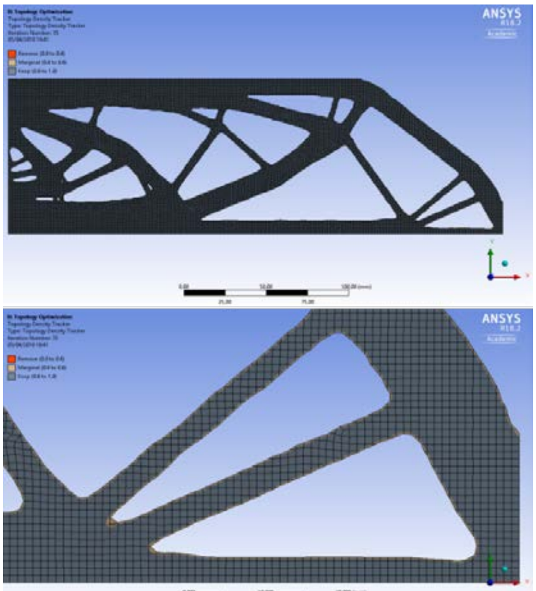

Figure 56 - Linear elements with fine mesh for a two-dimensional problem.

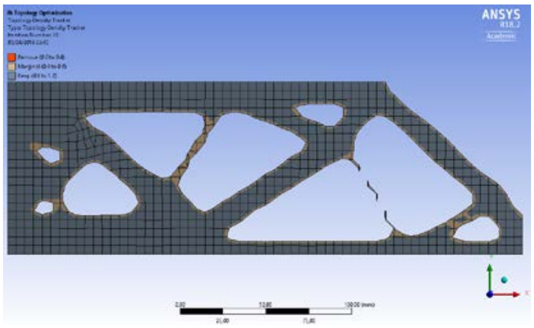

Figure 57 - Linear elements with medium mesh for a two-dimensional problem.

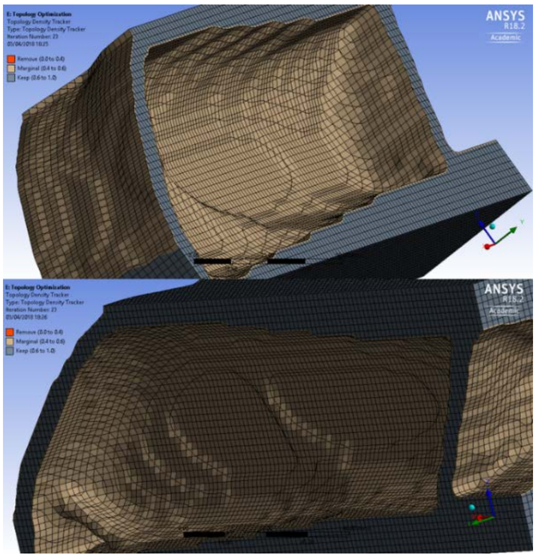

Figure 58 - Linear elements with fine mesh for a three-dimensional problem.

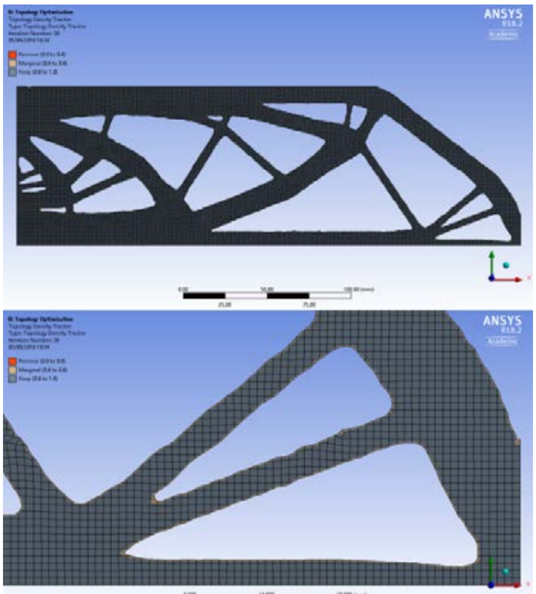

Figure 59 - Quadratic elements with fine mesh for a two-dimensional problem.

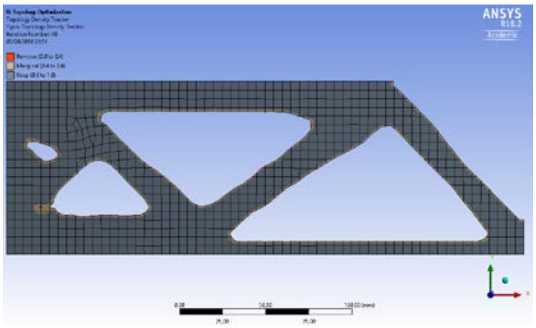

Figure 60 - Quadratic elements with medium mesh for a two-dimensional problem.

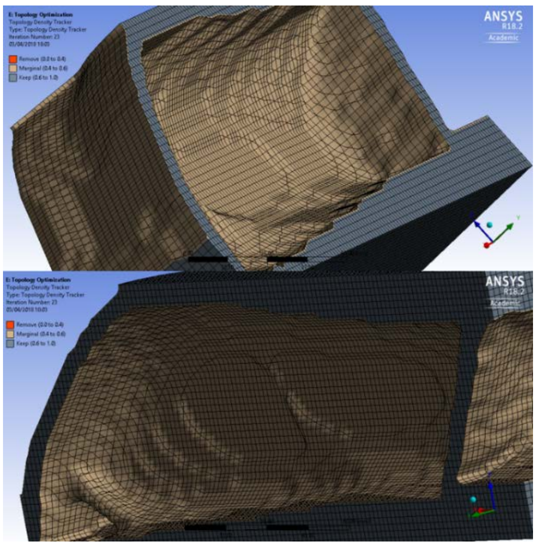

Figure 61 - Quadratic elements with fine mesh for a three-dimensional problem

Performance data: For these experiments, a few differences of the geometry quality between linear and quadratic elements were verified. However, it is important to emphasise that this result could change between software depending on the solver type, the element density value can change rapidly between each other for linear elements, causing checkerboarding. In these cases, a model with quadratic (higher order) elements are recommended because it reduced the likelihood of showing this behaviour (Altair University, 2015). The performance data is shown on (Table 3).

Table 3 - Spreadsheet with performance results of the elements order influence.

2D - Element tipe influence				
Order	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Linear[1]	35	2m 42s	335	0,73
Quadratic[1]	36	3m 50s	536	1,17
Linear[2]	39	1m 21s	94	0,04
Quadratic[2]	48	1m 43s	270	0,06
3D - Element size influence Problem (a)				
Order	**Number of iterations**	**Elapsed time**	**Memory used (mb)**	**Result file size (mb)**
Linear[1]	23	6m 23s	631	2,3
Quadratic[1]	23	17m 19s	2422,3	4,6
Mesh: [1]Fine; [2]Medium Objective: Minimize complain Response constraint: 50% mass				

2.4.1.4. Conclusion

The final geometry is mesh dependent on the number of elements; more elements, more ramifications and more details. Preference should be given to quadrilaterals and hexahedrons elements always when is possible; elements such as triangles and tetrahedrons must be avoided due to the generation of ripple surface aspect. No substantial difference of the solution quality between element order (linear has a faster solution), in which the risk of checkerboard pattern generation was identified.

2.4.2. Volume Domain Influence

Initial geometry domain limits the optimised region. But what form would be created if this initial geometry becomes so big that the TO algorithm could have total freedom to find the optimum material distribution? As it is possible to verify on previous examples, in areas where the algorithm tends to expand the material distribution but it is limited by domain geometry, the geometry lines accompaniment and accumulation of material can be found in these regions. The next experiments have the aim of only verifying how the material "ideal" distribution would be, without geometry domain (Figures 62, 63, 64 and 65).

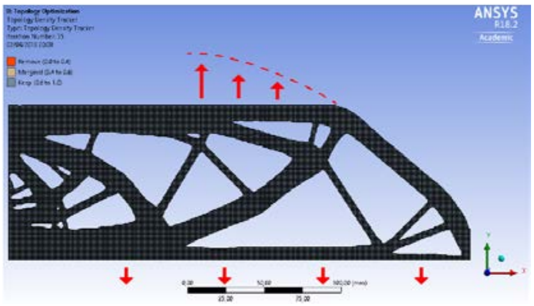

Figure 62 - The initial 2D geometry boundary limits the material distribution.

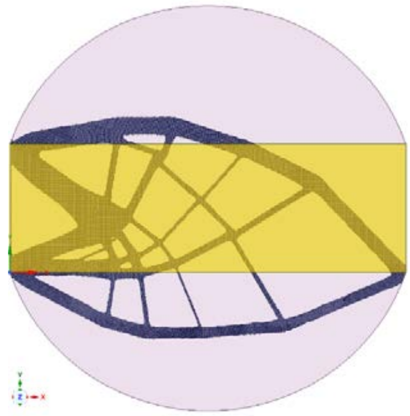

Figure 63 - In yellow the first 2D geometry domain. In pink and background, the new geometry domain. In blue, the optimised geometry without the upper and lower limitation. This geometry has the same final mass than in Figure 62.

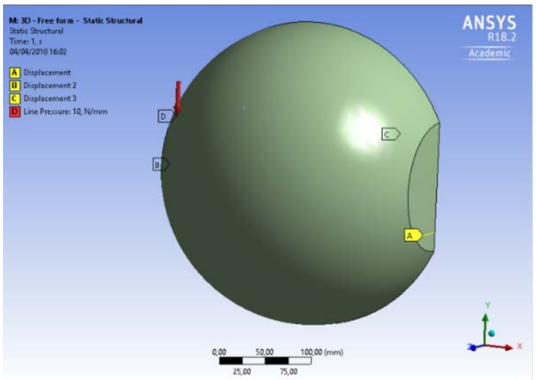

Figure 64 - The new 3D geometry domain, considering a problem approach with symmetry.

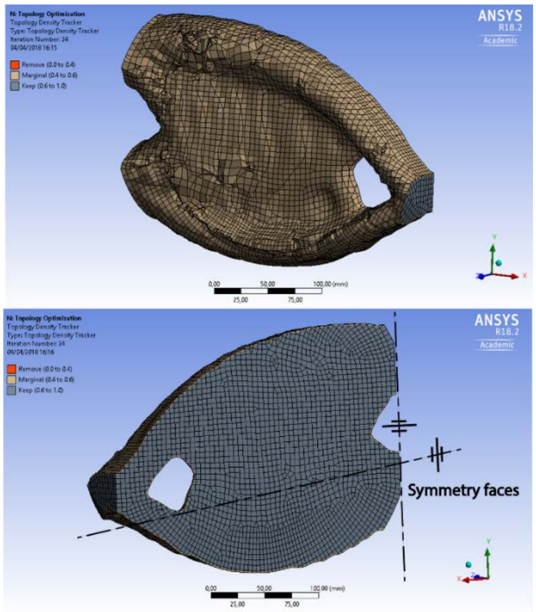

Figure 65 - The geometry found without volumetric limitations. This geometry has the same final mass than the previous 3D examples.

Conclusion: The final geometry does not necessarily use all domains if the initial volume is very big. In this case, the solution has the freedom to find an organic geometry with almost no straight line. If the volume domain is smaller than the free geometry, the geometry lines go along the frontiers and accumulate material in these regions.

2.4.3. Material Influence

When responses constraints are stress or a dimensionless value of mass or volume; in other words, not linked to material properties, and assuming that the structural problem has static strains within elastics limits, linear relationship between strain (ε) and stress (σ) (following the Hooke´s law) and the material is homogeneous, isotropic, and the Poisson´s ratio is positive. In this situation, there is no influence of the material to the final geometry. Even for ductile or fragile material.

In the case that material is not isotropic (orthotropic), such as composites; difference in final geometry is observed. The experiments tested (Figures 66 and 67) show that there are no differences in results to isotropic fragile and ductile materials, but a different result is found when an orthotropic material is used.

In cases where responses constraints are fundamentally linked to material properties such as displacement, natural frequency and reaction force; the final geometry will be influenced.

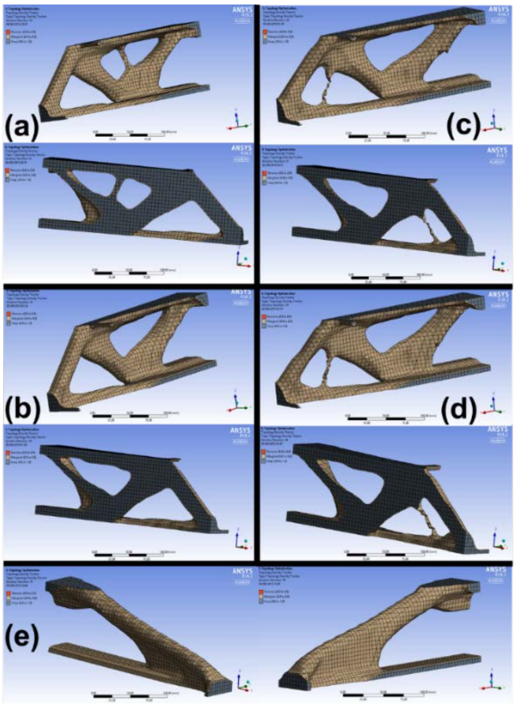

Figure 66 - (a) Concrete - fragile, (b) Gray casting iron - fragile, (c) Stainless steel - ductile, (d) Polyethylene – ductile, (e) Epoxy/Carbon fibre – max. strength in X direction. Between isotropic materials, there is essentially no structural difference.

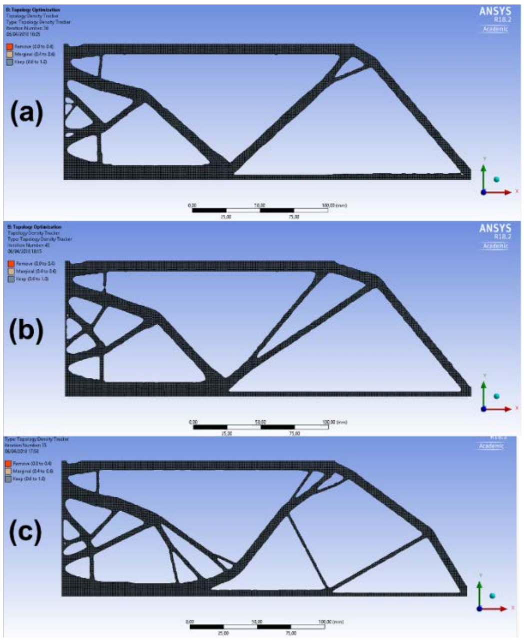

Figure 67 - Different materials tested to the same objective function (minimise compliance) and as constraints, mass reduction and maximum displacement allowed (dependent on the material), have different optimised solutions. (a) Structural steel, (b) Concrete, (e) Epoxy/Carbon fibre – max. strength in X direction.

Conclusion: If the problem is static, linear and the material is homogeneous, isotropic, and the Poisson´s ratio is positive, there is no influence of the material to the final geometry. But, if the responses constraints are displacement, natural frequency or reaction force, the final geometry will be influenced by material.

2.4.4. Mass and Volume Relationship

Being the material the same in the entire model (design region and exclusion region) and homogeneous, that is, the density is equal in all parts, the results from mass and volume constraint will be the same. However, in cases that the design region and exclusion region densities are different, the optimisation result may be different between the mass minimisation and the volume minimisation. In a case where the design region mass is almost equal to exclusion region mass, but the design volume is much smaller than the exclusion region, a choice of minimising mass will yield better results. If the design region volume is almost equal to the exclusion region, but the design mass is much smaller than the exclusion region, the volume minimising will provide better results (Altair University, 2015).

In sum:

- If $\rho_{DesignRegion} = \rho_{ExclusionRegion}$, then minimising mass or minimising volume is the same;
- If $\rho_{DesignRegion} \gg \rho_{ExclusionRegion}$, and $V_{DesignRegion} \ll V_{ExclusionRegion}$, $M_{DesignRegion} \cong M_{ExclusionRegion}$ then minimising mass is better;
- If $\rho_{DesignRegion} \ll \rho_{ExclusionRegion}$, and $V_{DesignRegion} \cong V_{ExclusionRegion}$, then minimising volume is better;

Where:

ρ-Density
V-Volume
M-Mass

2.4.4.1. Mass (or Volume) Reduction Influence

The experiments done (Figure 68 and 69) verify if the base strategy of mass distribution change or keep the same with mass (or volume) reduction.

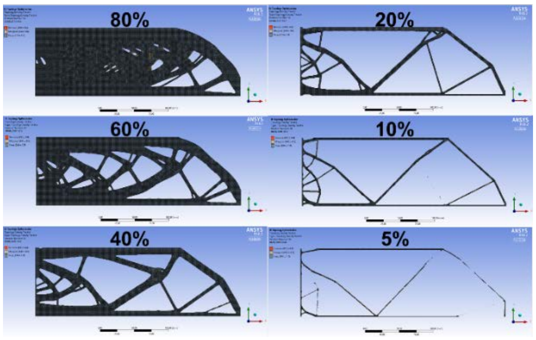

Figure 68 - Reducing the mass (or volume), the base frame is held in 2D geometry. There is not an identified direct relationship between time to solve and material reduction.

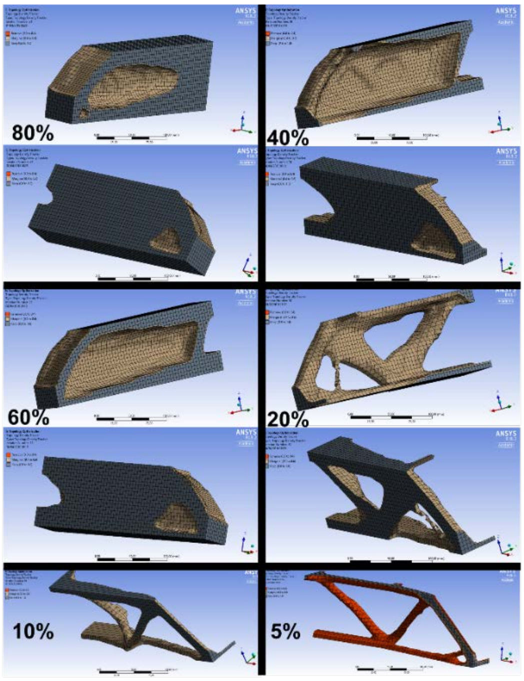

Figure 69 - Evolution of the 3D structure with mass (or volume) reduction.

Conclusion: If the material is only one and homogeneous, mass and volume are equivalent to the objective function and constraints. The reduction of mass (or volume) constraint will generate different geometries in a not scalable solution, it means, for instance, a reduction to 20% of mass does not have a proportional solution than a 60% of mass reduction. Both solutions would have a different aspect and not a proportional one.

2.4.5. Multi-objective

It is common that product design problems have more than one objective, that is, a multi-objective problem. Some objectives could be more critical than others, and also could be conflicting (improving one means deteriorating another). As a consequence, a set of acceptable solutions would be found (Pareto´s front) (Figure 70); as introduced in the section 1.4.2. The addition of weights of importance for each objective is a way to overcome this trade-off dilemma and to balance all objectives towards a better solution that will satisfy the design requirements.

Below is an example of a multi-objective problem formulation to minimise compliance and to minimise mass (conflicting objectives) with the response constraints a limited value of the global Von-Mises stress (Figure 71).

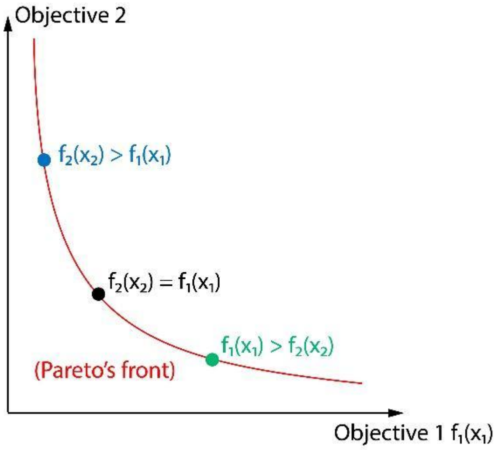

Figure 70 - Two-dimensional representation of a Pareto´s front, with two non-dominant and conflicting functions.

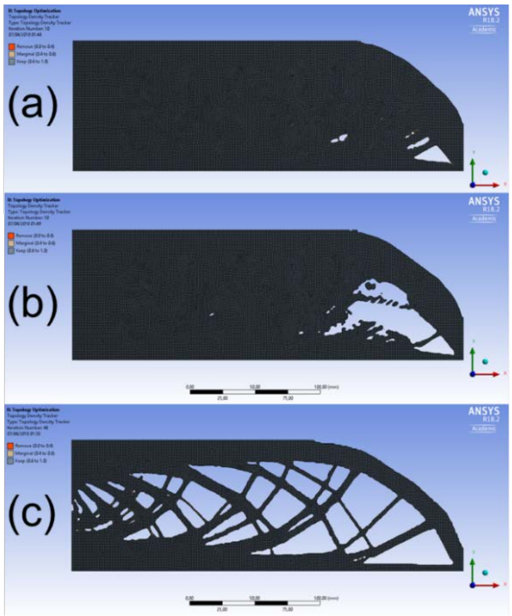

Figure 71 - A multiple-objective optimisation with three possible results for different weights for objective functions, and with the response constraint the total Von-Mises stress. (a) Minimise compliance = 1 and minimise mass = 0.5. (b) Minimise compliance = 1 and minimise mass = 1. (c) Minimise compliance = 0.5 and minimise mass = 1.

Conclusion: Different weights of objectives will provide different solutions. The weight becomes essential when there are opposite objectives.

2.4.6. Multiple Loads

In a real situation, it is common applying multiple loads at different times. If it occurs, it is necessary a solution as a multiple loading problem, to link all loads and sequence of time to perform the TO and to get the correct geometry. The TO experiment in Figure 72, shows two results where each load at an isolated time is considered. When the same TO problem is solved considering a sequence of multiple loading (Figure 73), the solution found in (a) is different if both geometries found in (51) were overlapping (b). However, more processing time is required for a computer to solve a multiple loads problem.

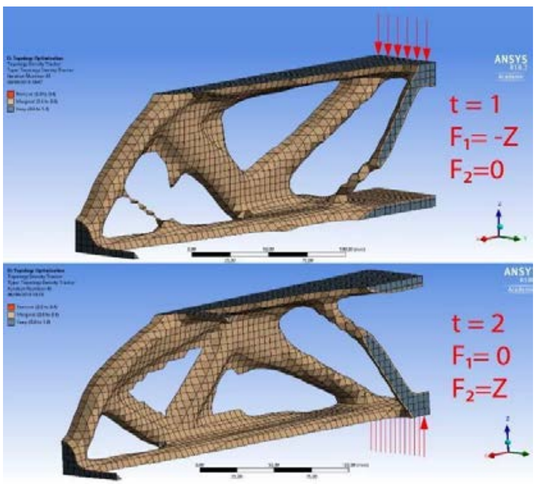

Figure 72 – TO result when different loads are simulated in isolated time.

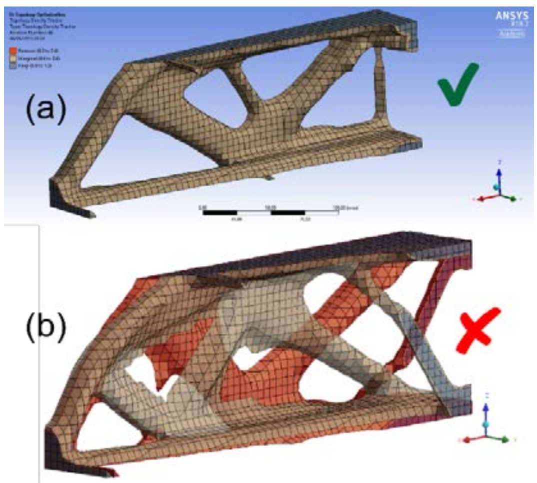

Figure 73 – (a) The geometry found from the solution of the 51 problem when solved as a multiple loading problem. (b) A geometry made by overlapping geometries found for each loading separated is not the correct solution

Conclusion: If the geometry is subject to different loads at different times, the problem must be solved with a multi-load approach. The geometry generated is different from each geometry generated with each load separately.

2.4.7. Manufacturability Influence

The free forms created by TO are organic and complex, often difficult to manufacture by most of the manufacturing processes available in the mass industry. Manufacturing constraints must be used to overcome limitations of the manufacturing process available, or even to other constraints such as budget, material, production scale etc.

Some of TO software available have special algorithms to generate geometries feasible to produce by specific manufacturable characteristics. An example of a cube subject to two loadings and supported by four supports will be explored (Figure 74). The following results obtained are: manufacturing non-constraints (free form) (Figure 75), member size (with ANSYS, it is possible to combine member size with other manufacturing constraints) (Figure 76), pull out direction (Figure 77), extrusion (Figure 78), cyclic (Figure 79) and symmetry (Figure 80).

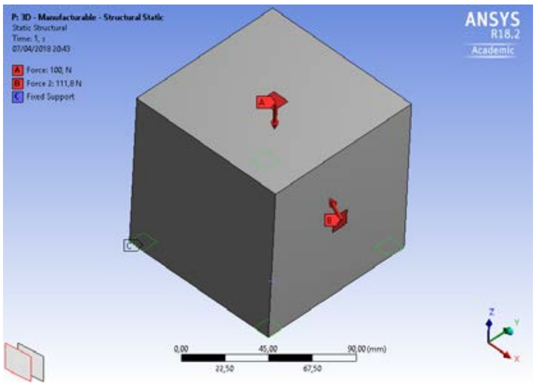

Figure 74 – The initial geometry and boundary conditions.

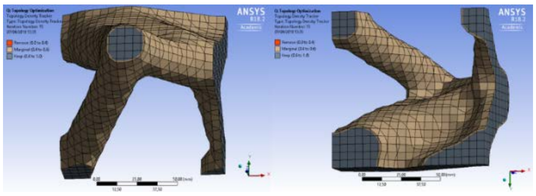

Figure 75 – The result with manufacturing non-constraints (free form).

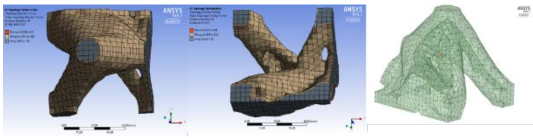

Figure 76 - The result with a value of maximum member size constraint. It is possible to see that there are voids in the geometry, requiring advanced manufacturing processes (e.g.: additive manufacturing). This constraint is connected intimately with a choice of mass (or volume) reduction

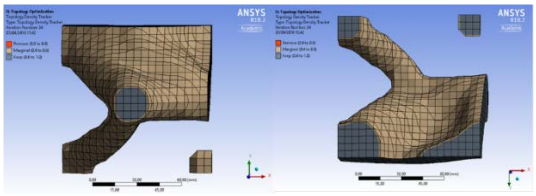

Figure 77 - The result with manufacturing constraint of pull out in Z-axis direction.

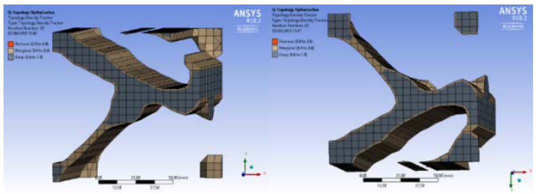

Figure 78 - The result with manufacturing extrusion constraint in Z-axis direction.

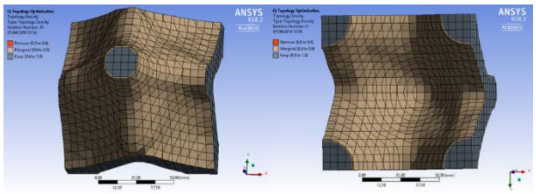

Figure 79 - The result with manufacturing constraint of cyclic in Z axis direction and four sectors.

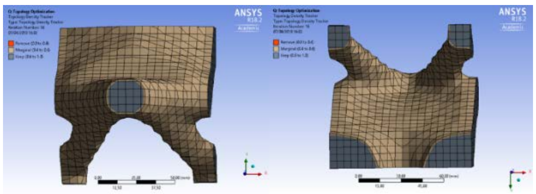

Figure 80 - The result with manufacturing constraint of symmetry in YZ plane.

Conclusion: The solution can radically change to allow a generation of a feasible geometry to be manufactured. The only constraint that can be combined with others is the member size.

CHAPTER 3

Biomimicry and Topology Optimisation

"Organisms in nature face the same challenges we do, but they meet them sustainably" Janine Benyus

“I think the biggest innovations of the 21st century will be at the intersection of biology and technology.” Steve Jobs

3.

3.1. Bio-inspired Design Domain

Bio-inspired Design creates products or services developed from natural principles, from the combination of bio-disciplines, generating the Biotechnology. Main disciplines found in the literature are Biomimicry, Biomimetic, Bionic, Biophilia, Biomechanics, Bio-utilisation, Bioremediation, Bio-survey, Biomorphic and Bio-affiliation. In general, these subjects are differentiated by the comprehensiveness of their purposes or even by authors. Biomechanics is the study of the mechanical physics of biological processes or structures. Examples of these studies are: the relation of muscles and bones movements, heart action, bio fluids, animal locomotion, ergonomy, stress on tissues etc. (Figure 81).

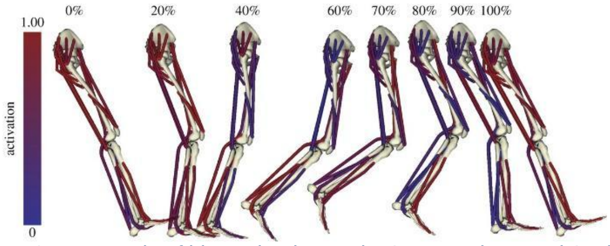

Figure 81 - Example of biomechanics study. Source: The Royal Society.

Biophilia is focused on human sensations looking for human's connection with nature through experiences replication derived from nature. The aim is to improve health and wellbeing supported by scientific studies. Most of the applications are found in architecture, interior design and urban design. Some of the benefits achieved with biophilia applications are stress reduction, cognitive performance improvement, and support positive emotions and mood. Thus, nature can be a Source of inspiration to harmonise the human relations with objects and the environment (Bernett, 2017) (Figure 82).


Figure 82 - Example of a biophilic office design. Source: VerHalen.

Bionics, first appeared in a 1960 US air force symposium, conceived by Jack Steele (a medical doctor), and it is defined as the creation of modern engineering systems or a set of function, based on biological systems and methods found in nature (Figure 83).

Biomimetics was introduced in 1969 by Otto Schmitt[4], and it can be understood as the study and creation of structures, models, function, material, systems and methods, based on biological solutions.

[4] Otto H. Schmitt (1913 - 1998), was an inventor, engineer and biophysicist. He was responsible for establishing the field of biomedical engineering, founding president of Biomedical Engineering Society and founding vice president of the Biophysical Society.

The term Biomimicry (the junction of Bio = *life* and Mimicry = *copy*) was introduced by Janine Benyus (Biologist and co-founder of Biomimicry 3.8[5] and the Biomimicry Institute[6]) in 1997 with the publication of the book *Biomimicry: Innovation Inspired by Nature*. By her words, “Biomimicry is learning from and then emulating nature’s forms, processes, and ecosystems to create more sustainable designs” (Biomimicry 3.8, n.d.).

Figure 83 - Example of a bionic device. Source: Rick Wilking/Reuters.

Given the fact that the sustainability of all human creations and actions has been gaining more importance, it has become one of the most important pillars of biomimicry, seeing that the solutions created by nature are sustainable, optimised and reliable due to the gradual evolution and natural selection. Both Biomimetics and Biomimicry can be considered emerging disciplines but not a new practice. Since the beginning of civilisation, the man has mimicked nature in several aspects, such as architecture, tools and behaviour (Figure 84). However, despite its importance, Biomimicry is one among other design disciplines capable of providing sustainable solutions and reducing the environmental impact of resources usage, such as eco-design and eco-efficiency, bioclimatic and climate design, low energy design, eco-mimicry and others. Some of them can be more efficient in certain aspects than others.

Bio-utilisation can be described as the care of the utilisation, manufacturing, process, life-cycle, chemical composes, of material and energy, whit the core aim of reducing the environmental impact. Bioremediation can be described as the study and identification of problems, and the strategies to solve them through the lowest ecological impact possible. Bio-survey is the collection, stratification, interpretation, organisation and creation of a big database that supports all other disciplines in the searching and development process. Biomorphic can be understood as an art creation from observation and mimicry of nature. Bio-affiliation is the defence of the idea that the human feels better and is healthier when in contact and connected with nature. The connection between each discipline and its main characteristics in the Bio-inspired Design is shown in (Figure 85).

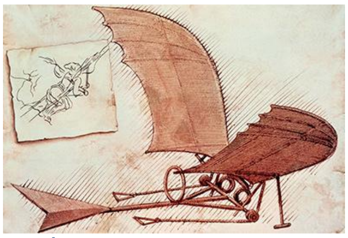

Figure 84 - Example of a Leonardo Da Vinci´s biomimetic/biomimicry flight machine. Source: leonardo-da-vinci.net.

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[5] Biomimicry 3.8 (https://biomimicry.net) is a bio-inspired consultancy offering biological intelligence consulting, professional training, and inspiration.

[6] Biomimicry Institute (https://biomimicry.org) is a non-profit organisation that has as aim to naturalise biomimicry in the culture through promotions and transfer of ideas, designs, and strategies to sustainable human systems design from the biology. Asknature (https://asknature.org) is an extension of the Biomimicry Institute, and is a website that seeks to support and inspire designers, engineers, architects, business strategists and other innovators with biological information relevant to their service or product design challenges.

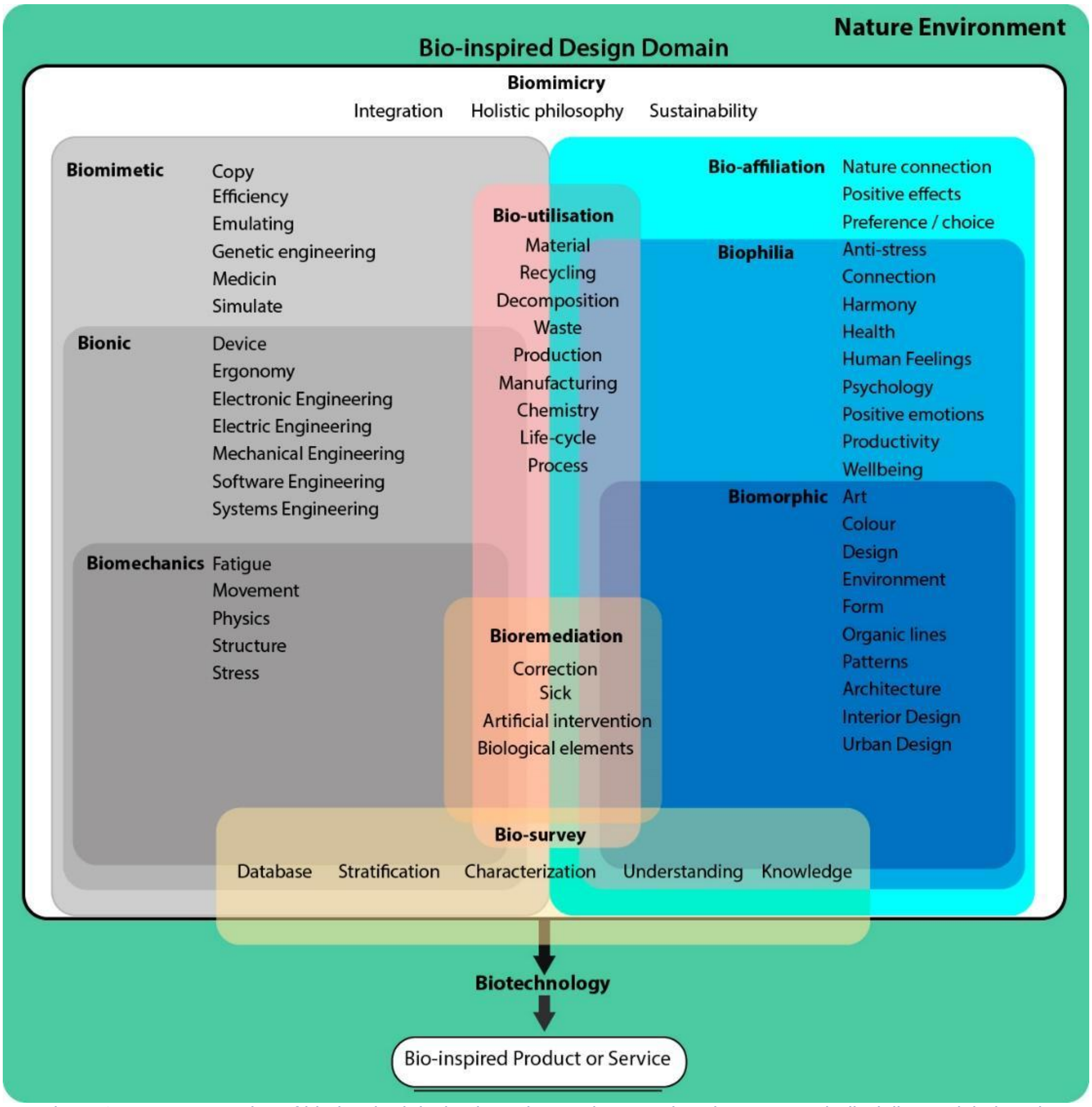

Figure 85 - Representation of bio-inspired design boundary and connections between each discipline and their main characteristics.

3.2. How Nature Works and its Optimisation Process

Nature is a very complex process and a complete understanding, demands an extensive description of its primary means. As the full explanation is not the main object of this study, a selection of principles and philosophy that can better fit with the product design and development process and Topology Optimisation (TO) will be described here.

3.2.1. Holistic and Mechanistic Philosophy

Holistic philosophy: Systems and their properties should be viewed as wholes, not as collections of parts. It means that in order to understand one part, it is necessary to understand how the whole influences it, and how this part influences the whole. The events of systems are cyclic, not linear.

Mechanistic philosophy: A complex system can be understood and explained as segregation and reduction of parts in a hierarchical model, wherein the whole is the sum of all parts, with linear and predictable events, in a Cartesian view. This paradigm has emerged around the 18th century during the Enlightenment, breaking down the world into various disciplines.

All the natural biological systems work holistically. It is not possible to develop some piece or system that is sustainable, without looking the whole and mutual influences and dependencies. The Modern Age is still in a mechanistic paradigm, the reason why all the development created has not been successful in being sustainable. At the moment, the human species is in a stage where it is necessary to change the paradigm for a long term to survival. (Capra, 1982).

3.2.2. Nature Principles to Sustainability

Every nature creation tends to be sustainable otherwise they tend to be eliminated along the time. While creation and natural evolution features do self-feedback loops such as learn and adapt, the human artefacts yet do not.

There are nine principles that govern and define how nature operates that make it sustainable (J. M. Benyus, 2009):

- **I.** Nature runs on sunlight;
- **II.** Nature uses only the energy it needs;
- **III.** Nature fits form to function;
- **IV.** Nature recycles everything;
- **V.** Nature rewards cooperation;
- **VI.** Nature banks diversity;
- **VII.** Nature demands local expertise;
- **VIII.** Nature curbs excesses from within;
- **IX.** Nature taps the power of limits;

As a complementary idea, The Biomimicry Institute suggests that six principles allow life to exist. These are shown in Figures 86, 87 and 88.

Figure 86 - Life´s principles of Biomimicry 3.8. Source: The Biomimicry Institute.

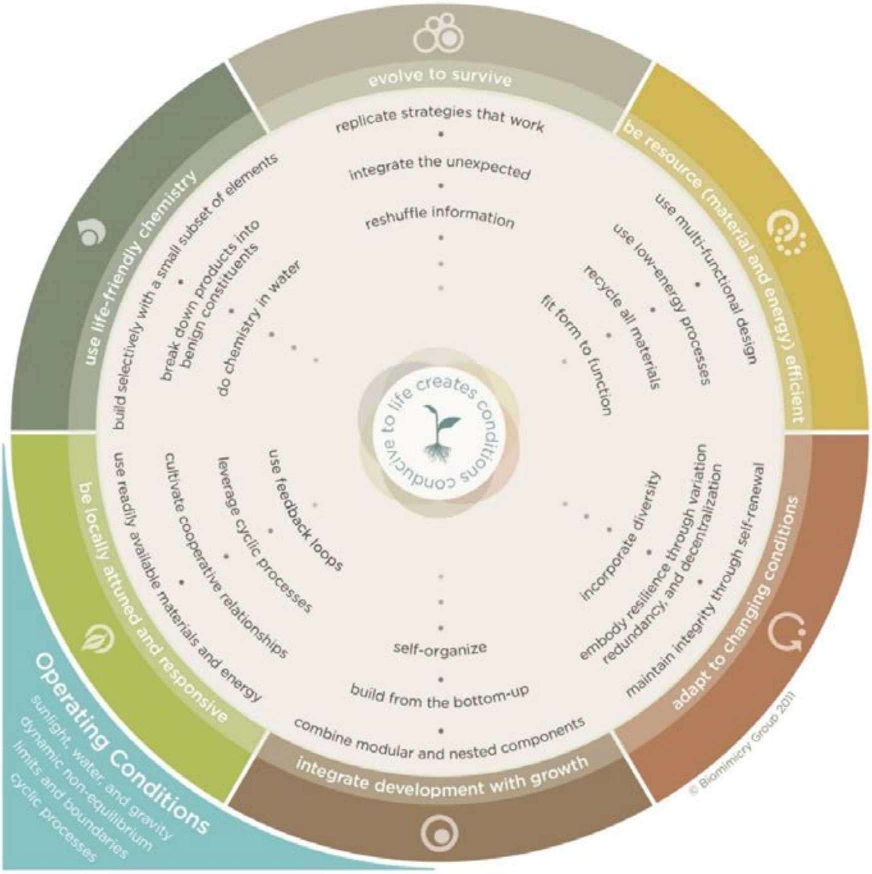

Figure 87 - Six principles of life. Source: The Biomimicry Institute.

Figure 88 - The six life's principles explanation. Source: The Biomimicry Institute.

3.2.3. Evolution

Formulated in 1859 (around one century before the DNA discovery) with the publication of the book On the Origin of Species, written by naturalist Charles Darwin, is nowadays the most accepted base of the evolution theory. The theory assumes that changes over time are a result of changes in heritable physical or behavioural traits. The theory works around two points. One is that all life is connected and related to each other, in an endless search for balance. The cooperation is essential to the survival of all system, instead of competition, that happens only between niches. The other point is that the life diversity is due to modifications in populations driven by natural selection.

The natural selection is defined as the survival of the fittest, and be the fittest is defined as who has the ability to survive and to reproduce face to external threats. Natural selection changes the species in two scales, small and big. The small-scale, called microevolution, changes gradually particular characteristic, such as colour or size, along with generations (it can be seen as a bottom-up modification). With an accumulation of micro changes along an extensive period of time, the big-scale, called macroevolution, can create entirely new species. Another key factor of the natural selection is the ability to the success of an organism attract a mate, called Sexual Selection (Than & Live Science, 2018). The Sexual Selection is so essential, that is common to observe that many species have created special modifications or behaviour that requires a lot of quantity of energy and material just to guarantee the reproductive success, even if these special characteristics in nothing influence the daily survival actions, such as, eating, hunting, escaping etc. (Figure 89). The sexual importance to life, including the humans, has been defended by Freud with the concept of sexual drive, as being one of the most significant drive forces of the human behaviour (Encyclopaedia Britannica, n.d.; Kandel, 2012; Stoléru, 2014), influencing deeply the unconscious and acting in the most of the intellectual productions and artistic manifestations, spreading until product design.

The small physical or behavioural changes happen due to random genetic modification in the reproduction of DNA passed to the new generations. It means that evolution creates information, increasing its complexity along the time in a process that never stops. However, it does not mean that all generation mutated is better than previous one. Better or worse organisms can be created but it is the natural selection that will make the best ones survive. That suggests that the evolution is a process marked by attempts and errors, through random changes. Moreover, the concept of better or worse is relative or, in other words, the evolution process creates information, but does not have "memory".

The time scale to note significant changes in species from evolution is of thousands or millions of years. For human perception, this scale of time is hard to imagine, but the planet Earth is around 4.5 billion years old. Life started to appear about 3.8 billion years with single-celled prokaryotic cells, such as bacteria. Only 570 million of years ago, more complex life forms started to appear with arthropods. Land plants have emerged around 475 million of years ago. Mammals have appeared approximately 200 million of years ago, and the Homo sapiens only 200 thousand years ago (0,004% of Earth's age) (BBC, 2018) (Figure 90). During all this period, nature has created more than 30 million species (J. M. Benyus, 2009).

Figure 89 - Sexual animal ornaments. At left picture a male moose displaying antlers. At right picture a Male peacock showing its tail. Source: Study.com

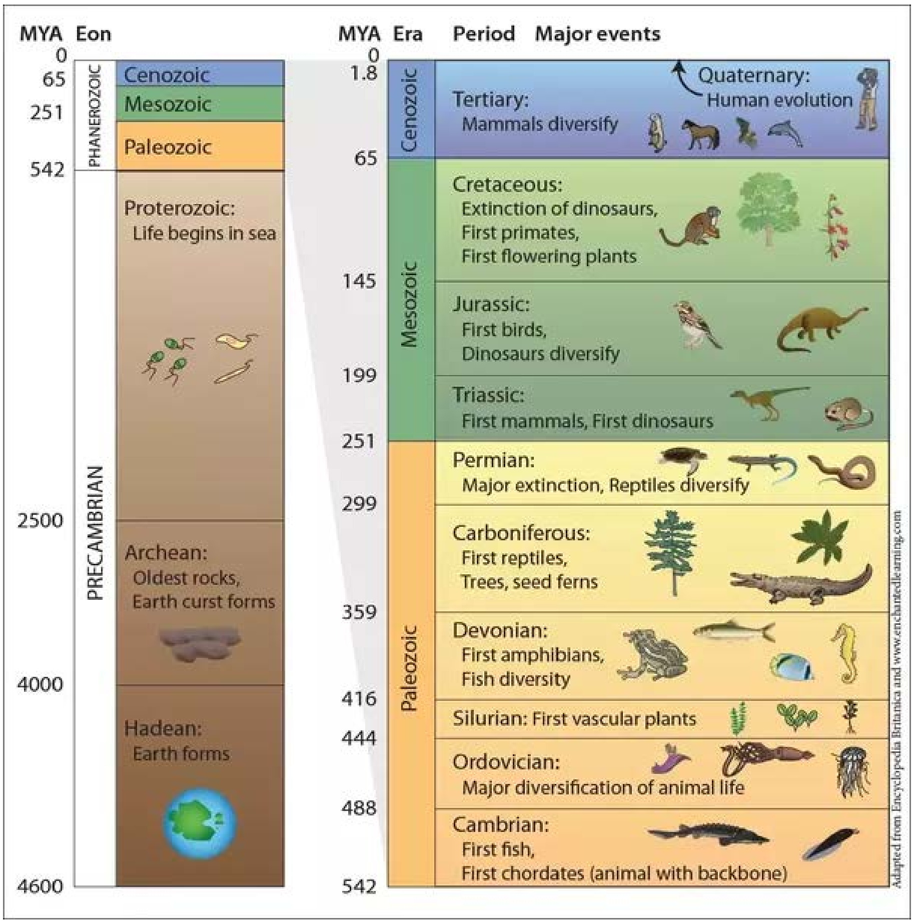

Figure 90 - The geologic time scale (GTS) from the origin of the earth to human origin. MYA: Millions of Years Ago. Source: IAS4Sure.

Some of the optimisation algorithms are based on evolutionary concepts, using nature-inspired strategies.

3.2.3.1. Types of Evolution

Over the time, the evolution can follow different patterns. Three more common patterns are convergent, divergent and parallel.

Convergent: When different species with different ancestry have similar characteristics (behaviour, structure, anatomy, appearance etc). This convergence happens due to the environment and other survival pressure in common among the species. Structures created by convergent evolution are called of Analogous Structures or Homoplasies. Examples of convergent evolution are birds, insects and bats. All of them created wings to supply the same need, to fly (Figure 91).

Divergent: When different species have different characteristics, but are from the same ancestry. This divergence happens when a group migrates to another environment. The divergence is responsible for life diversification of species and breed. Some species may develop Homologous Structures that are anatomically similar, with similar functions from a common ancestor (Figure 92).

Parallel: When different species evolves along the time maintaining the same level of common characteristics. These species do not necessary have a common ancestor, environment or survival pressures. But, they have created similar adaptations strategies. Plants are a good example of parallel evolution.

Understanding these differences allows to find some similar behaviour in the TO process. In particular to the convergence, and to homologous structures, supposing that structures with similar boundary conditions but with different applications could create similar solutions, and use them for standardisation of parts to decrease manufacturing costs.

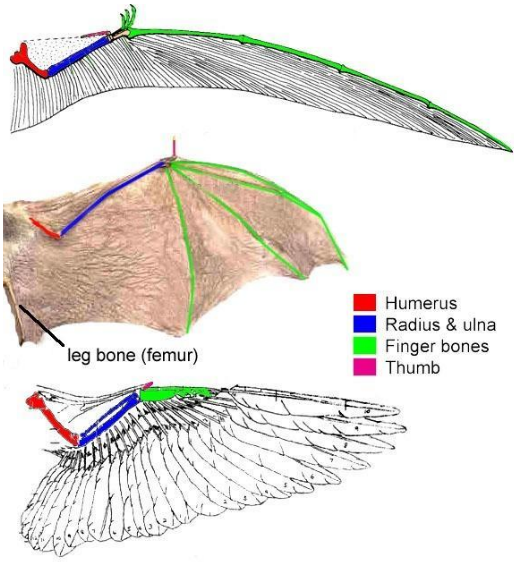

Figure 91 – Example of convergent evolution with wings of a pterosaur, bat and bird. All species have no common ancestor, but they all have created wings to the same function, to fly. Bones with the same colour are homologous structures. Source: National Center for Science Education.

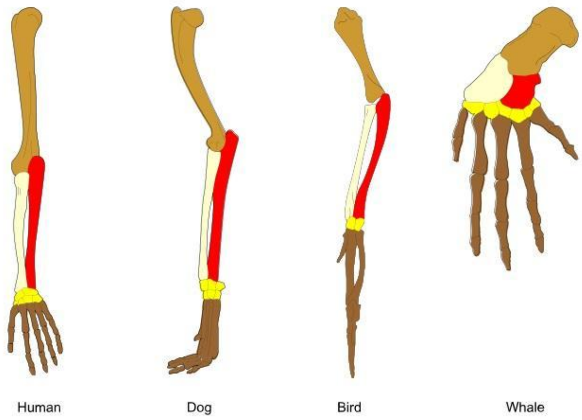

Figure 92 – Species from divergent evolution, with a common ancestor (vertebrates). Bones with the same colour are homologous structures. Source: Biology Dictionary.

3.2.4. Wolff's Law

Formulated in 1892 by anatomist and orthopaedic surgeon Julius Wolff, the Wolff´s Law states (Wolff, 1986):

> "Every change in the form and the function of a bone or of their function alone is followed by certain definite changes in their internal architecture and equally definite secondary alterations in their external conformation, in accordance with mathematical laws." (p.225)

In other words, it means that a bone in a healthy organism will adapt to changes in loads (intensity or directions), first in remodel of its internal architecture (trabeculae), followed by the remodelling of its external portion changing its thickness, in a dynamic process (the skeletons are constantly changing). If the loads increase, the bone becomes denser and stronger, if it decreases, it loses mass and becomes weaker.

other consequences of this adaptation process are: The ratio between strength and weight is optimised; The trabeculae will be aligned with principal stress directions; The self-regulation of bone cells is a response to mechanical stimulus (Folgado & Fernandes, 2011) (Figure 93).

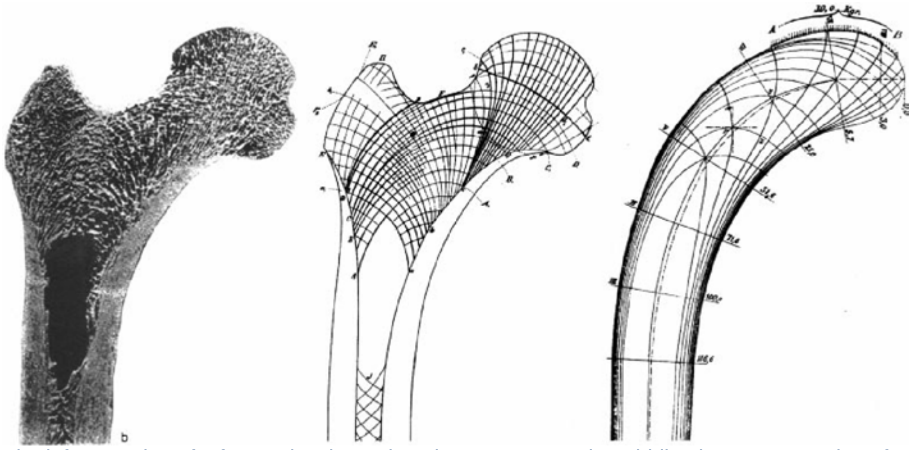

Figure 93 - In the left, a section of a femur showing trabecular structure. In the middle, the representation of principal stress directions (Meyer, 1867). On the right, the stress trajectories in a model analysed by Culmann. The curves are the representation of the orientations of maximal and minimal principal stresses trajectories that always intersect perpendicularly. Adapted from (Wolff, 1986)(translation). Source: (Huiskes, 2000).

This density adaptation process of bone is an interactive optimisation process that minimises the strain energy and ponders the relative densities as optimisation variables. A process similar in a Topology Optimization process in which the variable to optimise is the bone density, (that will add/increase the material density in higher stress regions and decrease/remove from lower stress regions). For this reason, TO can be used as a useful tool in biomechanical, for remodelling and adaptations models to bones.

3.2.5. Mathematics Relations in Nature

Most of nature's creation or optimisation processes are supported by mathematics and algorithm representations, and through this understanding, these relations can be applied to human products and services.

It was in 1202 when a 32-year-old Italian, Leonardo of Pisa, referenced as the greatest mathematical of middle age, and known as Fibonacci (is a shortening of the Latin *filius Bonacci*, that means the son of Bonaccio), finished one of the most influential books of all times, introducing the Hindu-Arabic numerical system to Western Europe. Before that, Europeans used Roman numerals in arithmetic. The Fibonacci Sequence (FS), or Fibonacci Numbers, is an integer sequence where the next number is the result of the sum of the two previous numbers, starting with 0 and 1 (Table 4).

Fibonacci Sequence rule:

$x_n = x_{(n-1)} + x_{(n-2)}$, where n is the number position on sequence (8)

Table 4 - First fifteen numbers of Fibonacci Sequence.

n	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
(X)(n)	0	1	1	2	3	5	8	13	21	34	55	89	144	233	377	…

Fibonacci presented the sequence due to an observation of an old 6th century Indian mathematical problem about rabbit reproduction starting with one male and one female, and for one year (Figure 94). The premises of this problem are: the initial couple have just been born. The rabbits´ sexual reproduction occurs at each month, and the gestation period is of one month. Each couple gives birth to one more couple. No rabbit dies for a year.

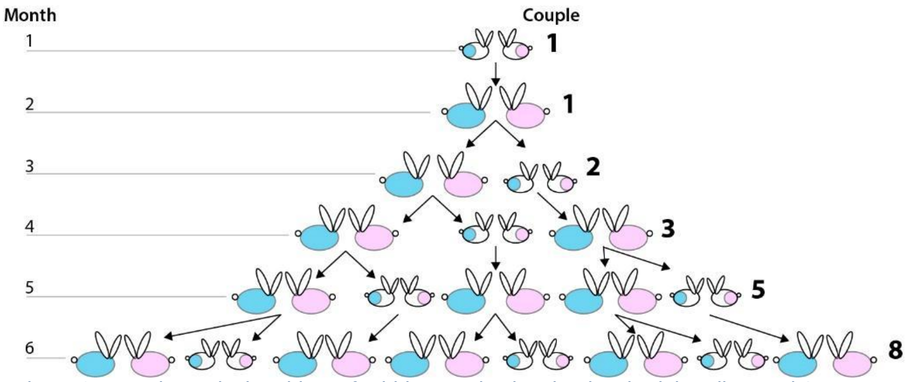

Figure 94 - Mathematical problem of rabbit reproduction that inspired the Fibonacci Sequence.

There are numerous curiosities and mathematical relations about the FS that have been discovered along the centuries see (Garland, 1987; Posamentier & Lehmann, 2007).

The Fibonacci Sequence is also found in numerous natural phenomena. But, before discussing this, it is necessary to first introduce the concept of the Golden Ratio (φ), also called the Golden Mean or the Divine Proportion. The Golden Ratio has been used since ancient times by the Egyptians and Greeks, and has attracted the attention of many talented minds over centuries such as mathematicians, physicists, biologists, artists etc. The Greek symbol φ (Phi) was adopted in the 1900´s in honour of Phidias (500 BC – 432 BC), a Greek sculptor and mathematician, that applied it to the design for the Parthenon and its arts (Meisner, 2012) (Figure 95). The number φ is equal to 1.6180339…, and it starts to appear when two sequential Fibonacci Numbers are divided by each other. Initial divisions have results far from φ, but with each successive division, the result comes closer and closer to φ (Figure 96).


Figure 95 - The use of the Golden Ratio there is in numerous details of the Parthenon. Source: Thenews-Today.info

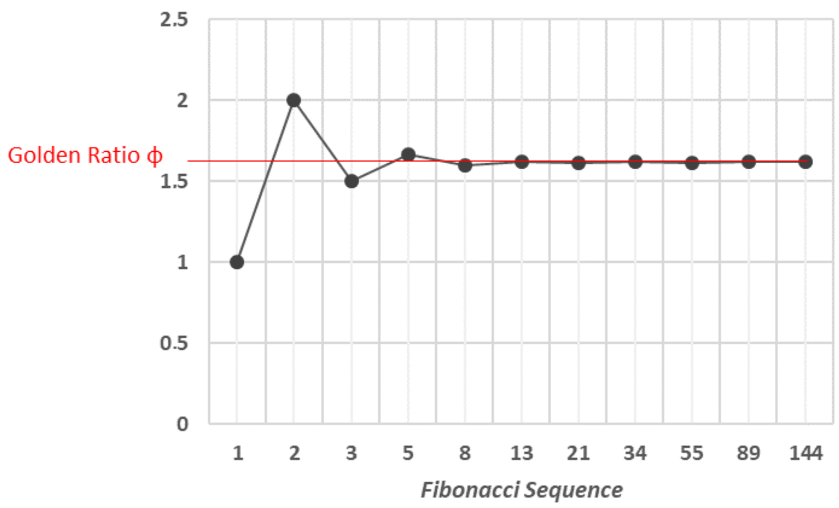

Figure 96 - The Golden Ratio (φ) starts to appear when two sequential Fibonacci Number are divided by each other.

Most of the Golden Ratio manifestation is found in geometry patterns. The golden rectangle is formed with any proportion of edges with 1 x φ if this rectangle has its bigger edge separated in 1 and 0,618… (creating one square and one rectangle), another golden rectangle will appear, and doing it again to the new rectangle, another rectangle will appear again, and again and again (Figure 97 (a)). If in this division, a $\frac{1}{4}$arc in square vertex is drawn, and again for the other smaller square, again and again, the golden spiral will be created (Figure 97 (b)). If all squares are measured, their dimensions will follow the Fibonacci Sequence (Figure 97 (c)). These geometries relationships are found in many natural events, alive or inanimate (Figure 98). There are many other geometries that show the Golden Ratio, found in literature. The Golden Angle (ψ) is the complementary angle found by the division of a complete circumference with φ, as:

$$\varphi = 360° - \frac{360°}{\varphi} \cong 137{,}507° \ldots \tag{9}$$

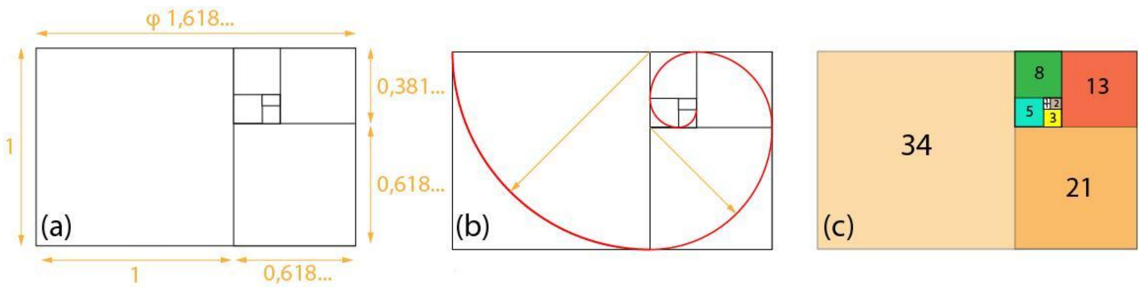

Figure 97 - Golden Ratio and geometry relationship. (a) Golden rectangles, (b) Golden spiral, (c) Square edges are a Fibonacci Sequence.

Figure 98 - Golden Ratio and geometry relationship are manifested in many natural events, alive or inanimate. Source: Totem Learning.

Fibonacci Sequences and Golden Ratio relationships are often present in plants (flowers, leaves, fruits, branches etc.). Many flowers use the Fibonacci Numbers as the number of petals and seed heads are organised following the golden spiral, the golden angle, and the Fibonacci Numbers quantities (Figure 99). This very efficient arrangement to catch solar energy gave inspiration to positioning mirrors to the creation of a thermal-solar energy generator (Figure 100).

Figure 99 - The number of petals of most of the flowers is Fibonacci Numbers. Source: The Fibonacci Sequence.

Figure 100 – Sunflower seed heads arrangement composed of golden relationships. That arrangement inspired the creation of a thermal-solar energy generator. Source: Solar Group.

It is also common to find golden relationships in animals and human (Figures 101 and 102). The human body has numerous divisions that respect the Golden Ratio (Figure 103).

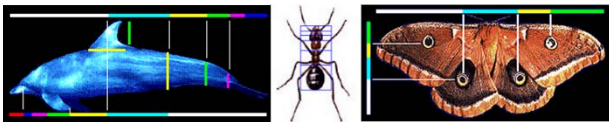

Figure 101 - Example of the Golden Ratio in animals. Source: GoldenNumber.net

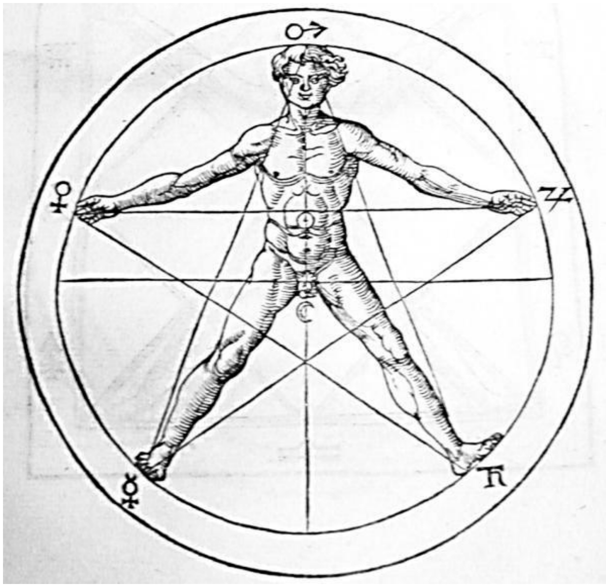

Figure 102 – Relation representation of a man with a pentagram, that has the Golden Ratio. Pentagram and human body of Heinrich Cornelius Agrippa (1486–1535), public domain.

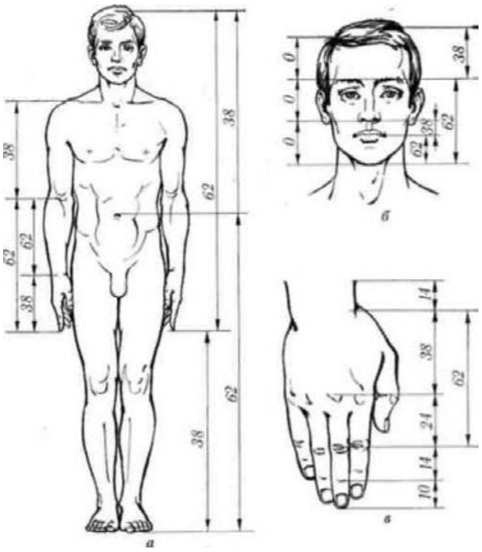

Figure 103 - Examples of divisions in human anatomy that is found the Golden Ratio. Source: Newhacks.info

According to Raymond and Schleiniger, (Raymond & Schleiniger, 2017), an explanation of why the Fibonacci Sequence often appears in patterns of growth in nature is that the growth and self-renewal cells process induce hierarchical patterns generation. This hierarchical pattern, in different scales, is the same as the problem of rabbit population growth. Thus, mathematical laws involving temporal and spatial rules for cell division and growth patterns, end up being the Fibonacci Sequence. However, it is essential to emphasise that the Golden Ratio only appears in living beings if they are healthy. Any mutation or interruption in the natural growing process will create anomalies that will not respect the proportion. For this reason, it is possible to suppose that the human brain unconsciously associates s that have the Golden Ration as harmony and beauty, regardless of culture or time, meaning that this proportion can be considered a universal beauty standard. Due to this peculiar property, the Golden Ratio has been intensively explored by artists, architects, designers, marketers etc. One of the most famous was Leonardo Da Vinci (Figures 104, 105, 106, 107, 108 and 109).

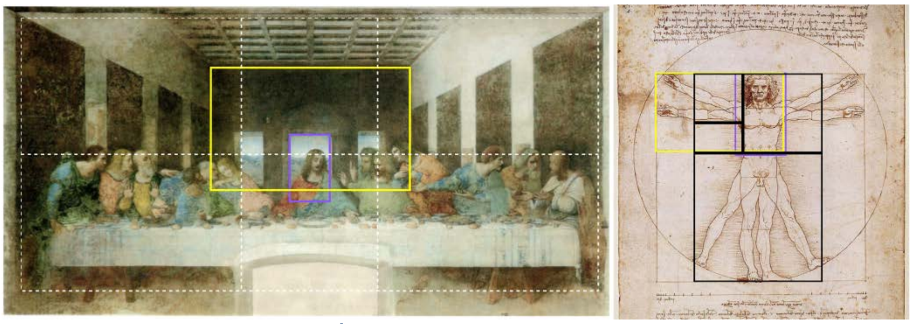

Figure 104 - Examples of Leonardo Da Vinci´s arts supported by some golden ratios. Source: Museum of Science.

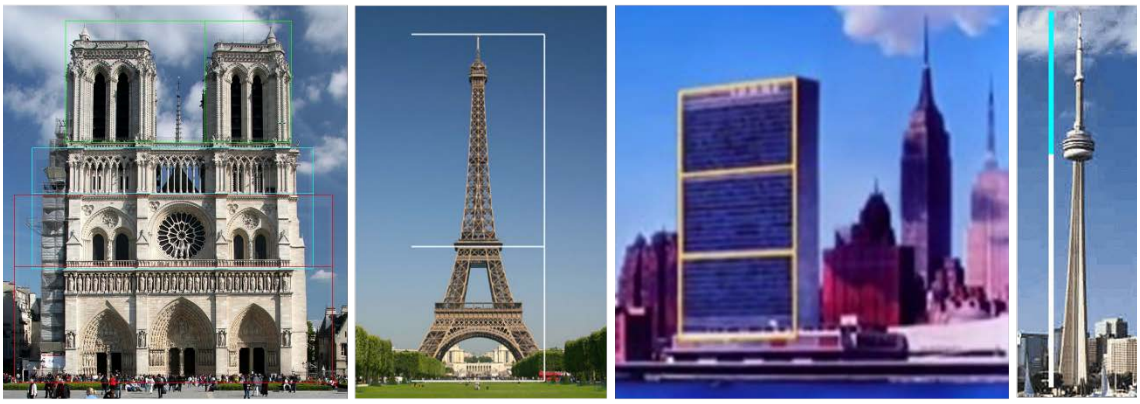

Figure 105 - The Golden Ratio in architecture: Notre Dame, Eiffel Tower, UN Secretariat Building, Toronto’s CN Tower. Source: GoldenNumber.net/Prototypr

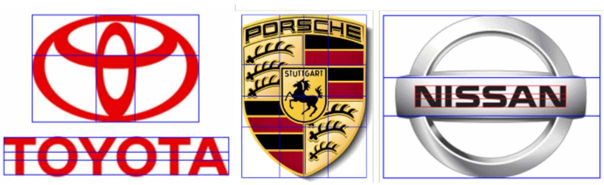

Figure 106 - Logo companies and the Golden Ratio. Source: GoldenNumber.net.

Figure 107 - Product design and the Golden Ratio. Source: GoldenNumber.net.

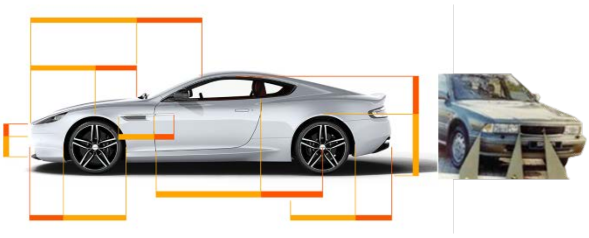

Figure 108 - Car design and the Golden Ratio. Source: GoldenNumber.net.

Figure 109 - Web design and the Golden Ratio. Source: Joshua Garity.

The maxillofacial surgeon Dr Stephen Marquardt, based on the Golden Ratio and studies of beauty patterns throughout history and hundreds of faces, created the beauty mask (Figures 110 and 111). The more a person's face fits with the mask, the more they are likely to be considered beautiful. Even if a person is not considered beautiful, through digital manipulation of the picture using the mask as a reference, it is possible to one be considered more attractive (Figure 112).

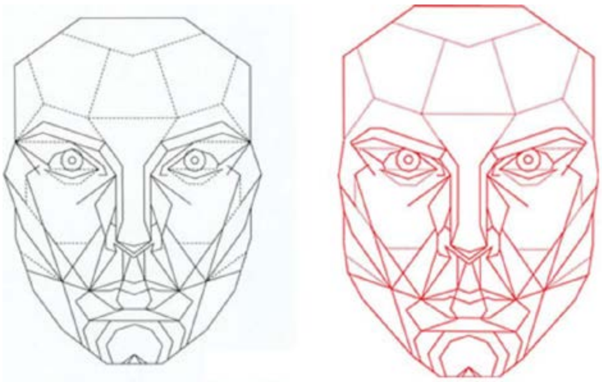

Figure 110 – Marquardt´s mask golden ratio. Source: Marquardt.

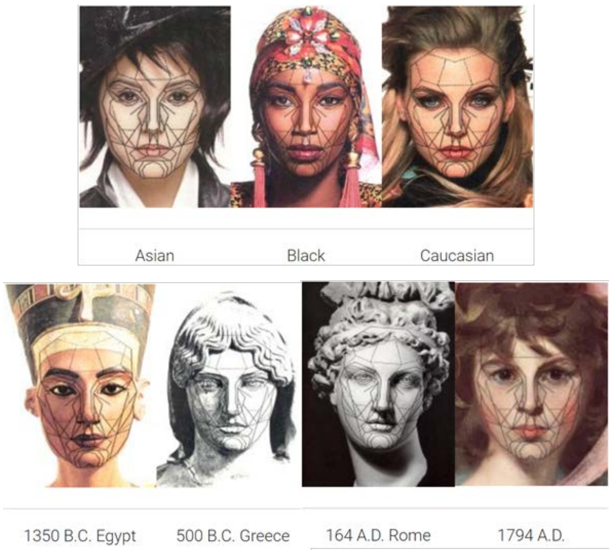

Figure 111 - Beauty standard over time. they all fit in the Marquardt´s Mask. Source: GoldenNumber.net.

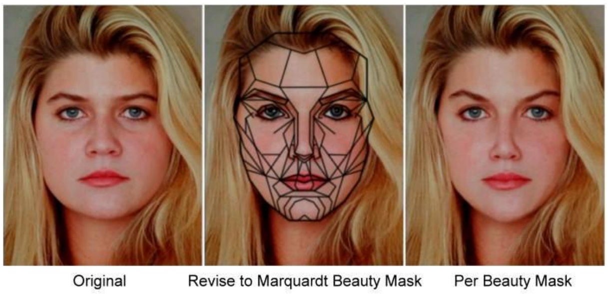

Figure 112 - Example of how a face can become more beautiful after digital manipulation with the Beauty Mask, based on the Golden Ratio. Source: GoldenNumber.net.

Another frequent pattern that appears in nature is the fractals. Fractals are geometric decomposition (or growth), on its edge, of a similar geometry (exact, approximate or statistical), but in different scales, that can repeat infinitely. Different from the Fibonacci Sequence, fractals have irregular properties that cannot be described by Euclidean Geometry[7] (Meakin, 1990), although, that does not mean that the Fibonacci Sequence and fractals cannot be found together in naturals phenomena, that in fact is possible (Figure 113).

[7] Euclidean Geometry is the study of lines, planes and solids figures based upon intuitive and deductible postulates, attributed to the Greek mathematician Euclid (c. 300 BCE).

Figure 113 - Examples of fractals in nature: Cauliflower (fractals and Fibonacci Sequence manifested together), Crystal of fluorite, Rain Source: (Meakin, 1990), and snowflake Source: Shutterstock.

All these mathematical manifestations in nature, the Fibonacci Sequence, the Golden Ratio and fractals, are an affluent source of inspiration to the product design and development. The incorporation of these in the creative process with Topology Optimisation, can give more options and unexpected solutions, and even control beauty and intangible aspects in the final form.

3.3. Biomimicry Applied to Product Design and Development, and Topology Optimisation

3.3.1. Usage

As previously explained, nature has created solutions tested and improved by millions and millions of years. These solutions are sustainable, optimised regarding resources (mainly material and energy) and reliable. Moreover, nature can be a source of inspiration of intangible aspects of design, such as colours, patterns, form, smell and sounds, and these sensations transformed in art to improve human interaction. These reasons turn nature into an excellent benchmark for efficient solutions. With biomimicry application in product design and development, as defended by (J. Benyus, n.d.) nature is now seen as model, measure and mentor:

Nature as model: A model to copy and translate the solutions found to human problems and necessities.

Nature as measure: To indicate references about how useful or right is the adaptation of the model to human use.

Nature as a mentor: The view of nature is turned from a source of resources to a source of knowledge, leading people to be concerned about the preservation of all species and their habitats.

From biomimicry, it is possible to find solutions to several aspects to modern human society, in fields such as nanotechnology, materials and molecular engineering, smart computers, arts, business and management models, structural and fluid-dynamics efficiency, medicines, special sensors, tissue and cellular engineering, energy systems etc (Figure 114).

This process of solution incorporation can happen in two ways (Stokoe, 2013):

Solution-driven approach: By learning, that is, after the identification of behaviour, characteristic or function of an organism or ecosystem, and converting that to human necessities through biology influenced design.

Problem-driven approach: By searching, that is, identifying a human need or design problem and looking in nature how organisms and ecosystems solve this.

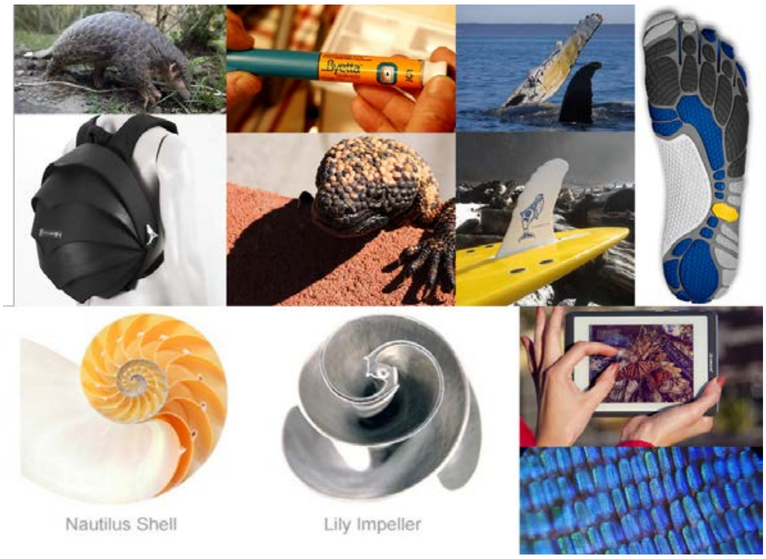

Figure 114 - Examples of solutions found from biomimicry/biomimetic. Source: BiomimicryNYC

3.3.2. Approach Methods

3.3.2.1. Biomimicry Thinking and DesignLens

This approach was developed by Biomimicry 3.8 (Biomimicry 3.8, 2015) to support any people to practice biomimicry while designing anything. This methodology sees everyone as designers, regardless of formal titles; thus, the term “design” is for everyone who is creating something new either cultural, technological, social, scientific or financial systems.

Sequence of implementation:

I. Essential Elements:

The biomimicry practice has three interconnected elements (Figure 115).

Ethos: Respect, responsibility and gratitude for all environment.

(Re)Connect: Human and nature are intertwined. Human is nature, and this relationship mindset must be recovered.

Emulate: Identify and apply in a sustainable way the principles, patterns, strategies and functions found in nature during design.

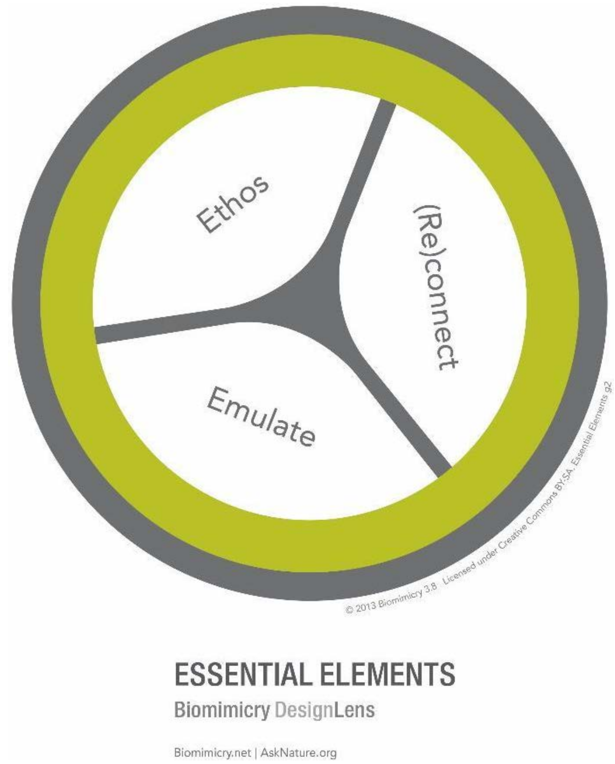

Figure 115 - Biomimicry DesignLens and its three essential elements Source: (Biomimicry 3.8, 2015).

II. Life's Principles:

Strategies to create sustainable conditions for life. In order to living species to survive and thrive, there are successful holistic principles, developed over 3.8 billion years. These principles give lessons to design the solution (Figure 116).

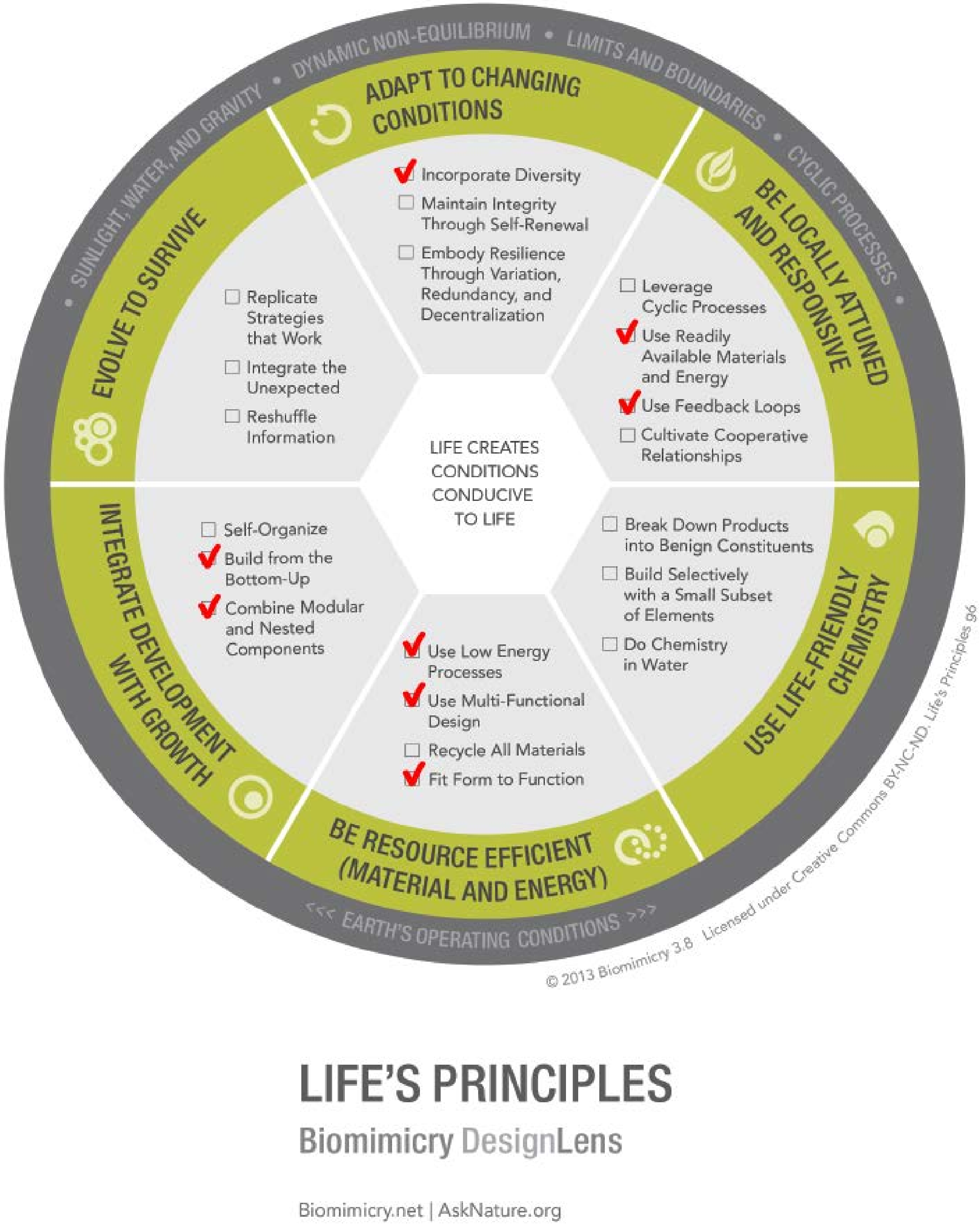

Figure 116 - Biomimicry DesignLens Life's Principles. Marked in red, direct or indirect propositions that can be applied supported by TO. Adapted from: (Biomimicry 3.8, 2015).

From the Biomimicry DesignLens Life's Principles it is possible to identify eight propositions in five lessons, that can be applied supported by TO.

Incorporate diversity: Through TO algorithms, it is possible to create several optimised solutions in a short time, and evaluate the benefits of each one.
Use readily available materials and energy: The TO algorithms can handle multiple- objectives functions and constraints, most of them, linked to mass (material) and energy reduction. Decreasing the effort to find optimised solutions through this tool.

Use feedback loops: The TO is an interactive process, and most of the boundary conditions can be collected by external environment.

Use low energy processes: TO creates structures that save manufacturing material, and energy reduction both in manufacturing and in use.

Use multi-functional design: The TO algorithms can handle multiple-objectives functions and constraints, respecting all design requirements.

Fit form to function: As defined in section 1.8 (Topology Optimisation in Industrial Design and Hiatus), the TO driven design puts the function in front of form.

Build form from Bottom-up: Although most of the TO process are Top-down (the boundary and external conditions lead to the solution), some local solutions - when successful - are able to force a readjustment of the whole design around this specific solution.

Combine modular and nested components: Complex modular or nested components can be created with less effort and time, with a diversity of options possible to be created allied to the possibility of TO algorithms handling multiple-objectives functions and constraints.

III. Biomimicry Thinking:

Provides context to where, how, what, and why biomimicry fits into the design process. Four areas will provide value to any design process: Scoping, discovering, creating, and evaluating. Biomimicry Thinking can be applied both to Biology and Design (Solution-driven approach) (Figures 117 and 118) or Challenge to Biology (Problem-driven approach) (Figure 119 and 120). In Biology to Design approach, the TO can be applied in three steps: Brainstorming (through creation and simulation of numerous possibilities), Emulating (using nature strategies to the creation of algorithms or new combinations) and Evaluating (through creation and simulation). In Challenge to Biology approach, the TO can be applied in two steps: Emulating and Evaluating.

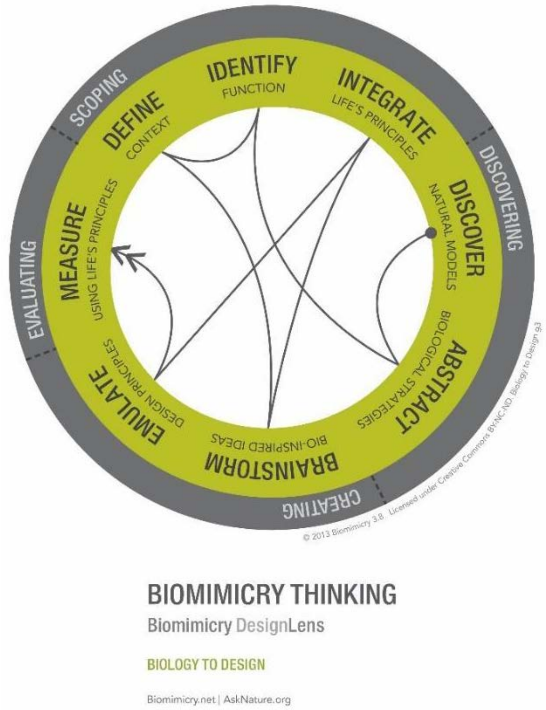

Figure 117 - Solution-driven approach. The sequence is: DISCOVER (Natural models), ABSTRACT (Design principles), BRAINSTORM (Potential applications), EMULATE (Nature´s strategies) and EVALUATE (Against Life´s Principles) Source: (Biomimicry 3.8, 2015).

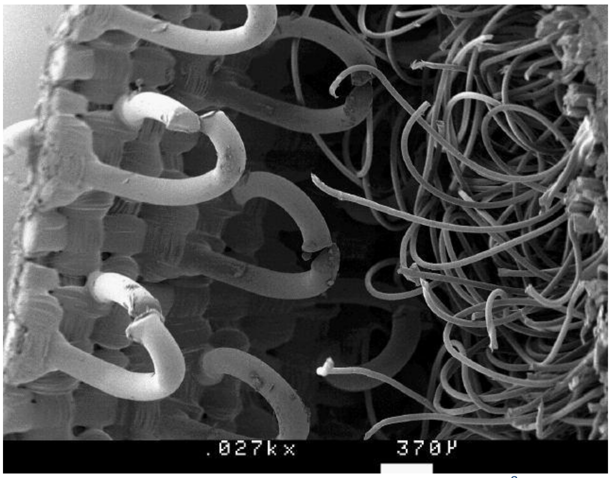

Figure 118 - Example of a Biology to Design application, the invention of Velcro®[8]. Source: (Biomimicry Institute, 2018)

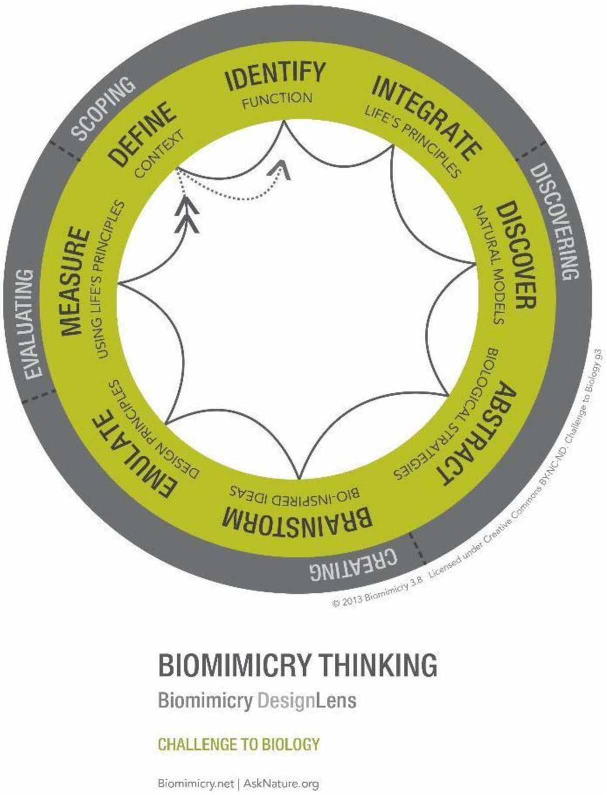

Figure 119 - Problem-driven approach. The sequence is IDENTIFY (Function), DEFINE (Context), BIOLOGIZE (Challenge), DISCOVER (Natural models), ABSTRACT (Into design principles), EMULATE (Nature´s strategies) and EVALUATE (Against Life´s Principles). Source: (Biomimicry 3.8, 2015)

[8] Swiss engineer George de Mestral went for a hike with his dog one day. Later, as he was pulling burdock seeds from the dog's fur, he realized the hooked barbs of the seed could be a model for a new type of hook and loop fastener (Biomimicry Institute, 2018).

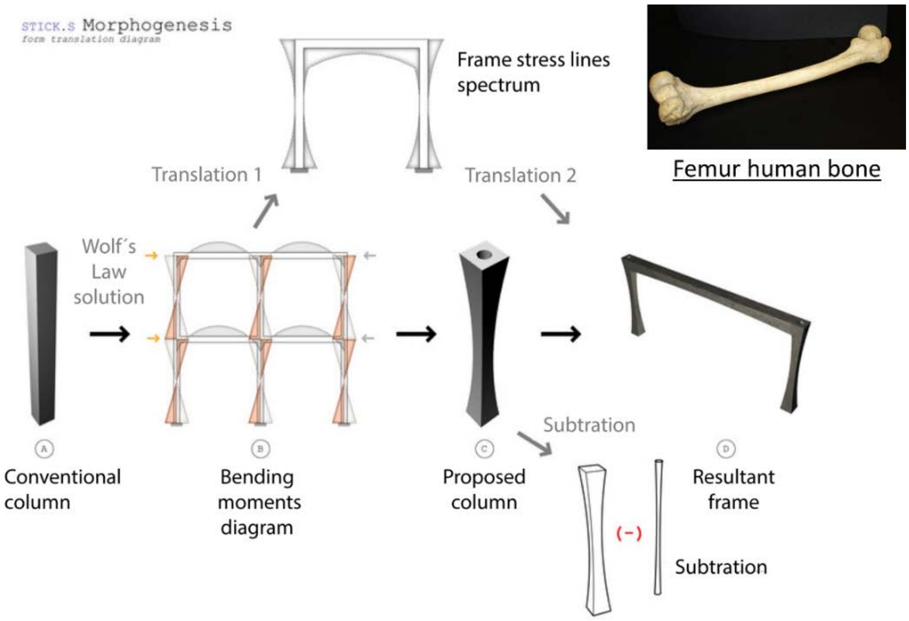

Figure 120 - Example of a Challenge to Biology application, Stick System. It is a lightweight structure model adapted for beams and columns, which are stronger, use less material and are more resistant to earthquakes. It was developed in the search of a structure stronger and antiseismic based on Wilfredo Méndez architect studies about bones structure and Wolff's Law. Adapted from (AskNature, 2016b).

3.3.2.2. Biomimicry Taxonomy

Biomimicry Taxonomy (ANNEX) is a classification system developed by AskNature (AskNature, 2016a) that organise all biological content on its website (https://asknature.org) helping the researcher to find more comfortably possible solutions created by nature. The interface of this approach was developed to give directions from a question about "How nature does something…". This "something" is a function. For this methodology, functions are strategies that organisms or living systems develop to face functional challenges, and these functions can have potential solutions to similar human challenges. The taxonomy is arranged in levels of functions. There are three levels: Group, Subgroup and Function. The level Group represents a broad function performed in nature. The second level is a subgroup of functions. The third level is the specific function. In total, the Biomimicry Taxonomy has eight Groups, with 30 Subgroups and more than 160 Functions. Table 5 shows an example of research using the Biomimicry Taxonomy.

The application for human use of some Biomimicry Taxonomy functions is not direct, being required adaptations and iterations until the final solution is found. For this process, the TO is an excellent tool that can be integrated into search process and solution development. For structural TO, according to concepts found in Chapter 2, it is possible to work combined, directly or indirectly, with the following functions: Manage Structural Forces (Shear, Thermal shock, Impact, Tension, Turbulence, Creep, Compression), Prevent Structural Failure (Buckling, Deformation, Fatigue, Fracture/Rupture) (Figure 121), Modify Physical State (Size/Shape/Mass/Volume, Density), Adapt/Optimise (Adapt behaviours, Optimise space/materials), Transform/Convert Energy (Thermal Energy, Mechanical Energy) (Figure 122), Physically Assemble (Structure), Send Signals (Vibratory) (Figure 123).

Table 5 - Example of research using the Biomimicry Taxonomy Source: (AskNature, 2016a).

Organism	**What is the organism?**	Namib desert beetle
Challenge	**What challenge must it address?**	Capturing water in a very arid climate
Strategy	**How does the organism address this challenge?** (strategy)	The beetle's wing covers gather water from the air using nanoscale bumps and body position. **View this strategy page on AskNature**.
Function	**Why does the organisms need this strategy?**	To capture liquid This is represented by the Biomimicry Taxonomy as: ➤ **Group**: Get, store, or distribute resources ➤ **Sub-group**: Capture, absorb, or filter resources • **Function**: Capture, absorb, or filter liquids

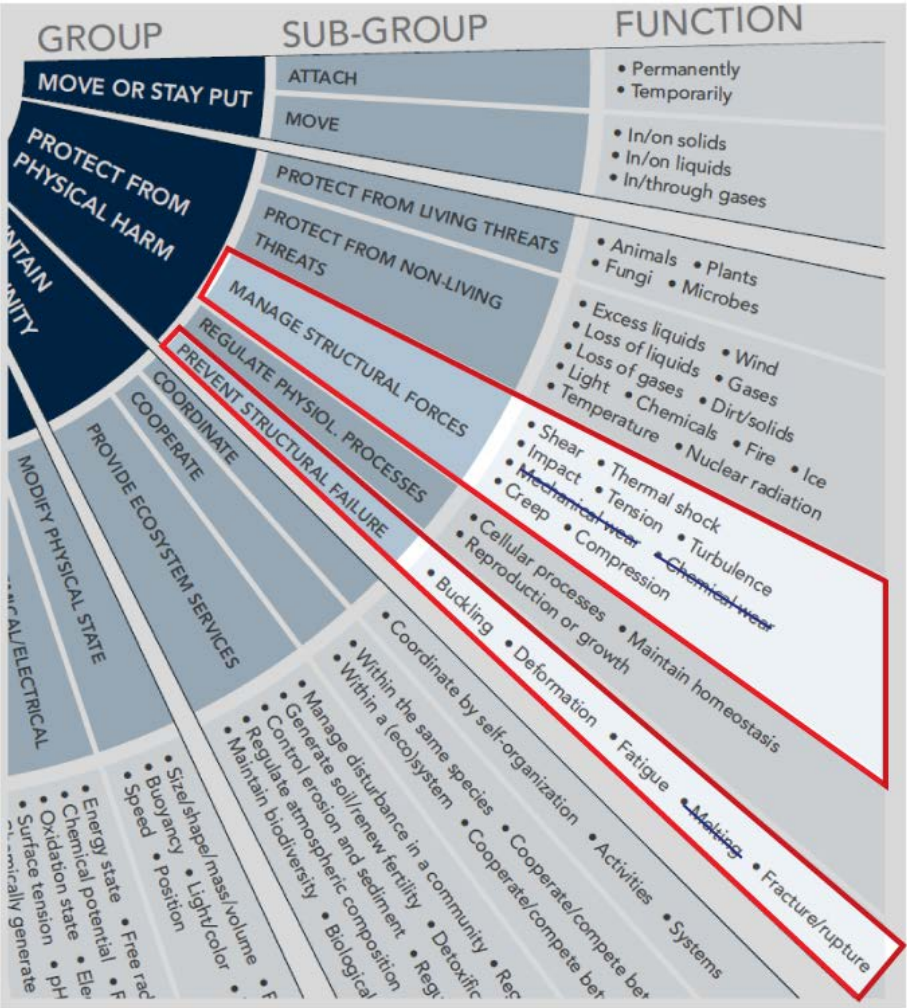

Figure 121 – Some functions likely to combine, directly or indirectly with structural TO. MANAGE STRUCTURAL FORCES (Shear, Thermal shock, Impact, Tension, Turbulence, Creep, Compression), PREVENT STRUCTURAL FAILURE (Buckling, Deformation, Fatigue, Fracture/Rupture). Adapted from (AskNature, 2016a).

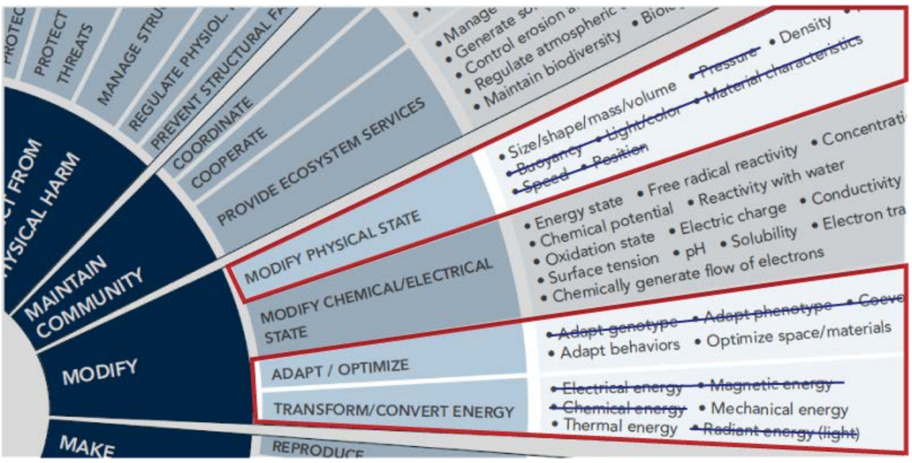

Figure 122 - Some functions likely to combine, directly or indirectly with structural TO. PREVENT STRUCTURAL FAILURE (Buckling, Deformation, Fatigue, Fracture/Rupture), MODIFY PHYSICAL STATE (Size/Shape/mass/Volume, Density), ADAPT/OPTIMISE (Adapt behaviours, Optimise space/materials), TRANSFORM/CONVERT ENERGY (Thermal Energy, Mechanical Energy). Adapted from (AskNature, 2016a).

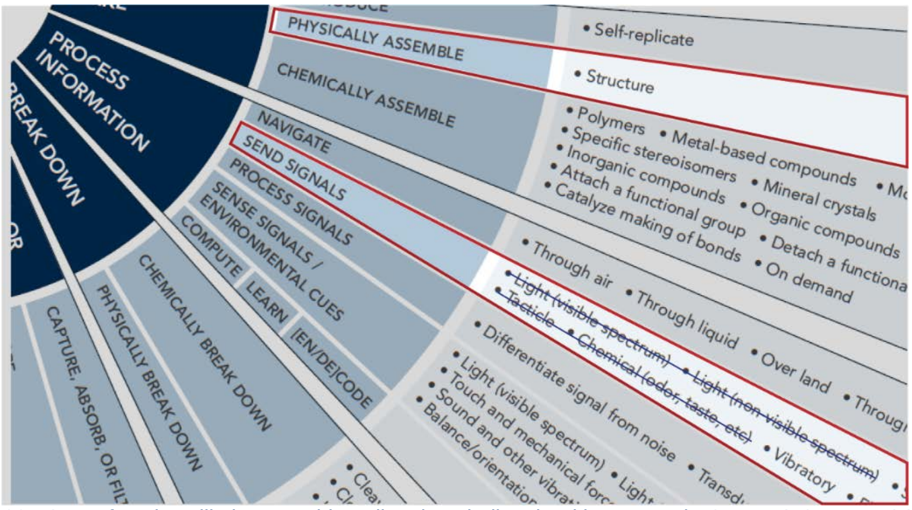

Figure 123 - Some functions likely to combine, directly or indirectly with structural TO. PHYSICALLY ASSEMBLE (Structure), SEND SIGNALS (Vibratory). Adapted from (AskNature, 2016a).

3.3.2.3. Biomimicry Design Spiral

Biomimicry Design Spiral, developed by Biomimicry Institute (Biomimicry Institute, 2017), is a Biology to Design approach (Solution-driven approach), with some similar strategies of the Biomimicry Thinking method.

This method is divided into six steps. The spiral is broader in initial stages, with more options of search, and tapering at the end, with more limited options. The six steps are Define, Biologize, Discover, Abstract, Emulate, Evaluate. This sequence of steps is a suggestion in which the course can change according to the project's necessities. The reason why this approach was designed in spiral shape (Figure 124).

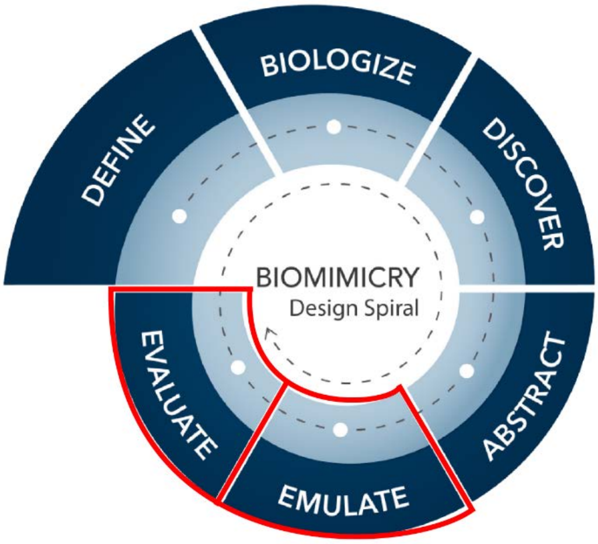

Figure 124 - Biomimicry Design Spiral for a solution-driven approach. Delineated in red, some ofthe steps that could be supported by TO. Modified from: (Biomimicry Institute, 2017).

Define: Describes the challenge, aims, criteria and constraints of the project.

Biologize: Unravel the functions and context of the project objectives and translate them into biological terms.

Discover: Search for organisms and ecosystems that have the same functions and context. Identify what are the strategies used to support their survival and success.

Abstract: Study and comprehension of the essential features or mechanisms that make the strategies successful.

Emulate: Search for patterns and relationships between the strategies until they reach a full comprehension. Apply it to design concepts. This search can be supported by the use of TO through its constraints and multiple solutions likely to be found.

Evaluate: Check if the design concept(s) meet all the requirements in *Define* step and if the technical and business model are feasible. Review previous steps if necessary until it reaches a viable solution. TO and FEM, together are a feasible tool to evaluate and select some of the best solutions found in the Emulate phase.

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3.3.2.4. Typological Approach

This methodology created by Maibritt Pedersen Zari (Zari, 2006), is a stratification searching method composed by the three levels of biomimicry (Organism, Behaviour, Ecosystem), followed by five models for each: Form (shape), Material (properties), Construction (arrangement or composition), Process (mechanism), Function (use) (Figure 125).

Organism: The whole organism or a particular feature is analysed.

Behaviour: Comprehension of how the organism relates to the environment.

Ecosystem: Common principles of successful ecosystem are emulated or recreated.

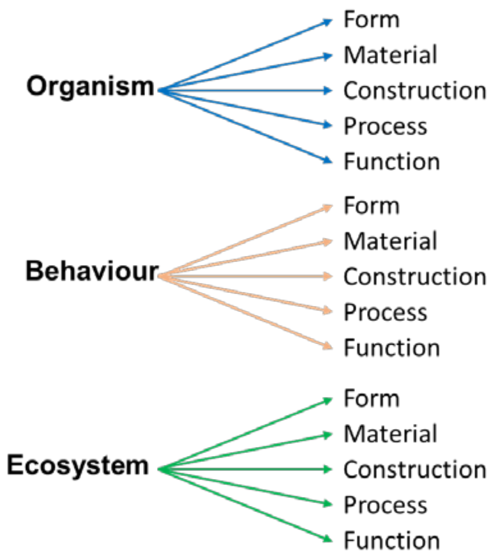


Figure 125 - Illustration of a Typological Approach.

3.3.2.5. Design Thinking Adapted

This methodology was created by Hasso Plattner Institute for Design (aka “d.School”) (Biomimicry Institute, 2018) at Stanford University as an adaptation of traditional Design Thinking method. This adapted method does not change the traditional; it just includes directions to better match the approach to the biomimicry universe, defining essential questions and context vision that the designer needs to have (Figure 126).

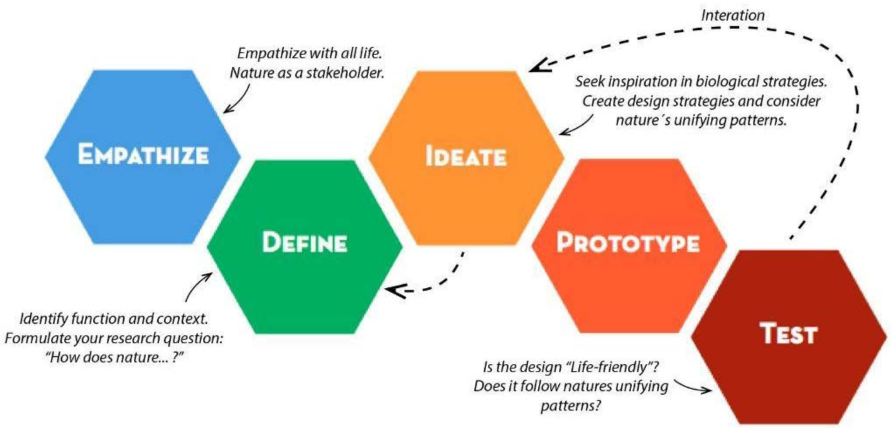


Figure 126 - Design Thinking adapted to Biomimicry. Modified from: Hasso Plattner Institute of Design at Standford.

3.3.2.6. Engineering Design Process Adapted

Engineering Design Process (EDP), created by NASA, is a teaching guide designed as an iterative process to be used as a problem-solver. Designers and engineers ask questions, imagine solutions, plan designs, create and test models, and then make improvements (NASA, 2018). This adaptation (Biomimicry Institute, 2018) includes directions to fit better the approach to the biomimicry universe, defining essential questions and context vision that the designer or engineer needs to have. In step 2, function and context are defined. From step 3 to 5, biology search for inspiration, strategies translation, and nature's unifying patterns are included. Step 8 is the validation of the solution (Figure 127).

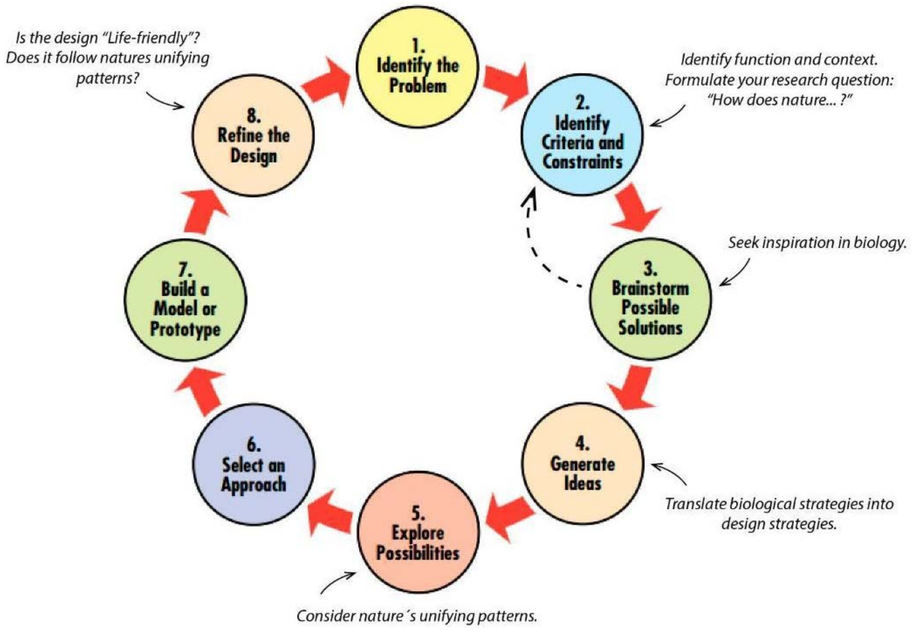


Figure 127 - Engineering Design Process (EDP) adapted to Biomimicry. Modified from: NASA.

CHAPTER 4

Concepts of Shape Exploration with Topology Optimisation

4.

4.1. Shape Exploration in Product Design

Some of the statements in this section were based on studies of Miquel Prats, 2007, but with complementary conclusions; in which the influence of the product shape in the design process is explored.

Usually, the term *shape* of the product is related to its two-dimensions silhouette of an object and the term *form* is related to three-dimension (Miquel Prats, 2007). In this dissertation, *shape* means a contour at all of an object, even being two or three-dimension. The term *product* here is always related to tangible objects, composed of form and function.

Fundamentally, product development is motivated to meet a human's problem or necessity, through the creation of an object with form and function properties. The relation between form and function has been subject of discussion through time by several designers. The architect Louis Sullivan (1856-1924) declared in the end of 1910, "Form follows function". Next, the architect Frank Lloyd Wright (1867-1959), changed this statement to "Form and function are one", in a holistic vision based in nature as the best example of this integration, introducing the organic design. Indeed, the balance between form and function with tangible and intangible aspects transits depending on discipline and the objective of the project. The model presented by Gotzsch (1999) allocates the limits between Engineering, Industrial Design and Art in the product creation process, and a similarity with natural design process can also be placed relating form and function (Figure 128).

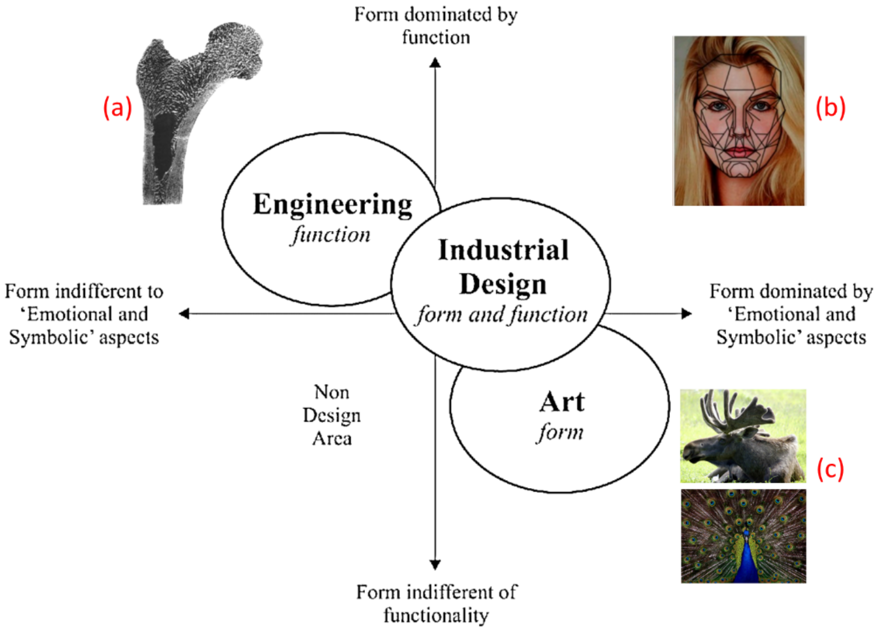


Figure 128 - The balance between form and function with tangible and intangible aspects and creative discipline boundaries. Comparison with natural creation process: (a) Bone, (b) a face with a Golden Ratio frame, as a beauty model, (c) animal sexual ornaments. Modified from: (Gotzsch, 1999).

According to Hierarchy of Consumer Needs proposed by Jordan (2000), there are three levels of satisfaction that a product provides to the user. These are: Function, Usability and Pleasure (Figure 129). These levels work similarly to the human needs model proposed by Maslow (1970), where the user will only consider reaching for the following level when he is completely satisfied with the previous one. It does not mean that one level is more important than the other, but this is the sequence sought by the user. An attractive product can fail if it is not usable and functional, or a usable and functional product cannot have success if it is incompatible with user values. Typically, in competitive markets, all these needs must be satisfied, and the more pleasurable a product is, the more the customer is willing to pay. As defended by industrial designer Raymond Loewy (1893 – 1986), "Between two products equal in price, function and quality, the better looking will outsell the other", and "Ugliness does not sell". The achievement of all these needs is strongly linked to the product shape (Miquel Prats, 2007).

The design process of a product is a complex activity, with several methodologies in the literature. Essentially, the process starts by describing and understanding a problem or opportunity, followed by an exploration of potential solutions, and then proceeding to tests and refinement. It is a learning process with an unpredictable end, where there are numerous possible solutions, in which several iterations are necessary to be done according to feedback loopings, and all this process is majorly supported by visual representations to communication and exploration. As announced by (Palmer, 1999), "The shape can convey more information about an object than any other properties…" (Figure 130). Many requirements must be satisfied, with mutual dependence and sometimes with conflicting objectives. In sum, all these indicate that design is a holistic process, subject to constant evolution, such as nature does, a product is never finished, it is in constant evolution consonant to external pressures. The seeking process of solutions is strongly dependent on the designers' creativity, based on many cases in their past ex\xperiences and educational formation, to the influence of current social forces and personal states, and inspired by other solutions made by human or nature. It means that the solution space is always bigger than designer(s)'s solution space, being the designer's space dynamic and never static. Even the most brilliant designers require a long exploration time to find the adequate shape solution. Currently, new computational tools are emerging with the aim to decrease this exploration time or to expand the designer's solution space. The Topology Optimisation (TO) is an example of an emerging tool that can help the design process during the search of the ideal form, and which has the best balance between the form and function relation (Figure 131).

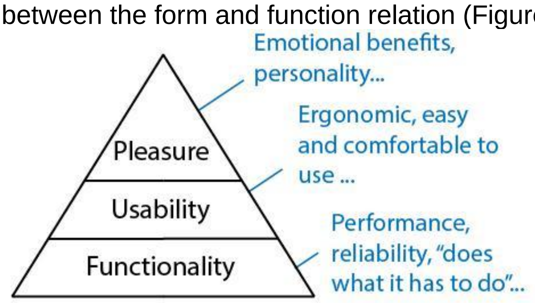


Figure 129 - Hierarchy of Consumer Needs proposed by *(Jordan, 2000)*.

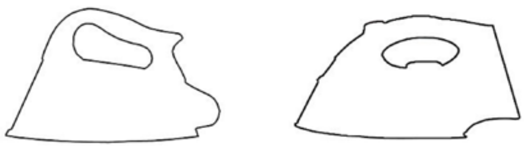


Figure 130 - By only observing the contour of the product shape, it is possible to collect primary information about it. In this case, it is possible to deduce that both products are steam irons, being the left a classical style and the right, a modern one. From: (Miquel Prats, 2007).

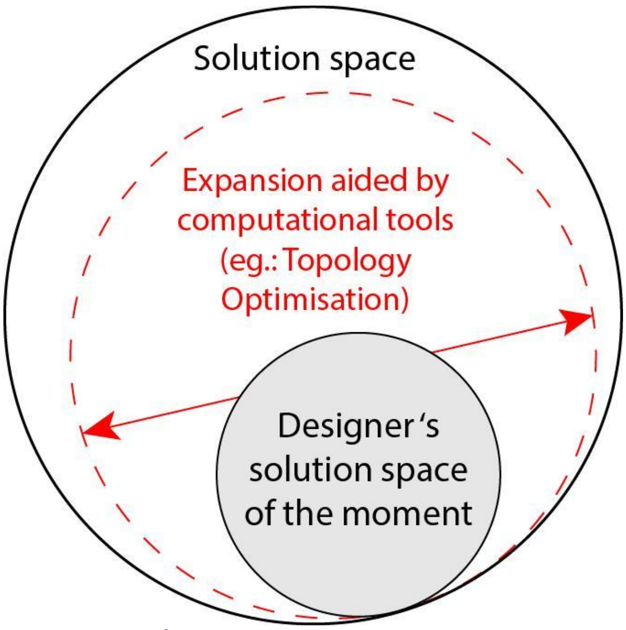


Figure 131 - Solution space and designer´s solution space in product development and the influence with the aid of computational tools.

After understanding the problem and its requirements, the first conceptual design is usually created with simple lines. These lines usually are enough to recognise the whole object with its primary form and function, but incomplete and devoid of details. In this stage, more options for exploration are available, and the development of concepts can take place in various ways. To find the best solutions, it is necessary to have several options for the design process. For Guilford (1967) the concept design generation can occur from convergent or divergent thinking. In the convergent, the shape is an evolution of one or a few concept models. In the divergent, aleatory new concepts are generated. According to (Goel, 1995), the exploration stages can be a lateral or vertical transformation. The lateral transformation is the development from one concept to other concepts by the addition of new elements. The vertical transformation occurs with the generation of a some improvements in the lines and details of the same idea, that is a potential concept solution (Figure 132). It is interesting to note that these exploration processes, have a similarity with the evolution process done by species in nature (see section 3.2.3.1 Types of Evolution).

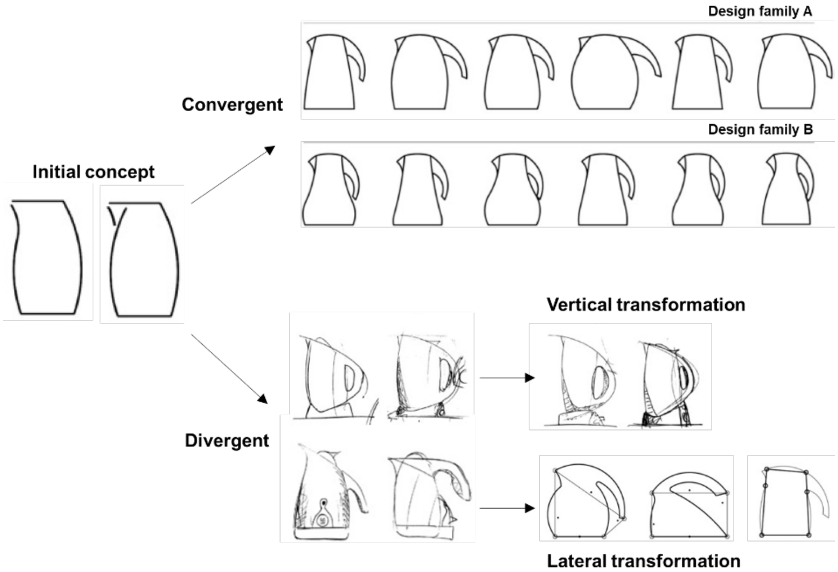


Figure 132 - Concept design generations. Adapted from: *(M Prats, Earl, Garner, & Jowers, 2006)*.

This same process of concept design generations can be performed through Topology Optimisation (TO), instead of the use of sketches only. Using the TO, new concepts are possible to be created changing one or more objective functions and response constraints, while functional performance desired are not significantly penalised, thus increasing with this tool the balance of form and function. The use of hand sketches could support the generation of the initial geometry boundary so that the TO performs possible solutions next (Figure 133). The design of a chair is a classic example of how function and form must be in balance. The chair must be comfortable, ergonomic, light, safety and reliable, beautiful and with beneficent sensory properties to the user, all of these at once. Without these requirements, there is a strong possibility that the chair fails in the market, and an extensive design exploration gives alternatives for the the designers to find the best option.

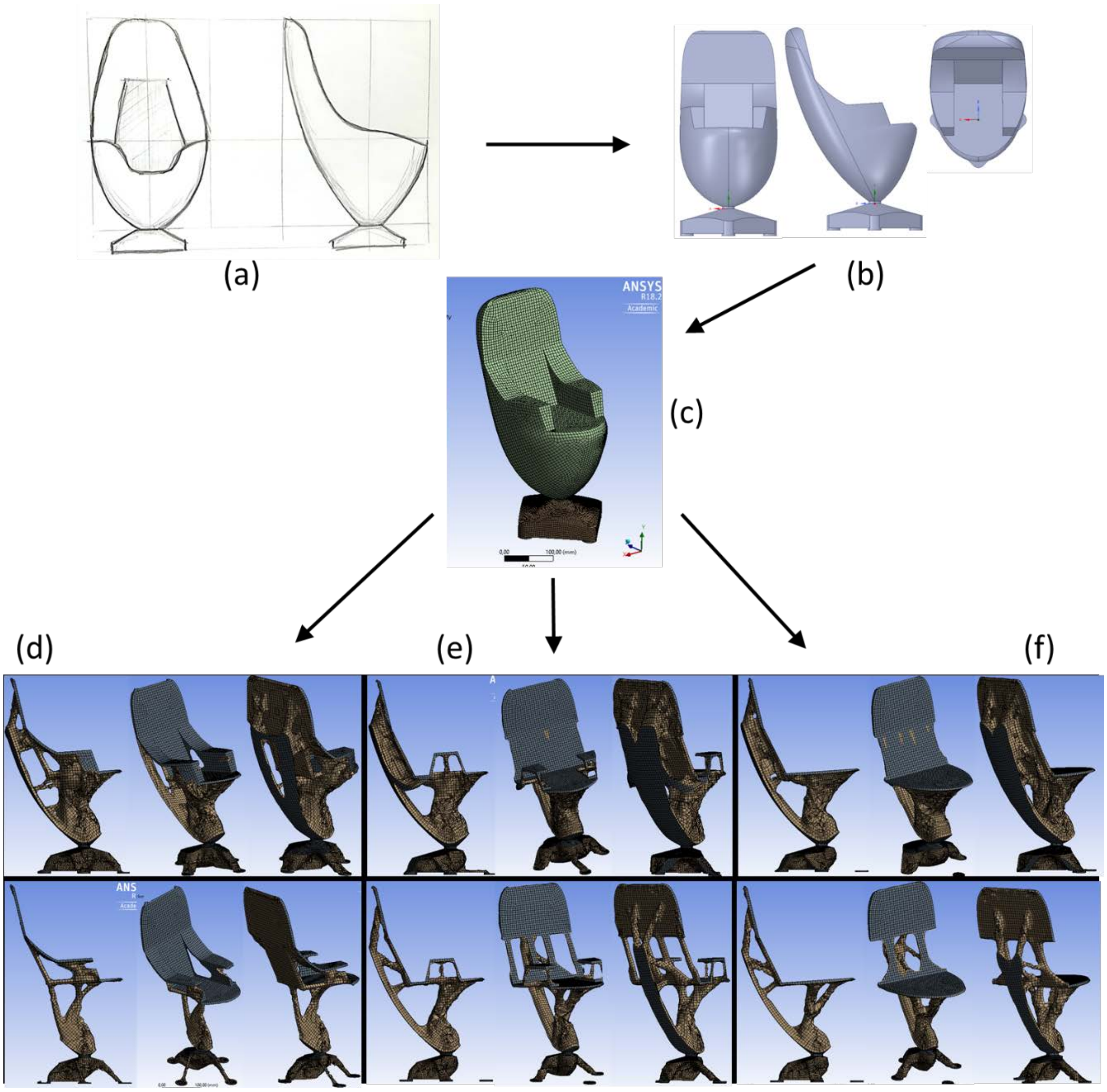


Figure 133 - Example of concept design generations using TO. (a) Sketch of an initial concept with simple lines; (b) CAD modelling, creating the geometry boundary to TO; (c) Discretisation through FEM; (d), (e) and (f) different concept design families created by TO.

4.2. Shape, and Emotional Reaction and Perception

The most of environment human perception comes from visualisation, and certainly the first emotional reaction of to a product is driven from shape, material, colour, and surface; all of them linked to optical properties (Gatzky, 2014). The emotional response to a specific shape of a product, depends on collective perception, guided by local culture, social status, current tendencies and future expectations, genetic programming from evolution, etc. Variations for the user's individual perception may occur but that depends on past experiences, current emotional state, values, social aspirations, etc. Therefore, finding the ideal form that can satisfy the individual user and at once reach to the most amount of people as possible in mass production has been a challenge to industrial design, especially nowadays, with a crescent demand by the consumer for personalisation and identification with products that they intend to purchase. In the Köhler's "Maluma" and "Takete" experiment (Köhler, 1929), the majority of people associate the Maluma (a non-dictionary name, and with a "flaccid" sound) to a smooth and rounded shape and Takete (another non-dictionary name, and with an "aggressive" sound) to a spiky angular shape. This experiment's evidences show an existence of some subconscious universal feelings to base shapes (Figure 134).

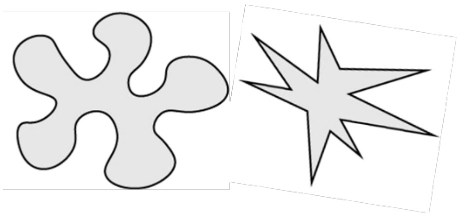


Figure 134 - Köhler's "Maluma" and "Takete" experiment.

Some theories in the literature attempt to explain the link between shape and emotional reaction, to find universal postulates that work to everyone; theories to explain why some things are beautiful and provide good feelings and why others cause repulsion and fear.

Based on Plutchik's primary emotions (Plutchik, 1991), Philippa Mothersill stratified this list of emotions and segregated them with basics design elements (form, rhythm and direction). In this context, a form is any composition of straight, curved or angular lines, rhythm is the size and frequency of oscillations and direction can be vertical, horizontal or diagonal, and move up or down (Table 6). Based on this segregation, the qualitative emotive design taxonomy was created, an idea to visualise the forms and the emotions associated to them (Mothersill, 2014) (Figure 135).

Table 6- Stratified list of Plutchik's primary emotions and the relation with basics design elements. Source: (Mothersill, 2014).

Primary emotions	Form	Rhythm	Direction	Form & Direction: Aspect ratio	Rhythm & Direction: Distribution of volume
Anticipation	Smooth	Big curves	Leaning slightly backwards	Flat and wide	Top-heavy
Trust	Smooth	Big curves	Leaning straight	Flat and wide	Bottom-heavy
Joy	Smooth	Medium curves	Leaning slightly forwards	Round	Middle-heavy
Surprise	Smooth	Small curves	Leaning forwards	Tall and round	Bottom-heavy
Fear	Angular	Small curves	Leaning heavily forwards	Tall and slender	Bottom-heavy
Anger	Angular	Medium curves	Leaning straight	Tall and round	Top-heavy
Disgust	Angular	Medium curves	Leaning slightly backwards	Round	Middle-heavy
Sadness	Smooth	Big curves	Leaning heavily backwards	Round and slender	Top-heavy

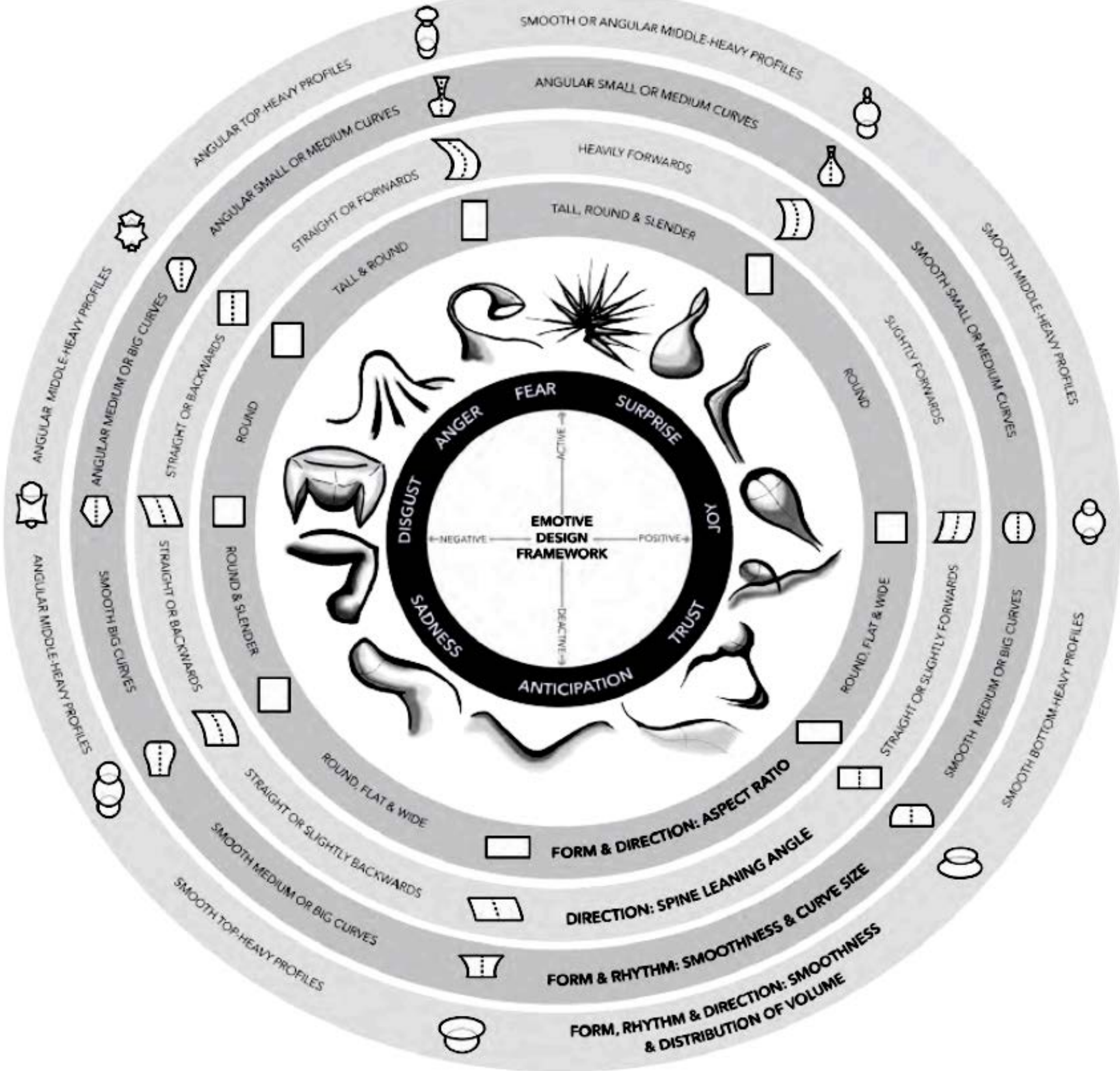


Figure 135 -Qualitative emotive design taxonomy, with design elements associated to Plutchik's primary emotions. Source: (Mothersill, 2014).

According to Jordan (2000) there are four pleasure categories that a product can provide:

Physio-pleasure: Derived from sensory organs, such as touch, taste and smell as well as a feeling of sensual pleasure.

Socio-pleasure: The social benefits achieved through a product possession, such as status, become part of a group, facilitation of relationships etc.

Psycho-pleasure: When a product facilitates a cognitive task, making the task easier, more efficient and effective.

Ideo-pleasure: Occurs when a product reinforces or evidences the personal values.

According to Norman (2004), pleasure shows three levels of appeals: Visceral, Behavioral and Reflective. The visceral level is related to instinct impulse that it comes from nature evolution heritage as a response to survive to the environment stimulus. Some examples of this instincts are finding a healthy sexual partner (with some relation with the Golden Ratio), identifying poisonous or not poisonous food, dangerous and venomous animals, foods with a good source of energy (fats and sweets), safe and dangerous places etc. These ancient instincts can manifest distortedly in modern life in some products such as sensual design lines of a car, delicious fast food and sweets, arts, music, perfumes, architecture environment etc. This impulse manifests at an unconscious level and can be felt by all sensory organs (visual, touch, taste, smell, sound). The behavioural stimulus is related to the use of things in which appearance and rationale do not matter so much, but performance does. The design of a product is ruled by the function. Reflective design is a conscious process and involves all about message, culture, and meaning of the product. For the user, it reflects his or her self-image through the message that the product sends to others, and the choice of buying it, comes from a conscious decision of colour etc, according to the personality, personal values, prices, and necessities. Products with visceral appeal cover a more significant number of users, while that the products with reflective appeal only, reach a specific group of users (Figure 136).

Figure 136 - The covering of the number of users according to design appeal. Source: *(Komninos & Interaction Design Foundation, 2017)*

According to Gatzky (2014) there are two possible types of a product perception: Impression of Order and Impression of Complexity. The Order Impression is associated with a low number of shape elements and arrangement features, with clearly composition, and the Complexity Impression is the opposite; with many shape elements and features and a confusing or even chaotic structure. It is also possible to find order and complexity patterns in nature (Figure 137). Each impression causes different psychological effects to the user (Figure 138). Impressions of Order and Complexity are also linked to harmonious and inharmonious lines of the design (Figure 139).

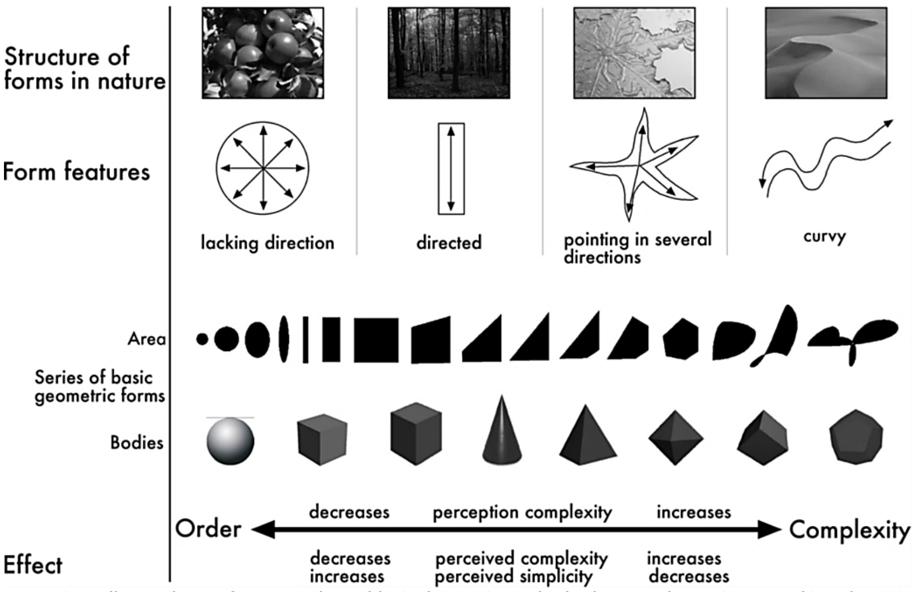


Figure 137 - Illustrations of geometries with Order or Complexity impressions. Source: (Gatzky, 2014)

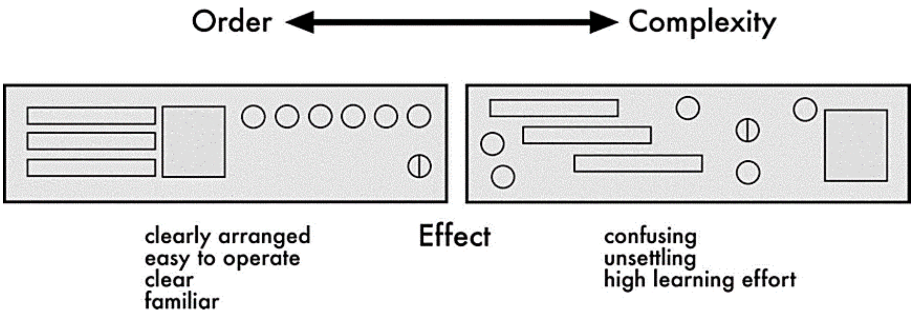


Figure 138 - Example of two radios user interface and its psychological effect to the user. On the left, Impression of Order and on the right, Impression of Complexity. Source: (Gatzky, 2014).

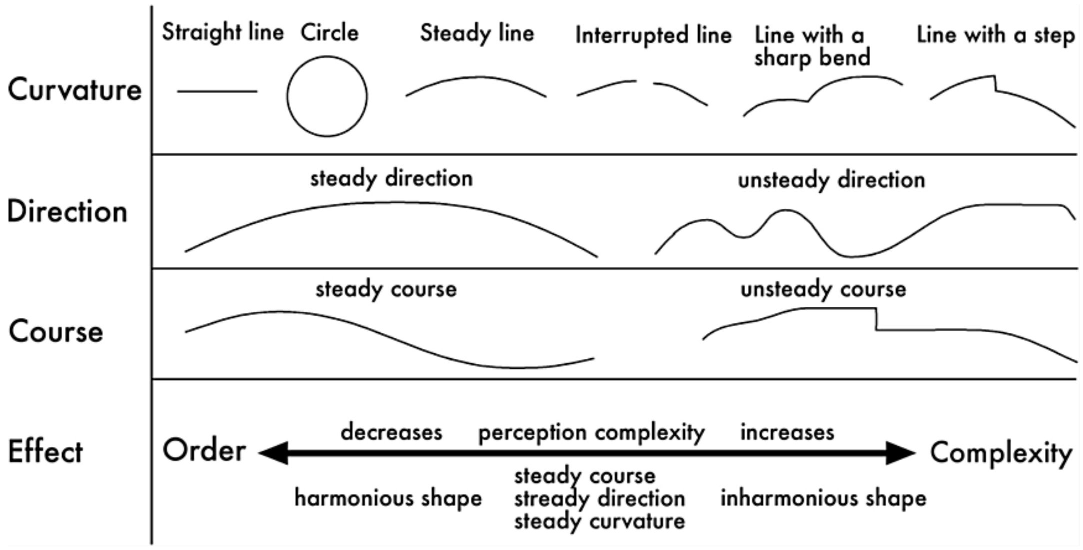


Figure 139 - Impressions of Order and Complexity are also linked to harmonious and inharmonious lines of the design. Source: (Gatzky, 2014)

For Gatzky, a design with high degree of order produces positive feelings such as:

- Clarity
- Transparency/Honesty
- Security
- Perfection
- Tastefulness
- High quality and value
- Long product life

It is possible that this preference for ordered design is associated with some evolutionary perspective of threats or opportunities of nature. When analysing some of the most poisonous and venomous creatures on Earth, it is possible to find complex structures in most of them (Figure 140). However, it does not mean that all creatures with this complexity are dangerous and a threat or all poisonous and venomous creatures are complex. But it is a pattern found more frequent in this situation. Complex and disordered structures found in diseases pattern can create uncomfortable feelings to most people. Trypophobia is a theory that visualisation of irregular patterns or clusters of small holes or bumps can cause uncomfortable feelings (Figure 141). Again, a more in-depth psychology investigation is necessary to check if there are other reasons such as empathy etc. However, these lousy feeling are found more frequent with a situation of complexity and disorder.

Figure 140 - It is possible to find complex structures and colours in some of the most poisonous and venomous creatures. Source: (Wildlife Facts, 2015).

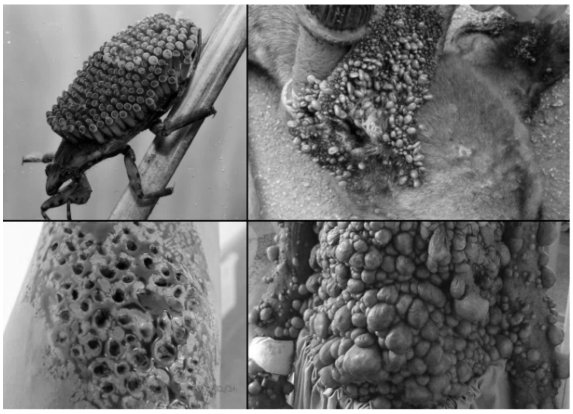


Figure 141 - Images of complex and disordered structures found in diseases pattern can create uncomfortable feelings to most people (Theory of Trypophobia). Source: (Click Curioso, 2017)

However, complex structures will not always cause uncomfortable feelings. Complex shapes with organised growing ruled for instance by Fibonacci Sequence, Golden Ratio or Fractals or another regular law, can produce amazing visual arts (Figure 142).

Figure 142 - Complex and organized shapes can create amazing results. Source: *(Bilderparade, n.d.; Galland, 2015; Glitterr & Pinterest, n.d.; Megapixl, n.d.; Reaktorplayer, 2015; Stone, n.d.; 毎週開催 & Connpass, 2016)*

Even a “disorganised” face with the Golden Ratio, could be more enjoyable than a normal face, but distorted about the Marquardt’s Mask of Golden Ratio (Figure 143).

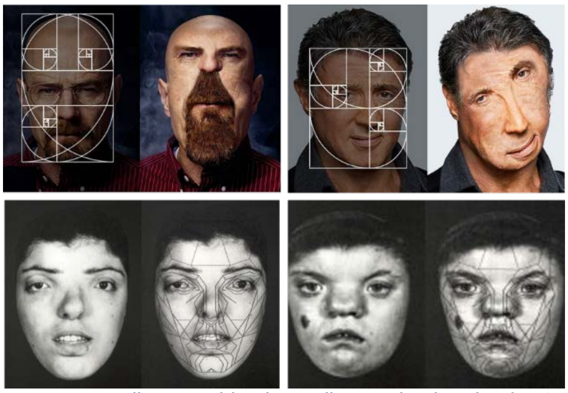


Figure 143 - Which of the faces are more disagreeable, those disorganised under the Golden Ratio (top) or the normal ones but that do not fit in the Marquardt’s Mask of Golden Ratio (bottom)? Source: (Furman & Onedio, 2017; Ivonette, 2011)

It was on the 20th and 21st century that simplicity and organisation emerged in Design as characteristics of quality, such as honest, easy to understand and authentic (Gatzky, 2014). It is noticeable to perceive that old objects and architecture were more complex than nowadays. For instance, a gun is a rather functional product than artistic; anyway, the old ones were often carved with complex poetic forms (Figure 144). Maybe, this preference for the simple comes from a need to rest the brain from the excess of information created by the current society or maybe by another psychological effect.

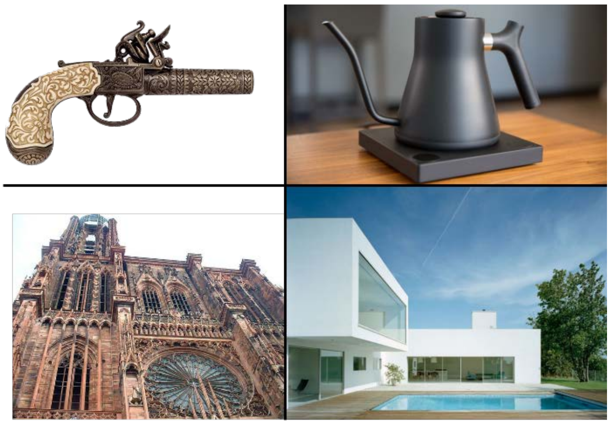


Figure 144 - On the left, the old design with complex details. On the right, modern design from the minimalist movement. Source: *(Allen & Pastemagazine, 2017; Instanonymous, 2016; Lindvall A&D, 2009; Schiteanu, 2005)*

Considering that the simple design is the contour or the whole shape and the complexity are the details and parts, in which is possible to create a good design using simple or complex shape: which one has superiority effects? Or what is more important: the simplicity or complexity of details? In fact, the whole is fundamental to recognise an object and its meaning, but there might be details that hold the attention and fascination of the user. For Stephen Palmer (Palmer, 2002), there is no consensus of which perception occurs first, between the local or the global on a shape. There are theories defending that the global precedes the local, another that the parts (local) are perceived first to see next, the whole. Another theory suggests that both occur in parallel, the local on the left brain hemisphere and the global, on the right one. This variance suggests that the sequence is dependent on the context, the person (dominant left or right hemisphere), the experience of the person, the culture, and other psychological aspects present at the moment. However, the author defends that the sequence global to local occurs more often:

> "Experimental evidence in several different tasks indicates that the global structure of whole configurations is often perceived before the local structure of its constituent parts. Global structure also appears to provide the frame of reference within which more local properties (such as the orientation, shape, and motion of subordinate perceptual elements) are perceived." (Palmer, 2002, p.228)

This statement is in accordance to Gestalt[9] psychology principles which states that to understand every part is necessary to first understand the whole, and the whole cannot be described from the sum of the isolated parts but as something bigger than the sum of these, in a Holistic view. For Gestalt: 1+1= 3. These principles are fundamental to understand how the perception of shapes works, when composed by several elements (a complex structure), and they are currently a guide to

[9] Gestalt psychology was the first school to study the principles of human visual perception, founded in 1920s in Germany by Max Wertheimer, Wolfgang Kohler and Kurt Koffka, "Gestalt" is a German word that means the way a thing has been "placed," or "put together." There is no exact equivalent in English. "Form" and "shape" are the usual translations; in psychology the word is often interpreted as "pattern" or "configuration" (Interaction Design Foundation, n.d.; Lotha & Britannica, 2017).

designers have more control in how the user will perceive a design, how to create harmony and increase the likelihood of interest in new products. There are a variety of principles, next, some basics of visual perception (Figure 145):

(a) Multistability (/Background selection): The ambiguity of an image in which the same objects can be perceived in the foreground or the background.

(b) Proximity: Elements placed close to each other are often perceived as one group, instead of each one individually separated.

(c) Similarity: Objects with similar components or attributes (shape, size, colour, etc) tend to be seen as organised when grouped together.

(d) Continuity: Similar objects that follow a line or a smooth curve direction are seen as a continuous group, even with different colours.

(e) Closure: The tendency to ignore gaps and complete unfinished lines with familiar shapes.

(f) Simplicity or Pragnanz (good): The interpretation of ambiguous images as simple and complete as possible, instead of complex or incomplete.

(g) Focal point or Segregation: The object that stands out of a group, will capture and hold the viewer's attention first.

(h) Common region: When a set of objects with the same shape, colour, distance, etc. are separated by barriers, they will be perceived as in different groups.

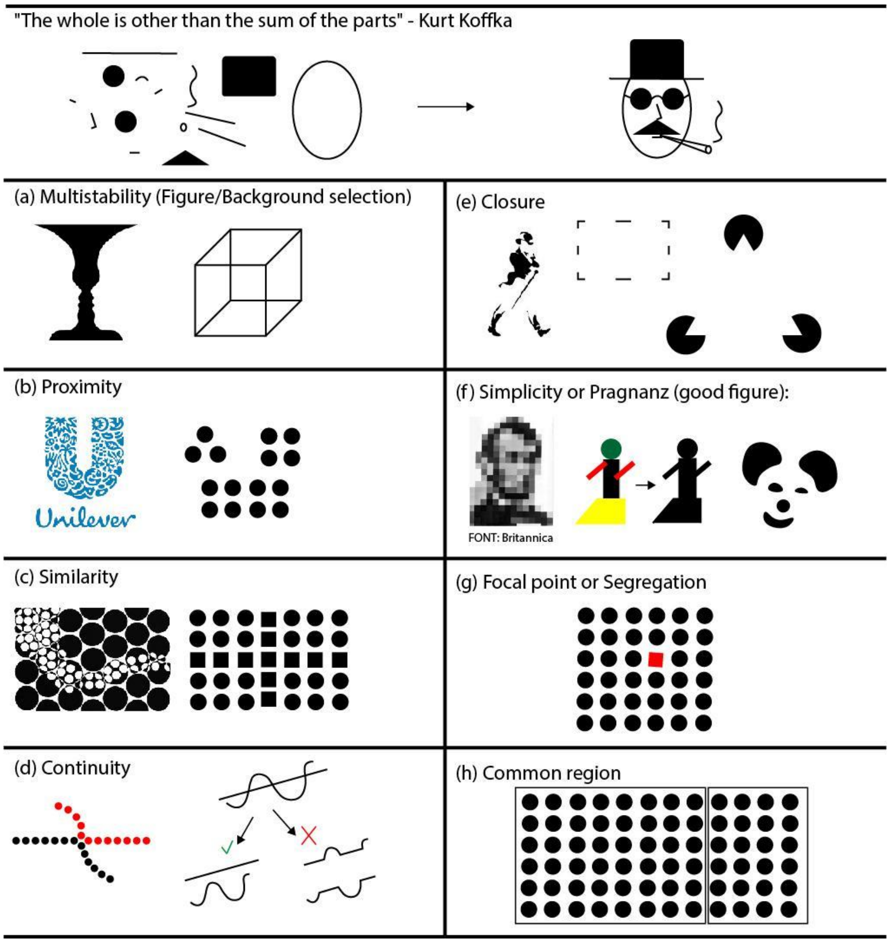


Figure 145 - Gestalt basics principles of visual perception.

This section has explored some of the main ideas of how shapes relate to emotional reactions and mechanism of human visual perception. These concepts will be used as support to create a set of postulates for the designer to have more control and a conscient exploration of geometries generated by TO.

4.3. Postulates for Geometry Generation with Topology Optimisation in Product Design

The Topology Optimisation algorithms at this moment, do not have the sense to define which geometry would be the best to human use under intangible criteria (emotional and symbolic aspects). A wide number of solutions can be created automatically, but without creation and selection criteria, finding the best options would be a matter of luck. The next postulates have the aim to be used as a guide during geometry exploration through Topology Optimisation. With that, the designer could have more control and criteria to the geometry generation and selection through TO. Fourteen postulates were identified:

- **I.** A tangible product for consumer must satisfy needs of functionality, usability and pleasure.
- **II.** The form is linked to function, emotional and symbolic aspects. A balance for all of these aspects must be found in a product.
- **III.** Function tends to be ruled by Topology Optimisation, but to the selection of proper solutions created by TO, emotional and symbolic aspects of the form must also be considered.
- **IV.** A spiky, angular shape is associated more with an aggressive and uncomfortable feeling, while a smooth and rounded shape is associated with friendly and safe.
- **V.** Some shape perceptions are instinctive, originated from natural aspects, such as identifying threats and opportunities related to surviving (sexual reproduction, avoid injuries, etc).
- **VI.** Nature is a good example of inspiration about what to do and not to do.
- **VII.** A shape perception also depends on social and personal aspects, such as culture, experience, emotional states and future expectations. And they must be identified to guide generation and selection of forms.
- **VIII.** A complex and disorganised structure tends to cause confusion, disturbance, and cognitive effort, on the other hand if a structure is complex but organised (under mathematical coherence or some harmonic rule), it induces to admiration and holds attention.
- **IX.** A simple and organised structure induces a perception of cleanliness, safety, reliability and easiness, but it is harder to holds attention in the long term.
- **X.** In average, people first see the whole (the simplicity) of an object, and after that, the details (the complexity) are observed.
- **XI.** A balance with simple and complex ordered structure is the best arrangement to catch and hold attention.
- **XII.** In a structure composed of numerous elements, they must have in harmony of shapes (similarities). If it is not possible, this structure must be covered (or partially covered) (Figures 146, 147, 148 and 149).
- **XIII.** To control complex structures perception, the Gestalt principles of visual perception are a good support.
- **XIV.** An initial geometry boundary to Topology Optimisation can be defined by a volume created by Golden Ratio or Bio-inspiration to increase the chance of success, acceptance and admiration of the form.

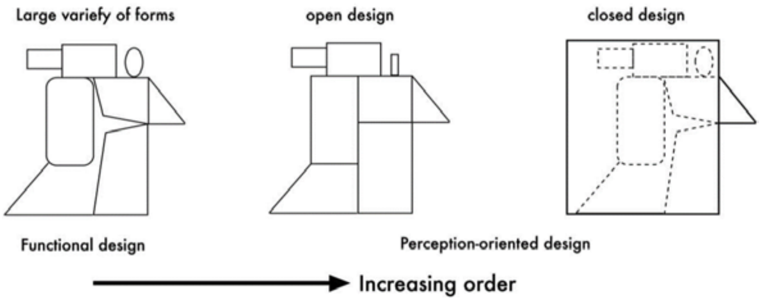


Figure 146 - Two strategies for simplifying and harmonise forms in a complex design with a variety of forms. Source: (Gatzky, 2014).

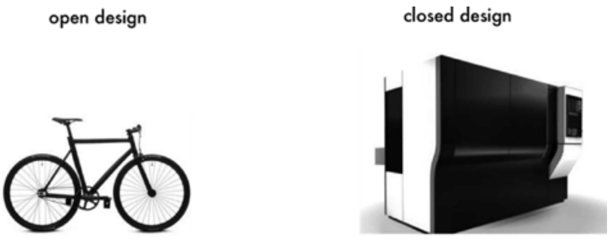


Figure 147 - Practical examples of harmonisation in an open and closed design. Source: (Gatzky, 2014)

Figure 148 - A vertebrate animal is an example of a closed design in nature. Source: (DK Find Out, n.d.; Galileo Ramos, n.d.)

Figure 149 - An example of harmonisation of complex design with similar elements (polygons). Source: (Lamborghini, 2018).

4.4. Product Design and Development Workflow Using Topology Optimisation

4.4.1. Product Market Life Cycle

There are two moments in which a product is designed. The first one, is when the product is new and has a development time before being introduced in the market (Figure 150, a). The second one is when this product starts do decline in its life cycle curve, and needs a prolongation through marketing and promotion strategies, or it is renovated through its redesign and the addition of new properties that add value (Figure 150, b). In such cases, it is possible to use the TO as the drive of the development process. Especially in most of the cases where the product is already in the market, the use of TO to renovation could be a good strategy do add value.

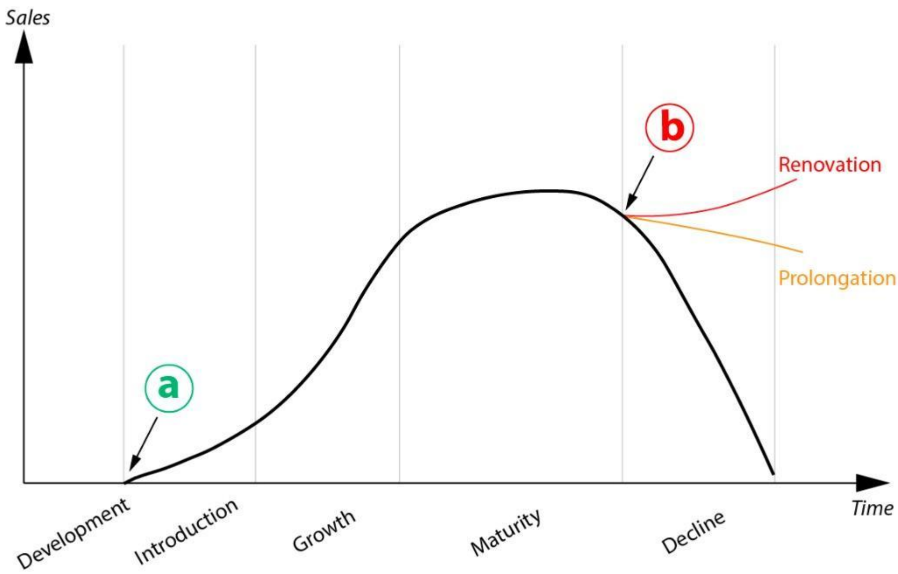


Figure 150 - A typical product market life cycle and two moments of design and opportunity to use TO, "a" and "b".

4.4.2. Workflow Using Topology Optimisation

In (Figure 151) a workflow suggested by this dissertation is shown, with main steps and feedbacks (dashed line) loops to a product design and development using topology optimisation, such as to moment “a”, and to “b”.

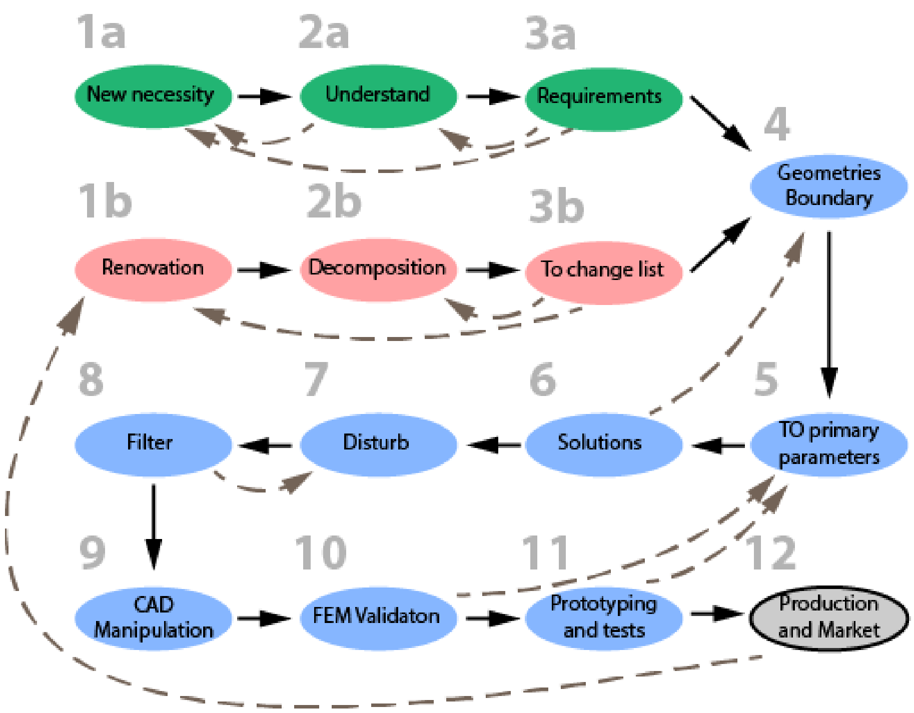


Figure 151 - Product Design and Development Workflow Using Topology Optimisation.

These steps are better explained next, as well as which tools are possible to be used in each one. Some indicated tools were not explained in this dissertation for the reason that they are common and almost standard in the design process.

1a. New necessity: It is identified a necessity or a new discovery to create a physical product to answer a human need or problem. Example of using tools: brainstorming, new manufacture technology, new design technology, bio-inspiration (see all chapter 3). Postulates to be considered: I and VI.

2a. Understand: Exploration of the problem or opportunity to understand all its dimensions, impacts and attributes. Example of some tools: 5W2H, Brief, Art state, interview, immersion and empathy, mood board etc. Using the bio-inspiration, all approaches methods discussed in chapter 3 are possible to be used in this step. Postulates to be considered: I, II, III, VI, VII, X.

3a. Requirements: After having understood the essence of the product, it is necessary to list all the requirements in qualitative or quantitative parameters and attribute weight of importance for each one, for instance: Kano Model, QFD (Quality Function Deployment) / House of Quality etc. The restrictions should be listed too and in general, they are mandatory - such as standards and laws, cost limits, manufacturability, natural laws, etc. Some bio-inspiration tools used to set requirements: biomimicry DesignLens, Life's Principles, Biomimicry taxonomy, Biomimicry Design Spiral. Postulates to be considered: I, II, IV, V, VI, VII, VIII, IX, X, XI.

1b. Renovation: A product starts its market life declination and needs a design renovation to become more attractive to customers.

2b. Decomposition: All product attributes are decomposed to understand all requirements and restrictions it has. A process of reverse engineering can be used, as well as an attempt to find parallel relationships with other current technologies, new inventions or new discoveries, tendencies etc. The bio-inspiration and approaches methods discussed in chapter 3 may be used in this step. Postulates to be considered: I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII.

3b. Changes list: In this step it is listed what attributes must keep in the current design and which ones should be changed. In this case, the same tools of step 3a can be used. Postulates to be considered: I, II, III, IV, V, VI, VII, VIII, IX, X, XI.

4. Geometries boundary: For initial TO iteration. The geometry boundary can be defined according to ergonomic and anthropometric requirements, maximum space available for the product (in special when it is a part of a whole product), standards, assembly or modular requirements etc. Golden Ration and Bio-inspiration can be a good anchor for an initial geometry approach. More than one geometry boundary can be created in this step, to next test each one and choose the best possibilities. Postulates to be considered: XIV.

5. TO primary parameters: In this step the minimum parameters to perform the TO and to ensure that all mandatory requirements in steps 3a or 3b will be fulfilled are settled. With this, it is possible to ensure a minimum viable product and yet have space to add new parameters (in step 7) to generate more solutions with TO. See all chapter 2.

6. Solution: First minimum viable products are created by TO. The quantity of solutions created depends on the quantity of geometries boundary and minimal TO parameters possible to change.

7. Disturb: After the analysis of the solutions found, it will be easier to identify the behaviour and some trends of the solutions for each parameter and geometries boundary. Then, new parameters can be added to perform the TO, without losing the minimum requirements of the product. It is possible yet to apply a few changes in the geometry boundary. See section 2.4.

8. Filter: With the generation of numbers of solutions, the best option will be the one which fits better with all the requirements listed in steps 3a or 3b. Postulates to be considered: IV, V, VIII, IX, XI, XII, XIII.

9. CAD Manipulation: In general, the geometry created by TO is a rough design. This geometry is not feasible to perform FEM validation due to the poor elements quality that will be created from its rough aspect. Moreover, other reasons include the requirement of smoother and quality geometry such as visual good looks, manufacturability, mechanical fatigue etc. All this requires a post-treatment of the geometry through CAD manipulation.

10. FEM Validation: The FEM validation is essential to save resources and achieve more reliability to the design before the product prototyping and test. It is in this step also that the TO solution will be validated about functional and engineering requirements.

11. Prototyping and tests: This step is necessary to validate the product for both functional and engineering requirements and for intangible aspect such as comfort, usability, feelings etc. For some intangible aspects, virtual simulations can be used before the construction of a real prototype, such as rendering, virtual reality and augmented reality.

12. Production and Market: After all validations, the new product is ready to be manufactured and to go to the market.

CHAPTER 5

A Practical Cases for Product Design

5.

5.1. A Bio-inspired Table

5.1.1. Development Sequence

5.1.1.1. New Necessity

In 2020, it is expected that stress will be the major contributor to the increase in mental disorders and cardiovascular disease (World Health Organization, 2013). Considering the potential health benefits of a biophilic environment, this project will create a table inspired by tree structures. The shape of this structure will be explored through Topology Optimisation under functional and aesthetic conditions.

5.1.1.2. Understand

Biophilic architecture environments are related to the positive influence in mental health, such as the mitigation of stress, work satisfaction, productivity, and social benefits like collaboration, mentoring, higher morale, employee retention and so on (Gray & Birrell, 2014).

Considering the potential social benefits of biophilic, the table project will be directed to a meeting room, given the fact that is the most important furniture to this room and due to its social symbolism. A roundtable is a symbol of a non-hierarchical relationship, democratising the relations and facilitating socialisation.

There are many possible natural tree structures and tree-based tables in the market. The mood board (Figure 152) shows some possibilities.

Figure 152 - Mood board to tree-based table inspiration. Source: *(Corbin Bronze ltd, 2012; Dekor Store, n.d.; Ethical Panda;, 2017; Expominera2017, 2018; Kekely, 2017; Khvostichenko, 2008; Rojal, 2016; SPI Home, n.d.)*

5.1.1.3. Requirements

Considering the possibility to manufacture with a complex and organic shape, it is expected that metal or plastic be used as material to the final product as, currently, they are used as materials with good mechanical properties and likely to be used in additive manufacturing. It is necessary that the table supports loading on it. Assuming that the table is for six people, and with total objects loads on weighing 100 kg (980 N). The height of the table should be between 737 and 762 mm, with a minimum arc length of 762mm to be occupied by a person (Panero & Zelnik, 1979) (Figure 153).

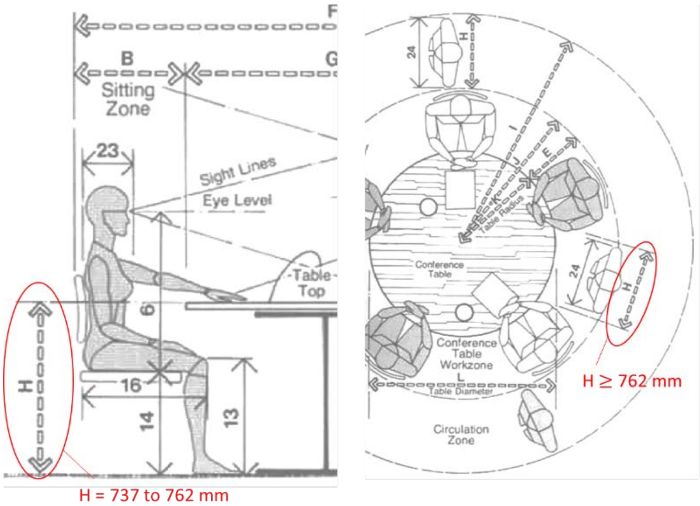


Figure 153 - Dimensions references for a conference table based on an average man and woman in the US and Occidental EU populations. Adapted from: (Panero & Zelnik, 1979).

5.1.1.4. Geometry Boundary

The initial geometry to TO will be a cylinder (Figure 154). If the table is for six people, so the minimum diameter is calculated next:

$$C = \pi \times d \qquad (10)$$
$$6 \times 762.00 = 3.14 \times d;\ d \geq 1456.00 \text{ mm}$$

Where,
C = Circumference length (mm);
π (Pi) ≅ 3.14;
d = Diameter (mm);

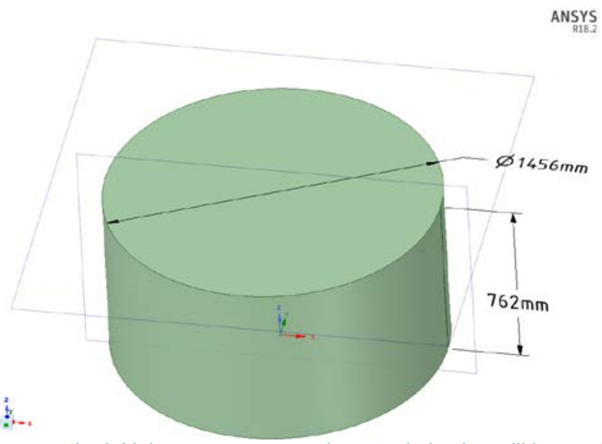


Figure 154 - The initial geometry to Topology Optimisation will be a cylinder.

5.1.1.5. TO Primary Parameters

This table can be considered as a low responsibility engineering application. It means that this structure does not put lives in danger directly and some of the engineering aspects could be simplified or disregarded such as vibration analysis and fatigue, design safety coefficient etc. Therefore, for this first interaction, this problem was solved with static loading and fixed support and the objective function will be to minimise compliance, and as the response constraints, reduce the mass.

5.1.1.6. Solutions

For initial solutions, the first boundary geometry was a cylinder. After checking the behaviour of the result, two divergent families were created. One with the bottom diameter being the upper diameter divided by φ (see section 3.2.5), and other with the bottom diameter equal to 300mm (Figure 155).

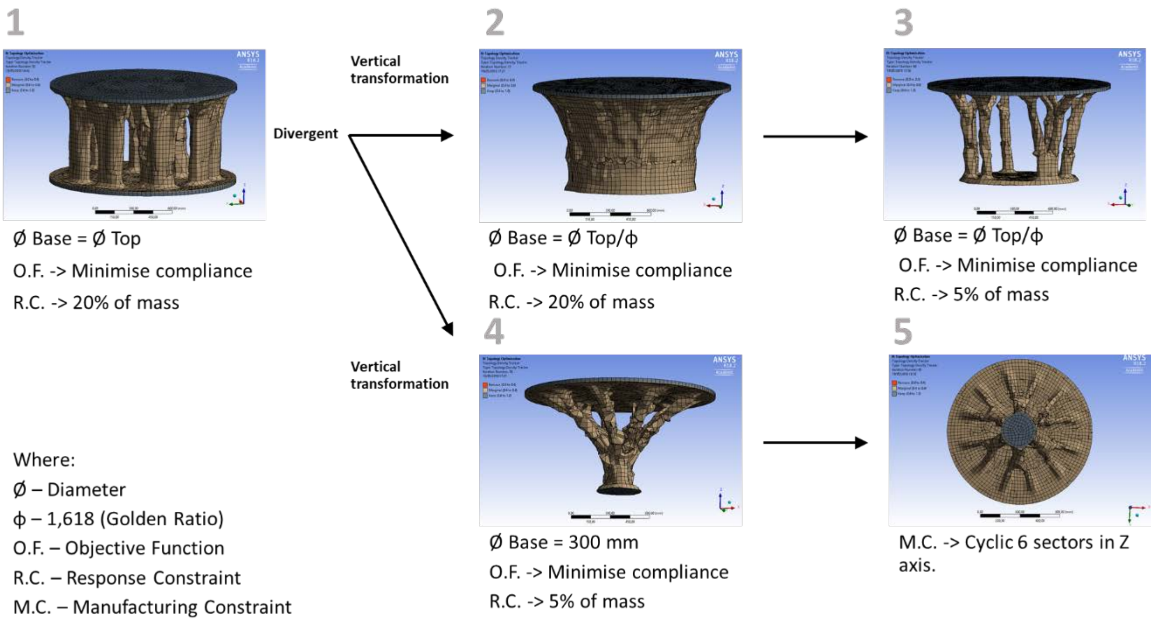


Figure 155 - Initial solutions and their sequence of exploration.

5.1.1.7. Disturb

The disturb is performed by changing optimisation parameters and boundary geometry, based on initial results found. These parameters will not penalise the essential requirements to the table to work instead, these will add new functionalities or aspects to the design (Figures 156, 157 and 158).

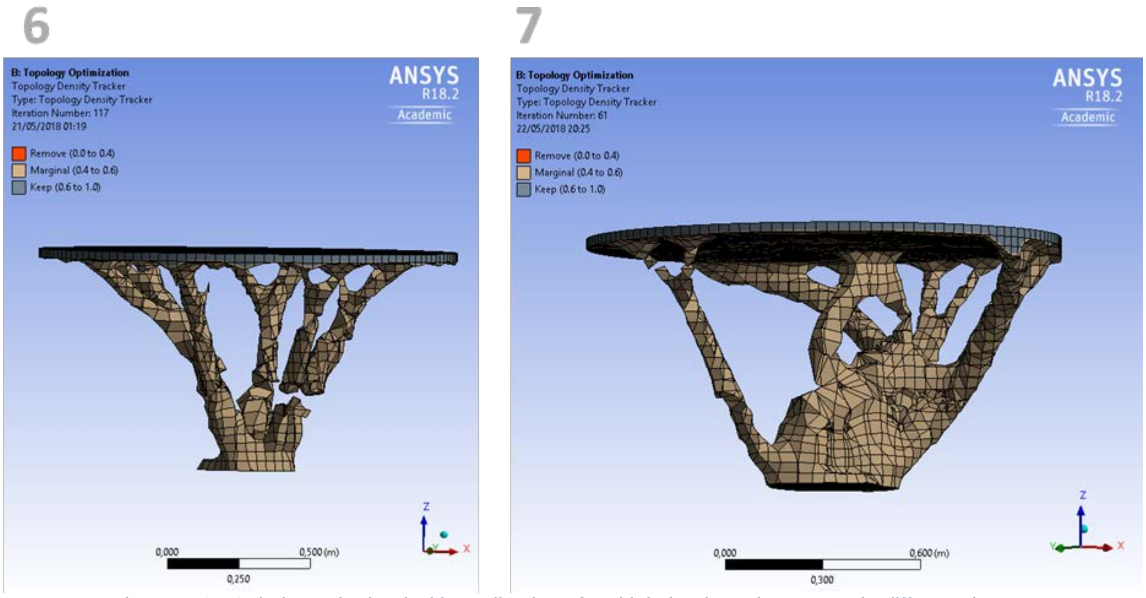
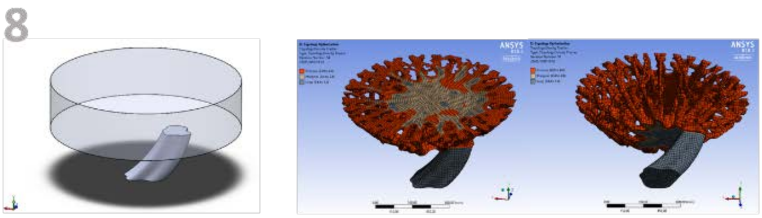
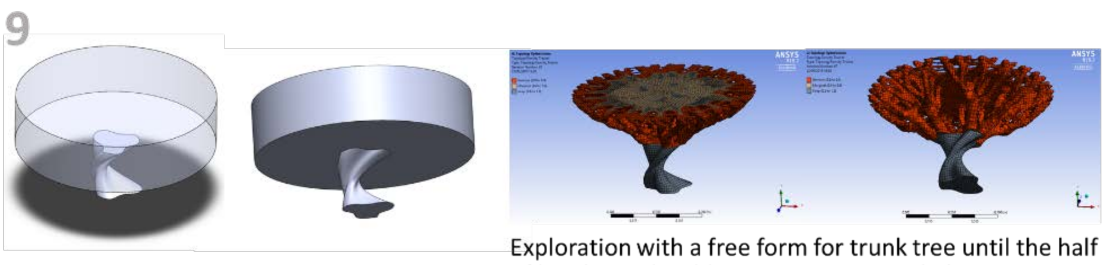


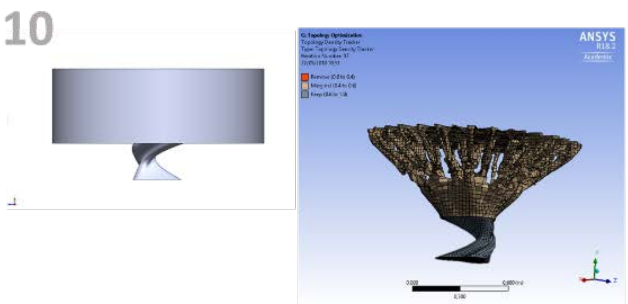
Figure 156 - Solutions obtained with application of multiple loads and moments in different times.



Exploration with a free form for trunk tree until the half of height (762/2=381mm).



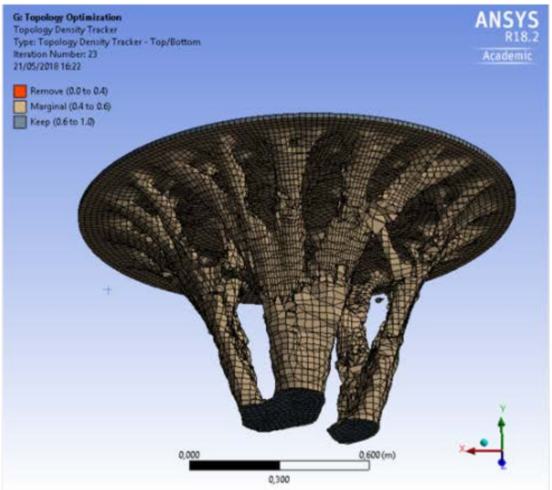
Exploration with a free form for trunk tree until the half of height, and Golden Ratio torsion with ψ= 137º,5.



Trunk tree with lower height base on Golden Ratio (762x(1-1/ ϕ)), and torsion with ψ.

Figure 157 - Explorations with trunk tree free form.

11



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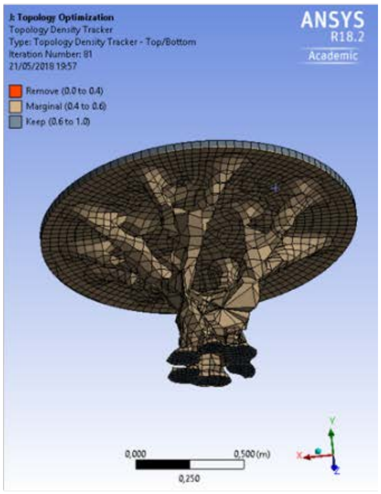

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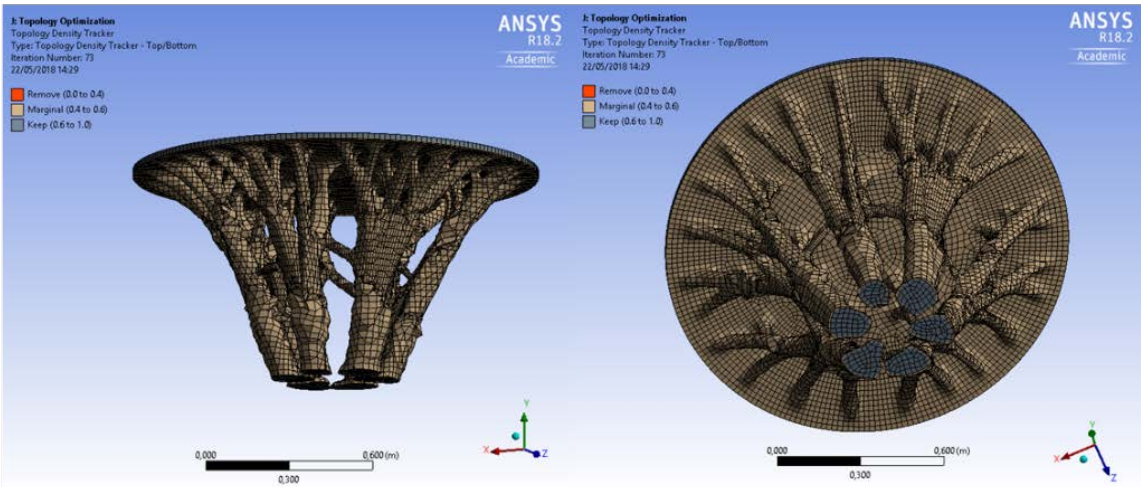

Figure 158 - Explorations with free forms of the tree base.

5.1.1.8. Filter

For the selection of the most appropriate geometry, it is necessary to use as criteria the form that better fits to the emotional and symbolic meaning of the purpose, the manufacturing feasibility, and cost. Considering that this table is more artistic than functional, some criteria are more important than others. So, attributing qualitative weights of importance for each aspect, the emotional and symbolic meaning is more important, followed by the possibility of manufacturing and finally the cost as the less important. Therefore, the geometry chosen was the number 13. As an emotional and symbolic meaning, it has a good similarity with a tree, its six blocks could symbolize each element around the table,holding the table top, representing the union of the teamwork to achieve a common purpose (Gestalt principles) To manufacture the table it is possible to use methods as additive manufacturing to the final part, or to create a matrix to lost-wax casting for example. The total volume of the part is about 54,64 litres, so the maximum weight that this structure could have is shown on Table 7 depending on the type of material, considering 100% of volume filled by the material.

Table 7 - Maximum weight for some possible materials.

Material	Density		Weight	
	g/cm³	lb/in³	Kg	lb
Glass	2,5	0.09	136,6	301
Brass	8,4 to 8,73	0.03 to 0.32	459 to 477	1012 to 1052
Aluminium	2,7	0.1	147,528	325
Plastic	0,9 to 1,5	0.03 to 0.05	49 to 82	108 to 180

5.1.1.9. CAD Manipulation

After the selection of the geometry to the project, its treatment must occur before the FEM validation. This treatment consists in removing noise, choppy, redundancies and any other unconformity that may disturb the FEM validation, such as decreasing the visual aspect of the surface.

To manipulate the CAD generated by TO, free software Blender and MeshLab were used, due to their vast tools options to mesh manipulate and each one with particular benefits.

The CAD treatment was performed in ten steps:

Blender:

I. **Converting triangles elements into quads:** Quads elements facilitate a more precise control of subdivisions and smoothing of the model to the next steps.
II. **Subdividing the mesh:** The subdivision will split the elements in even smaller elements to reduce a loss of accuracy of topology in the smoothing steps.
III. **Laplacian smooth modifier:** It keeps the topology and volume of the geometry but reduces the “noise” of the surface. The smoothing process, in general, tends to decrease the body volume and loss of topology information.
IV. **Smoothing vertex:** A low deep Smooth Vertex process is performed to increase the surface quality but with care so that there is no decrease in the body volume nor topology loss.

MeshLab:

V. **Removing non-interesting regions:** In this case, the table top was removed.
VI. **Surface Cleaning:** Consists in looking for and removing non-manifolds edges and vertices, and self-intersecting faces. These are essential to perform the next steps better.
VII. **Surface smoothing:** HC Laplacian and Taubin Smooth filters were used.
VIII. **Opened surfaces closing:** It is possible that the previous steps have created open regions.
IX. **Mesh simplification:** Decreasing the number of elements and removing of redundancies.
X. **Opened surfaces closing:** It is possible again the creation of open regions.

After these steps, a significant improvement was achieved in geometry and its file size decreased, which benefits the computational processing (Figure 159). In order to support the structure on the floor, a circular plate was added on the base (Figure 160). The final mesh geometry was also converted to other CAD formats to allows other manipulations such as rendering.

Figure 159 - On the left, the initial geometry without the top table. On the right the simplified final geometry after CAD manipulation.

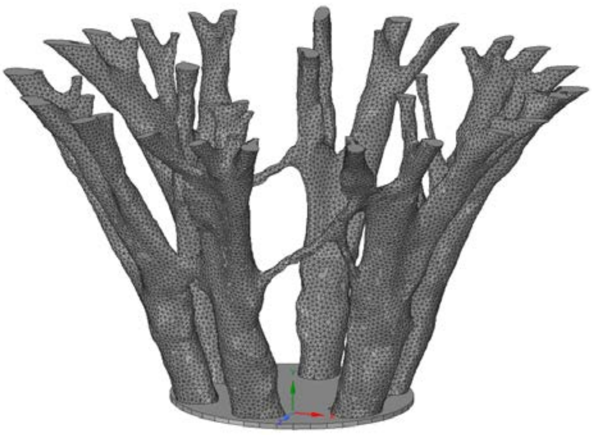

Figure 160 - Circular plate added to support the structure on the floor.

5.1.1.10. FEM Validation

The main functional requirement of a table is supporting things that users normally put on it. To ensure that the table structure will not fail for this condition, the CAD after treatment was simulated by FEM. Due to the freedom of choosing some materials, numerous simulations would be generated for each of these materials. Thus, for a clarification purpose, the material used was ABS (30% Glass Fiber Filled) in a solid body. The main reason to simulate a solid body is that if a shell structure was used, it would be only possible to be manufactured by Additive Manufacturing, and in this case, the material has an anisotropic behaviour and there is an absence of specific reliable material data for this simulation. The reason for the ABS choice is because it has good stress and impact resistance, good hardness, easy casting, good visual aspect and the possibility of having a chromed surface finish. The ABS properties to simulation were collected from MatWeb (2018) - Table 8.

Table 8 – Physical and mechanical properties of Acrylonitrile Butadiene Styrene (ABS), 30% Glass Fiber Filled. Source: (MatWeb, 2018)

Physical Properties	Metric	English
Density	1.17 - 1.50 g/cc	0.0423 - 0.0542 lb/in³
Filler Content	25.0 - 33.0 %	25.0 - 33.0 %
Water Absorption	0.120 - 0.300 %	0.120 - 0.300 %
Moisture Absorption at Equilibrium	0.100 - 3.00 %	0.100 - 3.00 %
Maximum Moisture Content	0.0200 - 0.150	0.0200 - 0.150
Linear Mold Shrinkage	0.00100 - 0.00900 cm/cm	0.00100 - 0.00900 in/in
Linear Mold Shrinkage, Transverse	0.00300 - 0.00600 cm/cm	0.00300 - 0.00600 in/in
Melt Flow	0.100 - 10.0 g/10 min	0.100 - 10.0 g/10 min
Ash	25.0 - 31.0 %	25.0 - 31.0 %

Mechanical Properties	Metric	English
Hardness, Rockwell R	88.0 - 115	88.0 - 115
Tensile Strength, Ultimate	38.0 - 103 MPa	5510 - 15000 psi
Tensile Strength, Yield	38.0 - 117 MPa	5510 - 17000 psi
Elongation at Break	1.00 - 6.00 %	1.00 - 6.00 %
Elongation at Yield	1.00 - 6.00 %	1.00 - 6.00 %
Modulus of Elasticity	4.30 - 10.0 GPa	624 - 1450 ksi
Flexural Yield Strength	12.8 - 162 MPa	1850 - 23500 psi
Flexural Modulus	3.80 - 10.0 GPa	551 - 1450 ksi
Izod Impact, Notched	0.402 - 1.23 J/cm	0.753 - 2.30 ft-lb/in
	0.600 - 0.600 J/cm @Temperature 0.000 - 0.000 °C	1.12 - 1.12 ft-lb/in @Temperature 32.0 - 32.0 °F
Izod Impact, Unnotched	2.14 - 4.81 J/cm	4.00 - 9.00 ft-lb/in
Izod Impact, Notched (ISO)	4.00 - 7.00 kJ/m²	1.90 - 3.33 ft-lb/in²
Izod Impact, Unnotched (ISO)	17.0 - 20.0 kJ/m²	8.09 - 9.52 ft-lb/in²

The mesh created at initial iteration has 427,922 elements, tetrahedrons due to the geometry complexity. The analysis of elements indicates an average of 0.81 of quality (being 1.00 the best quality and 0.00 the worst) (160). In general, an average of over 0.80 is the indicate to get accuracy results (Costa, 2018b).

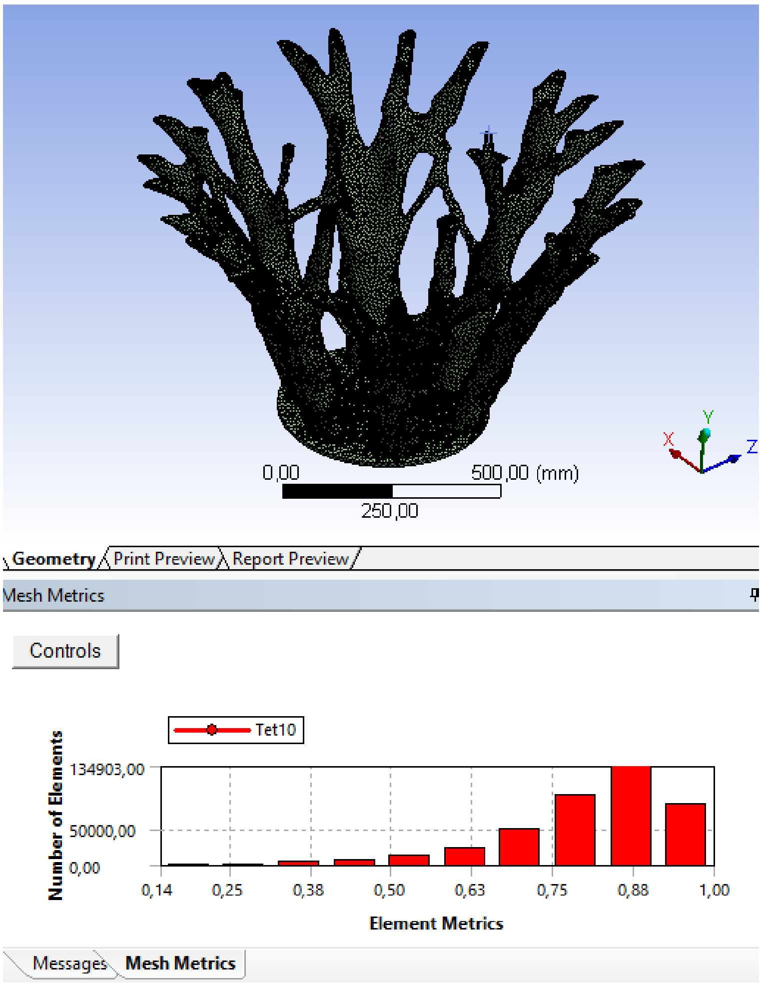

Figure 161 - Elements and mesh quality analysis.

The simulation was performed in a static structural, setting the next boundary conditions: Fixed support in the circular plate base (Figure 162), remote displacement with free movement at x, y and z-axis and locked rotation for all axis, simulating the table top influence (Figure 163). The load was 980N at (-)Y-axis direction (gravity action) and distributed on top of all contact between the structure and table top (Figure 164).

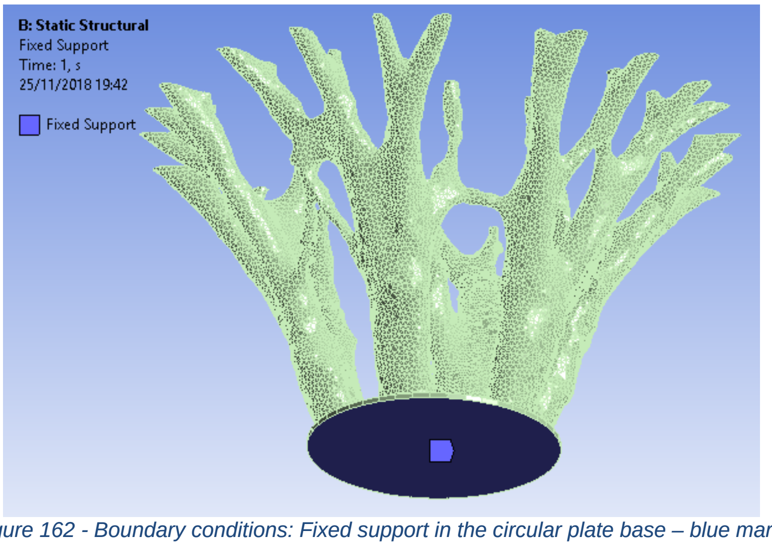

Figure 162 - Boundary conditions: Fixed support in the circular plate base – blue mark.

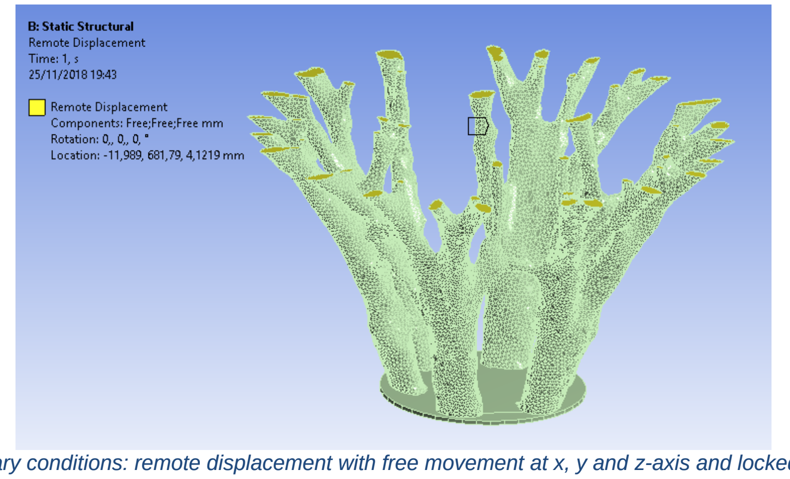

Figure 163 - Boundary conditions: remote displacement with free movement at x, y and z-axis and locked rotation for all axis – yellow marks.

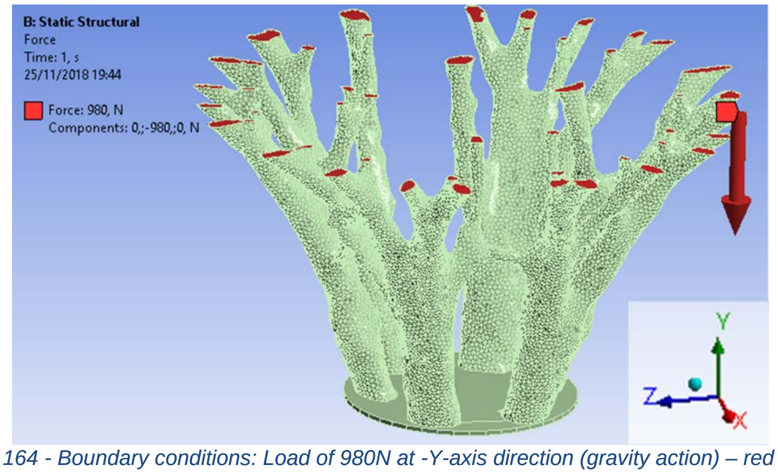

Figure 164 - Boundary conditions: Load of 980N at -Y-axis direction (gravity action) – red marks.

In the first iteration, the body presented the maximum value of total von mises stress of 2.77 MPa, (Figure 165), lower than the lowest material yield tensile strength (38.0 MPa), and maximum total deformation of 0.5 mm (Figure 166).

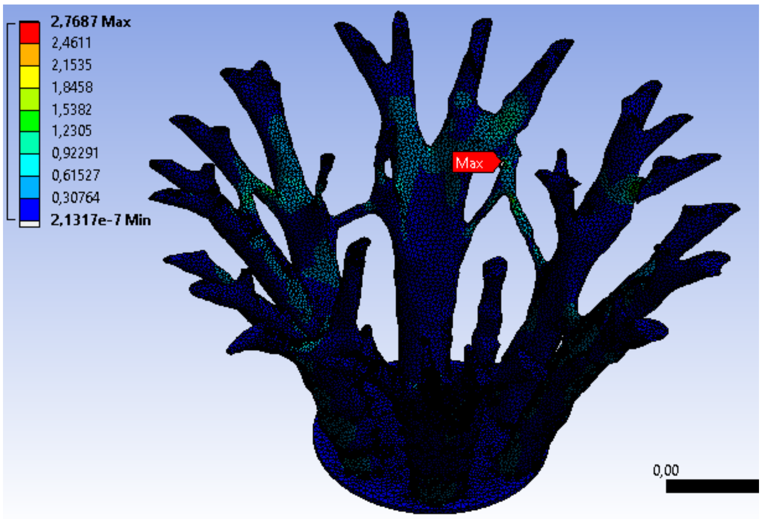

Figure 165 – The first iteration of FEM simulation of loading on the table - total Von Mises stress. It is pointed out where is the maximum stress value.

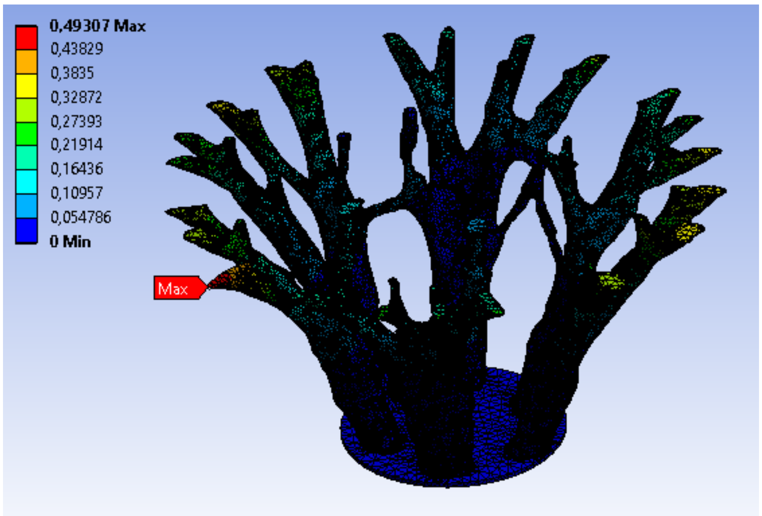

Figure 166 - The first iteration of FEM simulation of loading on the table - total deformation. Is pointed out where is the maximum value.

However, FEM is not an exact solution once it is dependent on elements quality and size. To get reliable results, it is necessary to provide a convergence test through mesh refinement techniques. Most FEM softwares have automatic tools to mesh refinement and convergence test, but in this case, the process will be done manually starting by refinement around the area of maximum stress to avoid unnecessary refinement in non-interest regions, likely to happen in automatic methods. During the convergence test, it is expected that values of maximum stress and deformation change with consecutive mesh refinement until a moment that the values start to be almost constant (convergence). In applications of low responsibilities, which is this case, a difference of 10% between values is enough to consider a convergence (Costa, 2018a). Consecutive refinements were performed at local of maximum stress until a convergence of less than 10% of error (Figure 167). The value of maximum stress converged around 4.69 MPa (Table 9) is lower than the lowest material yield tensile strength that is 38.0 MPa, therefore, for conditions mentioned previously, the structure will not fail.

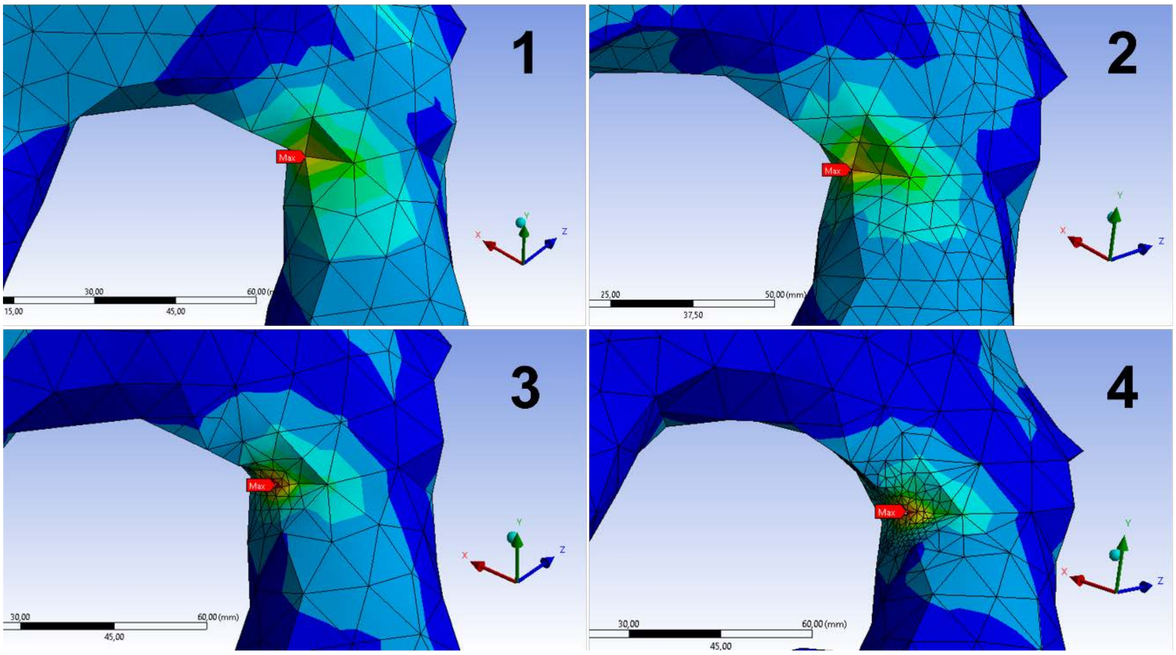

Figure 167 - Consecutive refinements were performed at local of maximum stress until the convergence.

Table 9 - Convergence Manual Control Spreadsheet.

Convergence Manual Control Spreadsheet			
Iteration	Metric Total stress - Von Mises (MPa)	Error (%) - Stop if < 10%	Total deformation (mm)
1	2.77	-	0.49
2	3.71	34.1%	0.49
3	4.45	19.7%	0.49
4	4.69	5.4%	0.50

5.1.1.11. Prototyping and Tests

Virtual prototypes were tested using rendering software (Figure 168 and 163). This approach aids the process of material choice, before producing a physical model, saving cost and time.

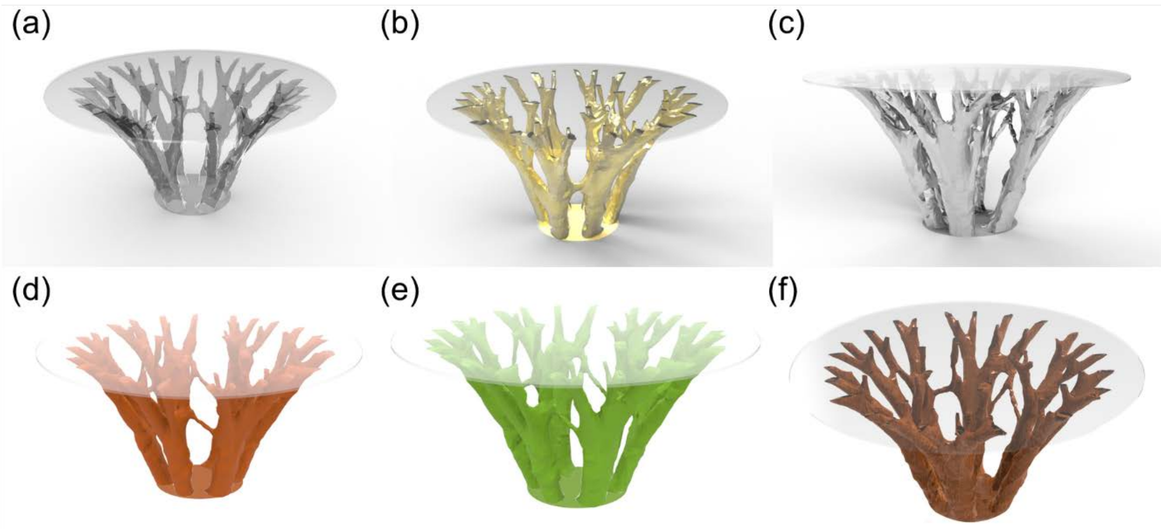

Figure 168 - Photorealistic images generated by a render software to explore the results with different materials aspect. (a) Glass, (b) Brass, (c) Aluminum, (d) and (e) Plastic, (f) Plastic with wood surface aspect.

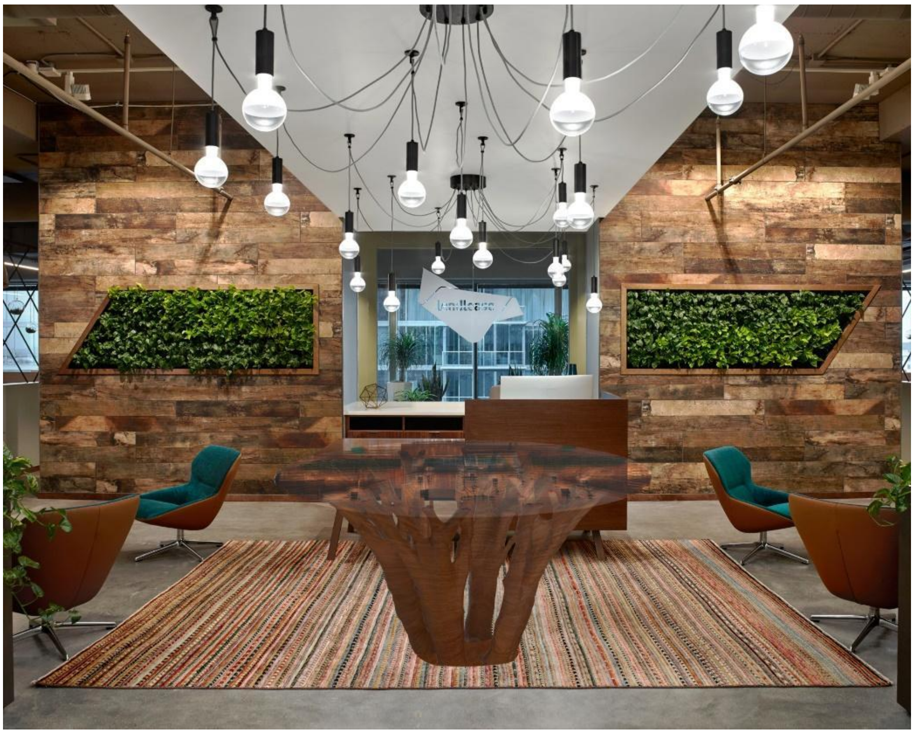

Figure 169 - Representation of the table in a biophilic environment. Modified from: (Turner, 2017).

With the objective of validating the final form with an interaction of the prototype, a scaled structure was produced using FDM additive manufacturing (3D printing) where the results obtained were satisfactory (Figure 170).

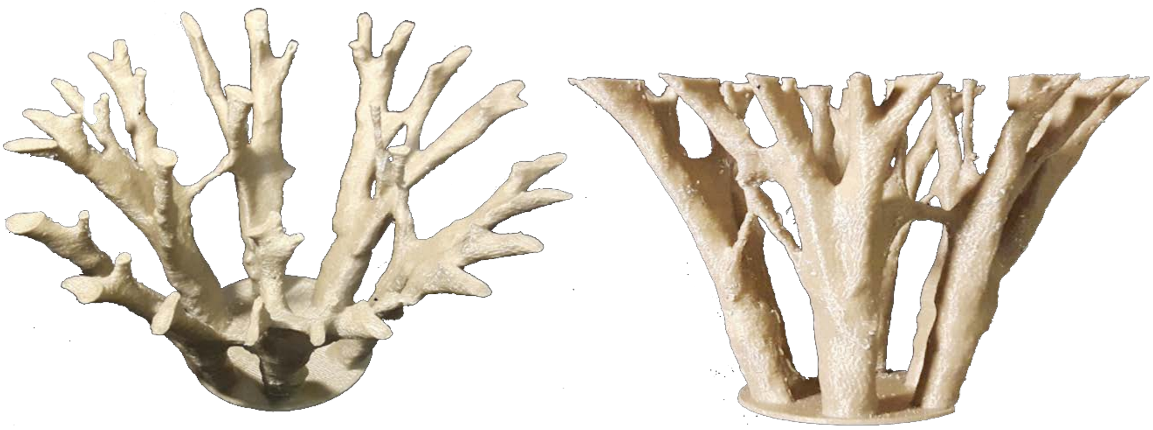

Figure 170 - The scaled prototype of structure made by 3d printer. Material is ABS.

5.1.1.12. Production and Marketing

The complex form of the table is not easy to be manufactured. Additive manufacturing (AM) is the best solution for this situation. The table structure could be made of plastic (Figure 171) or metal or even special ceramic using the AM. A matrix made of wax could be produced by AM to lost-wax casting process (Figure 172) if some special material is required. A surface post-treatment is also possible to be done in the structure, such as burnishing, painting, metal galvanization etc.

Figure 171 - Example of a large 3d printer able to create furniture. Source: (Top for 3D Printing, n.d.)

Figure 172 - Example of how lost-wax casting that can produce complex forms. Source: (Kick n Cast, n.d.)

CHAPTER 6

Conclusion

The development of this dissertation aimed to focus on how Topology Optimisation (TO) can be used as a springboard of possible solutions in product design. But why to expand the possibility of solutions and why to use the TO? First, for a dynamic market which requires better and more attractive solutions that are made faster and faster. Second, because the TO is able to improve structural projects through the point of view of efficiency and, essentially, TO is able to generate solutions that are faster than purely human work, for being a computational tool. Added to that, it is possible to say that its "imprevisibility" has the potential of generating disruptive forms to the current concepts of form. Leaving a Cartesian aspect and heading towards a more organic feel that mimics nature's structures.

Over this dissertation, the evolution of the TO methods were contextualised, as well as its current used, limitations and future perspectives. Practical aspects were explored to act as an initial guide for the Designer to make use of the TO. Next in exploration, there is Biomimics which has in common with the TO the ideas in which principles of how forms and their aesthetical appearances are generated. With Biomimics, it is noticed that nature is also a great inspiration when it comes to achieving solutions or optimised forms and, in case a Designer considers the creation of bio-inspired products, they must consider using TO tools.

However, nowadays, the TO considers only the functional aspects of a design,but the choice criteria of how a product should be, is part of a much broader universe, broader than merely quantitative performance criteria. "Something else" is necessary in order to be certain of the choice of which concept a product must have. This "something else" was better explored on chapter 4, when other aspects linked to the form and function of a product were investigated as well as how this product is perceived considering its form. Given the relative imprevisibility of the forms generated by the to and the big possible amount, the concepts considered on chapter 4 supported the creation of a "filter" which makes easier to choose the forms that are closer to the goals set for intangible aspects of the product. That is how the fourteen postulates for the generation of product geometries emerged from the TO.

By having gathered a good amount of knowledge, it was possible to create an itinerary on how to apply the TO on product design, considering its stage on the market, with twelve steps in a sequential methodology but which makes feedbacks and intermediary iterations possible, meaning - approaching the agile development philosophy. This itinerary was tested on chapter 5 with a bio-inspired project of meeting table for biophilic environments.

The practical part of chapter 5 showed that bottlenecks may exist when this methodology is used. One of them is found in the method for the creation of multiple TO solutions which, in this case, had its variables manually manipulated by the designer who had to remain available during the computational processing time in order to obtain a solution and then modify the variables in order to obtain another solution and so on.

Another bottleneck has to do with the treatment of the final form chosen, as the geometry generated by the TO mostly delivers a grotesque and irregular superficial aspect; for this reason, this geometry must undergo several suavisation and mesh quality treatments, which required time depending on the form's complexity. Added to the fact that with the original geometry manipulations, there is always a risk of having the geometry quotes decreased or increased as well as losing the concept of an optimised structure as these could present an excess or lack of mass, leading to a structural fail. Another point that needs attention is that even if the geometry has a good superficial aspect after the manipulation, its simulation in a FEM environment may be another challenge, once the CAD manipulated geometry may present tiny imperfections which sometimes may be hard to be detected or corrected, but are still capable of precluding the creation of a mesh of elements, standing on the way of the simulation's progress. Correcting the tiny imperfections may require several hours of analysis plus a CAD treatment and in case these geometric inconsistencies remain, a FEM simulation is impractical.

This project's conclusion shows that the TO is a good tool but with remarks. The choice of the form a product will have, must be approved according to an array of tangible and intangible requirements defined beforehand for the given project. The current TO tools are still not capable of considering all of these choice aspects plus, the designer's intervention for both the inputs and the results selection is always needed. In many of these cases, it is crucial the presence of a professional exclusively dedicated to this activity, a professional who has a know-how on these simulation resources and CAD treatment, which require hardware and software investments that can only be justified in projects of economical relevance. It is also important to consider the risk of spending additional time on the bottlenecks previously mentioned.

Suggested ways of process optimization would be through the application of programmable methods for s generation in sequential forms, abstaining the designer from manually adjusting the variables. The enhancement of softwares used for treatment and viabilisation of the form found is also needed, which would also decrease manual interventions. Last but not least, considering that this process may be repetitive in some of the steps, it may be suggested in another work, ways of of implementing intelligence algorithms to gather a great amount of information with the purpose of suggesting tangible and intangible choice criteria, generating forms and pre-select them for a final concept approval to be used by the designer - final element of decision and creation of the product.

Bibliography

Allaire, G., Jouve, F., & Toader, A. M. (2002). A level-set method for shape optimization. *C R Math*, 334(12):1125–1130. https://doi.org/10.1016 /S1631- 073X(02)02412-3

Allaire, G., Jouve, F., & Toader, A. M. (2004). Structural optimization using sensitivity analysis and a level-set method. *J Comput Phys*, 194(1):363–393.

Allen, J., & Pastemagazine. (2017). This Gorgeous, Minimalist Electric Kettle Helps You Brew the Perfect Cup of Coffee Every Time. Retrieved May 10, 2018, from https://www.pastemagazine.com/articles/2017/02/this-gorgeous-minimalist-kettle-helps-you-brew-the.html

Altair University. (2015). Practical Aspects of Structural Optimization.

AskNature. (2016a). Biomimicry Taxonomy. Retrieved April 14, 2018, from https://asknature.org/resource/biomimicry-taxonomy/#.WtJxLx65uUk

AskNature. (2016b). Novel antiseismic, sustainable structural system of reinforced concrete. Retrieved April 15, 2018, from https://asknature.org/idea/stick-s-lightweight-structural-system/

Baumgartner, A., Harzheim, H., & Mattheck, C. (1992). SKO (soft kill option): the biological way to find an optimum structure topology. *Int. Journey Fatigue*.

BBC. (2018). History of life on Earth. Retrieved April 22, 2018, from http://www.bbc.co.uk/nature/history_of_the_earth

Bendsøe, M. P. (1989). Optimal shape design as a material distribution problem. *Struct Optim*, 1:193–202.

Bendsøe, M. P., & Kikuchi, N. (1988). Generating optimal topologies in structural design using a homogenization method. *Comput Methods Appl Mech Eng 71*, 197–224.

Bendsøe, M. P., Olhof, N., & Sigmund, O. (2006). *IUTAM Symposium on Topological Design Optimization of Structures, Machines and Materials*. Dordrecht: Springer.

Bendsøe, M. P., & Sigmund, O. (2003). *Topology optimization: theory, methods, and applications*. *Engineering* (Vol. 2nd Editio). https://doi.org/10.1063/1.3278595

Benyus, J. (n.d.). A CONVERSATION WITH AUTHOR JANINE BENYUS. Retrieved April 14, 2018, from https://biomimicry.net/the-buzz/resources/conversation-author-janine-benyus/

Benyus, J. M. (2009). *Biomimicry: Innovation Inspired by Nature*. New York: HarperCollins. Retrieved from https://books.google.pt/books?id=mDHKVQyJ94gC

Bernett, A. (2017). Biomimicry versus Biophilia: What’s the Difference? Retrieved April 15, 2018, from https://www.terrapinbrightgreen.com/blog/2017/02/biomimicry-versus-biophilia/

Bilderparade. (n.d.). Bilderparade CCCXLV. Retrieved May 9, 2018, from https://www.langweiledich.net/bilderparade-cccxlv/3/

Biomimicry 3.8. (n.d.). What is Biomimicry?

Biomimicry 3.8. (2015). Biomimicry DesignLens - A visual guide. *Synapse*, *g1.1*. Retrieved from https://synapse.bio/blog/2017/10/18/free-download-biomimicry-designlens

Biomimicry Institute. (2017). The Biomimicry Design Process. Retrieved April 15, 2015, from https://toolbox.biomimicry.org/methods/process/

Biomimicry Institute. (2018). Other Pathways to Biomimicry. Retrieved April 16, 2018, from https://toolbox.biomimicry.org/methods/other/

Bourdin, B., & Chambolle, A. (2003). Design-dependent loads in topology optimization. *ESAIM Control Optim Calc Var*, 9:19–48.

Brennan, J. (2014). 20 Years of Topology Optimization: Birth and Maturation of a Disruptive Technology. Retrieved March 1, 2018, from https://insider.altairhyperworks.com/20-years-topology-optimization-birth-maturation-disruptive-technology/

Canaltech. (2016). Você sabe o que é design generativo? Retrieved June 21, 2017, from https://corporate.canaltech.com.br/noticia/design/voce-sabe-o-que-e-design-generativo-este-infografico-explica-76743/

Capra, F. (1982). *The turning point: Science, society, and the rising culture*. New York: Simon and Schuster.

Click Curioso. (2017). Conheça o seu nível de tripofobia VEJA AGORA! Retrieved May 9, 2018, from http://clickcurioso.com.br/conheca-o-seu-nivel-de-tripofobia-veja-agora

Conti, M. (2017). The incredible inventions of intuitive AI. Retrieved June 18, 2016, from https://www.youtube.com/watch?v=aR5N2Jl8k14

Corbin Bronze ltd. (2012). Tree Branch - Corbin Bronze. Retrieved May 19, 2018, from https://corbinbronze.com/projects/tree-branch/

Costa, P. (2018a). FEM: MESH QUALITY AND BODY SIMPLIFICATION (PART 5) - NUMBER OF ELEMENTS AND CONVERGENCE. Retrieved November 25, 2018, from http://phelipecostapde.blogspot.com/2018/03/fem-mesh-quality-and-body_13.html

Costa, P. (2018b). FEM: SIX STEPS TO ACHIEVE A PROPER MESH TO THE STATIC STRUCTURAL ANALYSIS. Retrieved November 25, 2018, from http://phelipecostapde.blogspot.com/2018/03/six-steps-to-achieve-proper-mesh-to.html

Dekor Store. (n.d.). farklı-ağaç-kökü-dekoratif-orta-sehpa - DekorStore. Retrieved May 19, 2018, from http://www.dekorstore.net/dekoratif-sehpa-modelleri.html/farkli-agac-koku-dekoratif-orta-sehpa

Dictionary.com. (n.d.). Topology. Retrieved April 8, 2018, from http://www.dictionary.com/browse/topology

DK Find Out. (n.d.). Rabbits and hares. Retrieved May 11, 2018, from https://www.dkfindout.com/us/animals-and-nature/rabbits-and-hares/

Dunning, P. D., Brampton, C. J., & Kim, H. A. (2015). Simultaneous optimisation of structural topology and material grading using level set method. *Materials Science and Technology*, *31*(8), 884–894. https://doi.org/10.1179/1743284715Y.0000000022

Encyclopaedia Britannica. (n.d.). Sexual motivation. Retrieved April 22, 2018, from https://www.britannica.com/topic/sexual-motivation

Erlhoff, M., & Marshall, T. (2008). *Design Dictionary - Perspectives on Design Terminology*. Basel, Switzerland: Birkhäuser Verlag AG.

ESSS. (2017). Os Pilares da Indústria 4.0. Retrieved June 22, 2017, from http://www.esss.com.br/blog/2017/01/os-pilares-da-industria-4-0/

Ethical Panda; (2017). Tree Facts – Ethical Panda. Retrieved May 19, 2018, from https://ethicalpanda.com/tree-facts/

Expominera2017. (2018). Tree End Table Red Oak Tree Stump Coffee Table Birch Tree Table Runner – expominera2017.com. Retrieved May 19, 2018, from http://expominera2017.com/tree-end-table/tree-end-table-red-oak-tree-stump-coffee-table-birch-tree-table-runner/

Fiebig, S., & Axmann, J. K. (2013). Using a binary material model for stress constraints and nonlinearities up to crash in topology optimization. *10th World Congress on Structural and Multidisciplinary Optimization*, 2013.

Fiebig, S., Sellschopp, J., Manz, H., Vietor, T., Axmann, J. K., Schumacher, A., & Ag, V. (2015). Future challenges for topology optimization for the usage in automotive lightweight design technologies. *11th World Congress on Structural and Multidisciplinary Optimization*, (June), 1–8.

Folgado, J., & Fernandes, P. R. (2011). Bone Tissue Mechanics.

Furman, T., & Onedio. (2017). How Would A Person's Face Look Like If It Really Fit The Golden Ratio. Retrieved May 9, 2018, from https://onedio.co/content/how-would-a-persons-face-look-like-if-it-really-fit-the-golden-ratio-16047

Galilei, G. (1638). *Discorsi e Dimonstrazioni Matematich, Intorno à Due Nuove Scienze Attenenti alla Mecanica & i Movimenti Locali*. (ELSEVIER, Ed.). Leiden, Netherlands.

Galileo Ramos. (n.d.). Oryctolagus cuniculus n1 Skeleton « Galileo Ramos – Art with Skeletons. Retrieved May 11, 2018, from http://galileoramos.com/esqueletos/gallery-of-skeletons-mammals/oryctolagus-cuniculus-n1-skeleton/

Galland, P. L. D. (2015). Biomimicry – The Future of Sustainable Innovation. In D&I TongJi University (Ed.), *Shanghai Green Drinks | Game Changers Series*. Shangai: BiDL Biomimetic Design Lab.

Garland, T. H. (1987). *Fascinating Fibonaccis: Mystery and magic in numbers.* Palo Alto: Dale Seymour.

Gatzky, T. (2014). Perception-oriented Product Design as a Design Challenge. *Design of Machines and Structures: A Publication of the University of Miskolc*, *4*, 120.

Glitterr, S., & Pinterest. (n.d.). Awesome Buildings & Structures - Esfahan, Iran. Retrieved May 9, 2018, from https://www.pinterest.co.uk/pin/440930619747527926/%0A

Goel, V. (1995). *Sketches of Thought*. Cambridge, MA: MIT Press.

Gotzsch, J. (1999). *Design orientation in new product development*. (B. Jerrard, R. Newport, & Trueman, Eds.). London, UK: Taylor & Francis.

Gray, T., & Birrell, C. (2014). Are biophilic-designed site office buildings linked to health benefits and high performing occupants? *International Journal of Environmental Research and Public Health*, *11*(12), 12204–12222. https://doi.org/10.3390/ijerph111212204

Gu, W. (2013). On Challenges and Solutions of Topology Optimization for Aerospace Structural Design. *10th World Congress on Structural and Multidisciplinary Optimization*, 1–7.

Guilford, J. P. (1967). *The nature of human intelligence*. New York, NY: McGraw Hill.

Haftka, R. T., & Gürdal, Z. (2012). *Elements of Structural Optimization*. Springer Netherlands. Retrieved from https://books.google.pt/books?id=2e5rCQAAQBAJ

Huiskes, R. (2000). If bones is the answer, then what is the question? *Journal of Anatomy*, *197*, 145–156.

Instanonymous. (2016). Tarikhmelayu. Retrieved May 10, 2018, from https://instanonymous.com/m/BMTcUZGjS6B

Interaction Design Foundation. (n.d.). What are Gestalt Principles? | Interaction Design Foundation. Retrieved May 10, 2018, from https://www.interaction-design.org/literature/topics/gestalt-principles

Ivonette, K. (2011). Analysis For Face Attractiveness: What Are The Scoring Ranges And Factors? Retrieved May 9, 2018, from https://pinkmirror.com/blog/photo-retouch-face-attractiveness-score/

Johnsen, S. (2013). Structural Topology Optimization, (June). https://doi.org/10.1533/ijcr.2004.0288

Jordan, P. W. (2000). *Designing Pleasurable Products: An Introduction to the new human factors*. London, UK: Taylor & Francis.

Kandel, E. (2012). *The Age of Insight: The Quest to Understand the Unconscious in Art, Mind, and Brain, from Vienna 1900 to the Present* (3.1). New York: Random House.

Kekely, F. F. (2017). One month in Madagascar III: The most beautiful trees in the world and we were very close to a wild fossa - TRAVELERS.SK. Retrieved May 19, 2018, from http://travelers.sk/one-month-madagascar-iii-the-most-beautiful-trees-world-close-wild-fossa/

Khvostichenko, B. (2008). Socotra dragon tree.JPG - Wikimedia Commons. Retrieved May 19, 2018, from https://commons.wikimedia.org/wiki/File:Socotra_dragon_tree.JPG

Kick n Cast. (n.d.). Kick ‘n Cast, quality manufacturers of jewelry.

Köhler, W. (1929). *Gestalt psychology*. New York, NY: Liverigh.

Komninos, A., & Interaction Design Foundation. (2017). The Reflective Level of Emotional Design. Retrieved May 9, 2018, from https://www.interaction-design.org/literature/article/the-reflective-level-of-emotional-design

Lamborghini. (2018). Automobili Lamborghini - Official Website | Lamborghini.com. Retrieved May 11, 2018, from https://www.lamborghini.com/en-en/

Larsson, R. (2016). Methodology for Topology and Shape Optimization : Application to a Rear Lower Control Arm.

Lindvall A&D. (2009). Villa M2 by Jonas Lindvall // Malmo, Sweden. Retrieved May 10, 2018, from https://www.yatzer.com/Villa-M2-by-Jonas-Lindvall--Malmo-Sweden

Lotha, G., & Britannica. (2017). Gestalt psychology | Britannica.com. Retrieved May 10, 2018, from https://www.britannica.com/science/Gestalt-psychology

Maeda, J. (1996). Maeda @ Media, Interview excerpt with John Maeda. Retrieved March 8, 2018, from http://www.paul-rand.com/foundation/thoughts_maedaMedia/#.WqF-Q6MpKUk

Maslow, A. (1970). *Motivation and Personality*. New York, NY: Harper & Row.

MatWeb. (2018). Overview of materials for Acrylonitrile Butadiene Styrene (ABS), 30% Glass Fiber Filled. Retrieved November 11, 2018, from http://www.matweb.com/search/DataSheet.aspx?MatGUID=b4916d0a6777469986e9d8687a8b4a69&ckck=1

Maxwell, J. C. (1870). On reciprocal s, frames and diagrams of forces. *Transactions of the Royal Society of Edinburgh*, *Vol. XXVI*, 1–40.

McLoughlin, J., & Sabir, T. (2017). *High-Performance Apparel: Materials, Development, and Applications*. Elsevier Science. Retrieved from https://books.google.pt/books?id=2eZGDgAAQBAJ

Meakin, P. (1990). Fractal structures. *Progress in Solid State Chemistry*, *20*(3), 135–233. https://doi.org/10.1016/0079-6786(90)90001-V

Megapixl. (n.d.). Illustration: Vector, Elegant Mandala, With Intricate Detail. Retrieved May 9, 2018, from https://www.megapixl.com/vector-elegant-mandala-with-intricate-detail-illustration-52778058

Meisner, G. (2012). History of the Golden Ratio. Retrieved April 20, 2018, from https://www.goldennumber.net/golden-ratio-history/

Meyer, G. (1867). Die Architektur der Spongiosa. *Archief Fur Den Anatomischen Und Physiologischen Wissenschaften Im Medicin*.

Michell, A. G. M. (1904). The limits of economy of material in frame structures. *Philisophical Magazine*, 8(Series 6):589–597.

Mlejnek, H. P. (1992). Some aspects of the genesis of structures. *Struct Optim*, *5:64–69*.

Mohammed, A. (2004). Homogenization and structural topology optimization of constrained layer damping treatments.

Mothersill, P. (2014). *The Form of Emotive Design*. MIT - Massachusetts Institute of Technology. Retrieved from http://emotivemodeler.media.mit.edu/images/Mothersill_The Form of Emotive Design Thesis.pdf

NASA. (2018). Engineering Design Process. Retrieved April 16, 2018, from https://www.nasa.gov/audience/foreducators/best/edp.html

Nobel-Jørgensen, M., & Bærentzen, J. A. (2016). Interactive Topology Optimization.

Norman, D. A. (2004). *Emotional design: Why we love (or hate) everyday things*. New York, NY: Basic Books.

Oliveira, J. (2013). *Topology Optimisation Methodologies for Structural Analysis*. Aveiro University.

Oxford Dictionaries. (n.d.). Topology. Retrieved April 8, 2018, from https://en.oxforddictionaries.com/definition/topology

oxforddictionaries. (n.d.). Definition of design in English: Retrieved March 8, 2018, from https://en.oxforddictionaries.com/definition/design

Palmer, S. E. (1999). *Vision science: photons to phenomenology*. Cambridge, MA: MIT Press.

Palmer, S. E. (2002). *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience*. (H. Pashler & S. Yantis, Eds.), *Stephens' Handbook of Experimental Psychology* (3rd ed., Vol. 1: Sensati). New York, NY: John Wiley & Sons, Inc. https://doi.org/10.1026//1618-3169.50.2.155

Panero, J., & Zelnik, M. (1979). Human dimension & interior space: a source book of design reference standards. New York: Whitney Library of Design. Retrieved from file://catalog.hathitrust.org/Record/000698563

Paredes, B., & ESSS. (2016). OTIMIZAÇÃO EM ENGENHARIA. Retrieved March 11, 2018, from https://www.esss.co/blog/otimizacao-em-engenharia/

Plutchik, R. (1991). *The Emotions*. University Press of America. Retrieved from https://books.google.pt/books?id=JaQauznPoiEC

Posamentier, A. S., & Lehmann, I. (2007). *The fabulous Fibonacci numbers*. Amherst, NY: Prometheus Books.

Prager, W., & Rozvany, G. I. N. (1977). Optimization of the structural geometry. In *In: Bednarek AR, Cesari L (eds) Dynamical systems* (p. pp 265–293). Gainsville, Florida.

Prats, M. (2007). Shape Exploration in Product Design: Assisting Transformation in Pictorial Representations.

Prats, M., Earl, C., Garner, S., & Jowers, I. (2006). Shape exploration of designs in a style : Toward generation of product designs, 201–215.

Qian, X. (2013). Topology optimization in B-spline space. *Computer Methods in Applied Mechanics and Engineering*, 265 (2013) 15–35.

Querin, Q. M., Steven, G. P., & Xie, Y. M. (2000). Evolutionary structural optimisation using an additive algorithm. *Finite Elements in Analysis and Design*, 34: 291-308.

Raymond, C., & Schleiniger, G. (2017). Why do fibonacci numbers appear in patterns of growth in nature?, *55*(5), 30–41.

Reaktorplayer. (2015). Complex, Beautiful And Very Easy To Make Fractal Graphics (Windows). Retrieved May 9, 2018, from https://reaktorplayer.wordpress.com/2010/10/15/complex-beautiful-and-very-easy-to-make-fractal-graphics-windows/

Rojal. (2016). Tree PNG Transparent Images | PNG All. Retrieved May 19, 2018, from http://www.pngall.com/tree-png

Roodsarabi, M., Khatibinia, M., & Sarafrazi, S. R. (2016). Isogeometric Topology Optimization of Structures Using Level Set Method Incorporating, *6*(3), 405–422.

Rozvany, G. I. N. (1972a). Grillages of maximum strength and maximum stiffness. *Int J Mech Sci*, 14:1217–1222.

Rozvany, G. I. N. (1972b). Optimal load transmission by flexure. *Methods Appl Mech Eng*, 1:253–263.

Rozvany, G. I. N. (1998). Exact analytical solutions for some popular benchmark problems in topology optimization. *Structural and Multidisciplinary Optimization*.

Rozvany, G. I. N., Zhou, M., & Birker, T. (1992). Generalized shape optimization without homogenization. *Structural and Multidisciplinary Optimization*, 4, 250–254.

Schiteanu, B. (2005). Old Architecture. Retrieved May 10, 2018, from https://www.trekearth.com/gallery/Europe/France/East/Alsace/Strasbourg/photo349583.htm

Sigmund, O. (2007). Morphology-based black and white filters for topology optimization. *Structural and Multidisciplinary Optimization*, *33*(4–5), 401–424. https://doi.org/10.1007/s00158-006-0087-x

Sigmund, O., & Maute, K. (2013). Topology optimization approaches: A comparative review. *Structural and Multidisciplinary Optimization*, *48*(6), 1031–1055. https://doi.org/10.1007/s00158-013-0978-6

Sokołowski, J., & Zochowski, A. (1999). On the topological derivative in shape optimization. *SIAM J Control Opt*, 37:1251–1272.

SPI Home. (n.d.). SPI Home - Cypress Tree Coffee Table. Retrieved May 19, 2018, from http://www.spi-home.com/cypress-tree-coffee-table_1288.aspx#.WwAuhUgvyUk

Stokoe, C. (2013). *ECOMIMESIS - Biomimetic Design for Landscape Architecture*. Malad: NS2.

Stoléru, S. (2014). Reading the Freudian theory of sexual drives from a functional neuroimaging perspective. *Frontiers in Human Neuroscience*, *8*(March), 1–15. https://doi.org/10.3389/fnhum.2014.00157

Stone, J. (n.d.). HoMe PaGe. Retrieved May 9, 2018, from http://www.noticiasargentinas.info/new/j/jama-stone.awp

Than, K., & Live Science. (2018). What is Darwin's Theory of Evolution? Retrieved April 22, 2018, from https://www.livescience.com/474-controversy-evolution-works.html

The American Heritage® Science Dictionary. (n.d.). Topology. Retrieved April 8, 2018, from http://www.dictionary.com/browse/topology

Thonet GmbH. (2015). SIMPLY LEGENDARY: THE UNIQUE SUCCESS STORY OF THONET'S ORIGINAL VIENNA COFFEE HOUSE CHAIR 214. Retrieved March 9, 2018, from http://en.thonet.de/service/press/history-214.html

Top for 3D Printing. (n.d.). Check out Drawn ultra-customised furniture built with a massive, robotic 3D printing arm | 3D Printing News. Retrieved June 17, 2018, from http://top43dprinting.com/check-out-drawn-ultra-customised-furniture-built-with-a-massive-robotic-3d-printing-arm/

Topology Optimization Guide. (n.d.). Software list. Retrieved March 11, 2018, from http://www.topology-opt.com/software-list/

Turner, A. J. (2017). Biophilia? It's a Good Thing - Ask Lendlease! - Anita Turner. Retrieved June 14, 2018, from http://www.anitainsights.com/blog/biophilia-at-lendlease-nashville/

Vatanabe, S. L., Lippi, T. N., Lima, C. R. d., Paulino, G. H., & Silva, E. C. N. (2016). Topology optimization with manufacturing constraints: A unified projection-based approach. *Advances in Engineering Software*, *100*, 97–112. https://doi.org/10.1016/j.advengsoft.2016.07.002

Wang, M., Wang, X., & Guo, D. (2003). level set method for structural topology optimization. *Comput Methods Appl Mech Eng*, 192(1– 2):227–246.

Wildlife Facts. (2015). *Top 10 Most Poisonous Animals In The World*. Retrieved from https://www.youtube.com/watch?v=D2jmNT35GPA

Wolff, J. (1986). *The Law of Bone Remodelling*. (R. Furlong & P. Maquet, Eds.). Berlin: Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-71031-5

World Economic Forum. (2016). The Future of Jobs Employment, Skills and Workforce Strategy for the Fourth Industrial Revolution. *Growth Strategies*, (january), 2–3. https://doi.org/10.1177/1946756712473437

World Health Organization. (2013). Mental Health Action Plan 2013-2020. *WHO Library Cataloguing-in-Publication DataLibrary Cataloguing-in-Publication Data*, 1–44. https://doi.org/ISBN 978 92 4 150602 1

Xie, Y. M., & Steven, G. P. (1993). A simple evolutionary procedure for structural optimization. *Comput Struct*, 49:885–896.

Zari, M. P. (2006). Biomimetic Approaches To Architectural Design for Increased Sustainability. *Design*, (April), 2006.

Zhao, D., Li, M., & Liu, Y. (2017). Self-supporting Topology Optimization for Additive Manufacturing. Retrieved from http://arxiv.org/abs/1708.07364

Zhou, M., & Rozvany, G. I. N. (1991). The COC algorithm, part II: topological, geometry and generalized shape optimization. *Methods Appl Mech Eng*, 89(1–3):309–336.
毎週開催(Every Week), & Connpass. (2016). 数学もくもく勉強会（Mathematics Mikumaku study group). Retrieved May 9, 2018, from https://connpass.com/event/35591/

ANNEX:

Biomimicry Taxonomy