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# Development of innovative design approaches based on design for additive manufacturing in medical and industrial applications

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# Summary

# Abstract

The project aims at developing a design paradigm to automatize product design, by means of tools for structural and topological optimization and knowledge-based solutions for exploiting recent and upcoming Additive Manufacturing (AM) technologies. In particular, design optimisation algorithms are combined with other technological tools in order to enable greater development and knowledge of Design for Additive Manufacturing (DfAM) methodologies integrated with different engineering approaches. The research will impact on the product development process proposing the generation of a technology-driven product shape. Actually, the proposed DfAM methods provide the optimal functional material layout, not only complying with the mechanical behaviour of the product but also with a specific manufacturing process and equipment. Existing state of the art optimization tools create product shapes on the base on the yield criteria and reference geometry. The searched paradigm will allow obtaining new boundary conditions and objective to generate the most suitable design solution respect to different available technology or approach company may already have or will decide to develop in different applications fields. The research programme will be characterized by a deep understanding of industry and market needs concerning both the product development process and the AM technologies. Commercial tools are quickly evolving and they have been integrated, tested and assessed to allow full integration with more robust and experienced approaches. The reached outcomes in terms of methods have been applied to case studies belonging to the industrial and medical field to check feasibility, efficiency and robustness of the solution provided.

# Introduction

In recent years, AM technologies have been experiencing a new period of strong innovation. This technological fervour has been due to a great technical improvement in the computational tools used, but above all to global economic and social conjectures that have changed the goals and needs of people and therefore the market. In particular, the strong focus on the environmental impact of conventional manufacturing technologies has led to an increasing evolution of design methodologies aimed at creating lighter, better performing and human-centered products throughout the entire life cycle. At the same time, the raw material crisis is driving the development of manufacturing technologies that minimise energy and raw material wastage while maintaining the mechanical characteristics of products. In an extremely dynamic global context of strong change, AM technologies and related design methodologies are receiving renewed attention and a strong innovative push. Most of the research carried out, however, is limited to implementing watertight production technologies, without the possibility of proposing innovative methodologies outside the technological limits of each production method. The economic and scalability limitations of additive technologies are the real obstacle for a more extensive use of 3D printing in various fields of production, especially high-volume production. The aim of the PhD thesis is to study, develop and propose new design methodologies considering the structural optimisation and Generative Design (GD) approaches proposed in the context of DfAM. In particular, the target of the research is to propose solid design methods in which structural optimisation and Generative Design are integrated with conventional design approaches to improve standard design processes and enhance DfAM methodologies emerged with the diffusion of AM. This result also permits to improve the performances of both the part designed and design process, increase the production efficiency in terms of time and costs. The methodology provided will positively affect different dimensions of the design framework: experts' knowledge on routine activities will be re-used to create an automatic procedure impacting on both human resources involved and on the organizational design process.

The thesis is divided into four main chapters, describing the three main stages of the research carried out in recent years. In the first chapter, the state of the art of optimisation and Generative Design methodologies is presented, to argue and expound the innovation of the thesis.

In the second chapter, the research carried out and the case studies tackled in the context of GD, an innovative approach for component optimisation, are set out. A detailed comparison between the GD methodology and topological optimisation is then proposed, so that both tools can be best handled and used for each proposed case study.

The third chapter presents the core of the research project and is dedicated to the development of the method to automatically design products while respecting mechanical behaviour, manufacturing constraints and the conventional design technology to improve. For this reason, the methodologies can be implemented in a framework, embedding applicative domain knowledge, to guide the automatic simulations and evaluate design results. At the same time, a workflow is implemented to create a defined process for the case studies. In this step of the research, innovative methods are applied to real case studies.

Finally, in the fourth chapter, conclusions and future developments in this research area are presented.

# Chapter 1
# State of the Art

## 1.1. Structural optimization

Nowadays, European directives regarding industry 4.0 are emphasising Additive Manufacturing (AM) technologies [1], [2]. At the same time, thanks to the greater design freedoms given by AM compared to classical subtractive manufacturing technologies, there is great excitement in the development of guidelines specified for 3D printing [3]. The proposed methodologies form the topic of Design for Additive Manufacturing (DfAM) [4] which includes mass customisation, parts consolidation and multi-material design [5], [6]. The leading field of research is structural optimisation and all techniques for improving the performance of a component by modifying its shape. The word *optimisation* comes from the Latin *optimus*, i.e. “to make the best” to an object, theory or methodology with the aim of overcoming previous results in relation to an aim or according to constraints [7].

In particular, structural optimisation is a type of optimisation that aims to find the best material arrangement for a particular load state under certain constraint conditions by maximising (bottom up) or minimising (top down) an objective function [8]. In this dissertation, the notion of optimisation will refer both to the shape of the product to be manufactured and to the methodologies developed because of this concept. In both cases the result can be explained by different characteristics developed in the component under study: an optimal geometry can be reflected in reduced and innovative overall dimensions, an optimal weight distribution, a more efficient aerodynamic shape [9], a more homogeneous distribution of strain, an improved ergonomics [10] and more. Structural optimisation is applied in industrial fields that place great emphasis on minimising mass while maintaining high mechanical performance, such as in the aerospace industry [11]–[15] and automotive [16]–[24] . At the same time, it is also used in the medical field [25]–[31] and is often juxtaposed with the current topic of environmental sustainability [32]–[38].

As noted in the scientific literature [39]–[43], the results of optimisation procedures have innovative but complex shapes that are difficult to produce with traditional manufacturing technologies. Two solutions can be considered to deal with this critical issue: using AM as a production process or introducing more strict manufacturing constraints on the shape of the component.

One of the most attractive aspects of Additive Manufacturing is the opportunity to realise products with complex and customisable geometries without producing significant scrap [44]. In fact, the layer-by-layer production methodology allows the creation of components with articulated internal structures and undercuts, relying on the use of support structures that can be removed in post-processing [45]. Another highlight is the theoretical cost-effectiveness of additive processes [46]–[48]:

- The complexity of a component's shape does not critically affect the cost of production
- The absence of significant waste favours the use of only the material needed to generate the product
- The lack of tools for material removal eliminates a significant tool wear cost
- Additive Manufacturing offers extreme production flexibility, which significantly reduces the cost of tooling for production changeover and increases the companies speed of response to market changes

On the other hand, AM is disadvantageous when used for mass production, in addition to having a significantly lower print volume than most of components' size produced with traditional technologies [49]. Other disadvantages lie in the quality of the moulded parts: the surface quality is lower and difficult to control compared to traditional technologies, which also leads to problems in dimensional control of the component and the inconsistent mechanical behaviour of identical components printed with the same specs [50]–[52].

The second possibility for managing the complex shapes because of optimisation methodologies is to introduce production constraints in the optimization algorithm according to the technology to be used [53]. For instance, to make a component by injection moulding, constraints can be introduced to avoid undercuts [54], [55]. Other constraints concern the direction of extrusion; maximum and minimum thicknesses based on die dimensions [56]; the overall dimensions and displacements of the tools for testing the feasibility of the product [57], [58]; finally, symmetry constraints to simplify the results.

As shown in Figure 1, Structural optimisation methods include Size Optimisation (SO), Shape Optimisation (ShO) and Topology Optimisation (TO) [8].

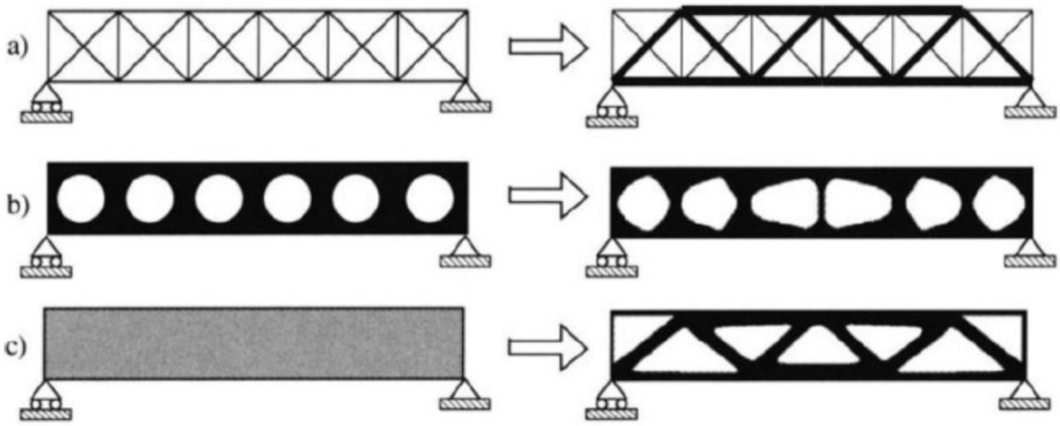



*Figure 1. Schematic representation of the three different types of structural optimisation: a) size optimisation, b) shape optimisation, c) topology optimisation [8].*

### 1.1.1. Size Optimization

Also *dimension optimisation*. It is the simplest method of structural optimisation. The geometry of the structure is not modifiable because the optimisation variables are the dimensions of its elements (diameters, lengths, thicknesses, etc.). The optimisation problem reaches convergence when the set of parameters is found that satisfies the requirements, i.e., when the optimal dimensions of the elements to resist a certain load condition are found. In a mass-minimisation problem, this means minimising the dimensions while ensuring adequate mechanical strength.

### 1.1.2. Shape Optimization

Also shape optimisation. It is a more sophisticated optimisation method than SO. The design variables are coordinates of the geometric shapes of which the structure is composed. With these variables, it is possible to modify the overall geometry, overcoming the limitation of SO, which only involves varying the dimensions of the structural elements. The optimisation process is divided into three parts: geometric representation, structural analysis and application of the optimisation algorithm. The geometric representation part defines the initial shape of the structure: this guides the solution towards a configuration that is not too distant from the starting geometry. This is the major limitation of Shape Optimisation, which will be overcome by Topological Optimisation. Structural analysis is generally performed using finite elements theory. After each analysis, the objective function is evaluated: if a minimum condition (or a maximum condition, depending on the objective function) is reached, the iterations stop. Otherwise, the iterative process is continued by applying the optimisation algorithm again [59].

### 1.1.3. Topology Optimization

The problem of Topological Optimisation was first approached in 1904 by Michell [60], an Australian engineer who was studying a method to find the minimum amount of material required for a structure to withstand a certain load condition, with application to minimising the volume of trusses subjected to a single load. Seventy years later Rozvany extended Michell's theory from trusses to single beams [61] and in 1988 Bendsoe and Kikuchi developed a first method for this purpose [62], represented in Figure 2.

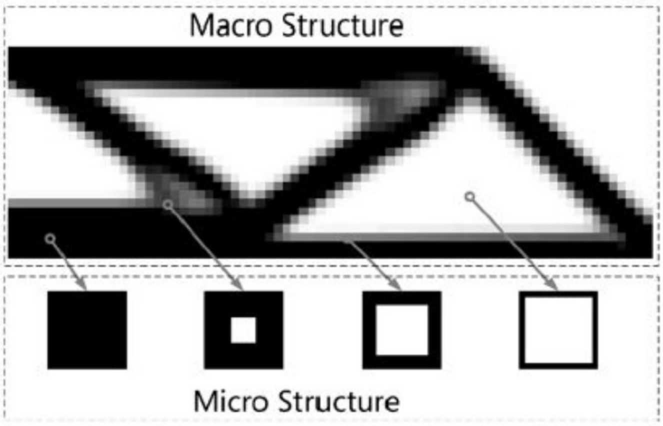



*Figure 2. Example of homogenised microstructures.*

In recent years, studies and applications relating to TO have been steadily increasing. This is thanks to the implementation of increasingly high-performance computational tools: the latest cloud computing technology has brought such computational capacity to the research field that it is possible to solve the problem in a relatively short time and with excellent detail of the results [63]–[65]. At the same time, the establishment of 3D printing, even with cost-effective products that allow good quality of the printed component, has fuelled the research on TO. This is mainly motivated by the possibility of obtaining complex shapes from the optimiser and being able to print them without the stringent constraints of conventional production technologies [66]. Topological optimisation is an iterative process that aims to find the optimal arrangement of material capable of withstanding a given load condition, while respecting certain boundary conditions such as available volume, constraints, etc. [67]. No initial shape is required, but a processing volume: this condition overcomes the shape limitation mentioned with respect to shape optimisation. In this volume, a customisable mesh is created, in which a variable of the full/empty type is associated with each element. At each iteration, these variables change defining a new geometry, while respecting the boundary conditions. In the TO process, many physical variables come into consideration (weight, stresses, deformations, thicknesses, resonance frequencies, etc.), of which some define the objective function, others define the limitations to the iterative process. For each iterative step, the starting point is an initial geometry on which a FE analysis is performed; the first iteration considers the entire working volume as the initial geometry. Depending on the results of the analysis, the optimisation algorithm modifies the full/empty variables of the mesh by creating a new geometry, which becomes the initial geometry of the next step. In summary, it can be said that TO removes material where stresses are low and adds material where stresses are high.

The basic optimisation problem starts with the search for the minimum (top down) or maximum (bottom up) of a function $f(x)$ and its component vector of variables $x$. All this with respect to boundary conditions, in the form of equations or inequality. Generally, the optimisation problem can be expressed as:

- $f(x)$ minimisation of the objective function
- $\underline{x} = [x_1; x_2; \dots; x_n]$ design variables, with *n* number of variables
- $h_j(x) = 0$ equality constraints, with $j$ number of constraints of the same type
- $g_k(x) < 0$ inequality constraints, with *k* number of constraints of the same type
- $x_{i_l} < x_i < x_{i_u}$ with $x_{i_l}$ and $x_{i_u}$ lower and upper limits of the variable $i$-th

If the constraints were not linear, a linearisation problem could be implemented within the iterative process. Starting from the general definition over the past 30 years, the concept of TO has evolved according to various approaches. In particular, the three main groups into which the methodologies are gathered are: "element-based", "discrete" and "combine" [68].

#### 2.1.3.1. Element-based approach

The traditional approach on which topological optimisation is based is the element-based approach. In general, this involves a discretization of the problem into a finite number of elements whose solution is known or can be approximated. Each of these elements is characterised by a certain number of nodes, which identify the points of connection with the other elements. The interactions of the discretized elements define the degrees of freedom of the nodes, which are used to create the equations of the system. The solution of these equations gives information about the overall behaviour of the system. This discretization of the problem into solid elements is also the basis of finite element analysis, which is often integrated into the iterative process. Among the element-based approaches, the main ones are density-based, the bubble method, level sets and phase fields [8].

*2.1.3.1.1. Density based*

Density-based (or gradient-based) approaches involve a discretisation of the design space. Among these approaches, the most widely used is the Solid Isotropic Microstructure with Penalisation (SIMP) method. This method considers the arrangement of material within a volume defined as the “design domain”, using boolean operations to remove or add material and the gradient method to find a maximum or minimum point of the objective function. The design variable is the relative density $\rho$, which is calculated for each finite element in which the design domain is discretized and can take values between 0 and 1, empty and full element respectively. The optimisation problem according to the SIMP method can be represented as follows:

$$C = U^T K U = \sum_{e=1}^{n} u^e k^e u^e = \sum_{e=1}^{n} (\rho^e)^p u^e k_0^e u^e$$

$$so\ that \qquad V = \sum_{e=1}^{n} \rho^e v_0 \leq Vmax$$

$$KU = F$$

$$0 < \rho min \leq \rho^e \leq 1$$

Where $C$ is the opposite of the stiffness $K$, $U$ and $F$ are the vectors of global displacements and loads, $K$ is the global stiffness matrix, $u^e$, $k^e$ and $\rho^e$ are respectively the displacement vector, the stiffness matrix and the relative density of the *e*-th finite element.

In this case, the objective is to minimise deformation, thus maximising stiffness, with the constraint of remaining below a specific maximum volume.

Otherwise, in a more simplified version, a relationship can be defined between a physical parameter of the $i$-th finite element and its relative density $\rho_i$. This parameter can be a type of stress, stiffness, thickness or the elastic modulus $E_i$, as shown below:

$$E_i(\rho_i) = \rho_i^p E_0 \quad whit \quad p \geq 1$$

Where $E_0$ is the stiffness tensor of the isotropic material and $p$ is the penalty factor of the optimisation function.

Having high $p$-values is computationally disadvantageous: on experience-based data, a value of $p \geq 3$ is recommended, as reported by Bendsoe and Sigmund [69]:

$$p \geq \left(\frac{2}{1-\nu_0}, \frac{4}{1+\nu_0}\right) \ in\ 2D \quad or \quad p \geq \left(15\frac{1-\nu_0}{7-5\nu_0}, \frac{3}{2}\frac{1-\nu_0}{1-2\nu_0}\right) \ in\ 3D$$

Where $\nu_0$ is the Poisson ratio of the isotropic material.

The goal of this method is to obtain an optimised final volume defined by elements with relative density 0 or 1, i.e., empty or solid elements. Therefore, if one associates the colour black with full elements and the colour white with empty elements, the result should present itself as a black and white pattern. Complications occur when elements with an intermediate relative density between 0 and 1 are present, representing partially filled elements and graphically presenting as coloured areas with grey scales. To remove these and obtain a black and white structure, interpolations are applied by using and increasing the p-value or by applying adjustments. As a result of these, however, a structure could be obtained in which black and white areas alternate adjacent to each other, visually forming a kind of checkerboard, giving the problem its name, 'the checkerboard problem', as shown in Figure 3.

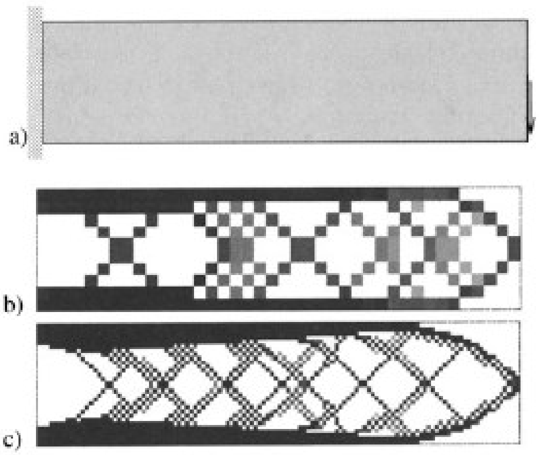



*Figure 3. The Checkerboard Problem on an embedded beam a) Design domain, b) Solution for 400 elements and c) Solution for 6400 elements.*

There are several variations and tricks that are added to the method to avoid the chessboard problem and thus achieve a mesh-independent solution. For example, a density filter that introduces the weighted average of the density of the finite elements within a certain radius as a second design variable; or a control on the perimeter or other parameters; or a mesh-refinement procedure (Figure 4); or the use of higher-order mesh elements.

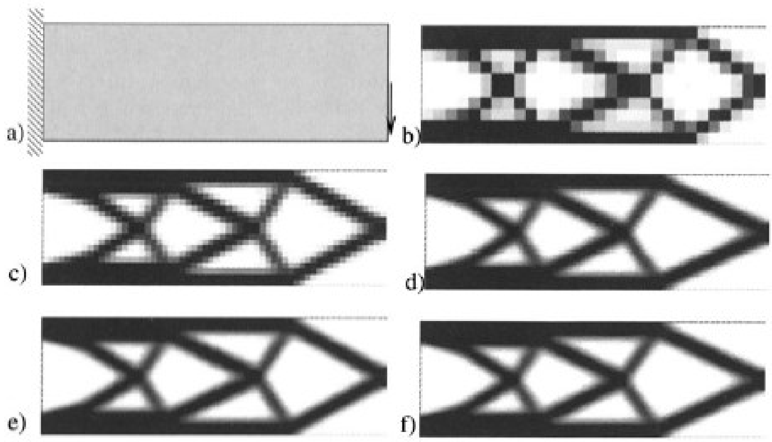



*Figure 4. Effects of varying the number of finite elements on an embedded beam. a) Design domain, b) 300, c) 600, d) 4800, e), 10800 and f) 19200 finite elements.*

Other approaches of this type include the Rational Approximation of Material Properties (RAMP) method, which, compared to the SIMP, has non-zero sensitivity at zero densities, i.e., it succeeds in solving some numerical difficulties in problems involving too low a density value [70]. The Optimal Microstructure with Penalisation OMP method, based on SIMP, uses optimal microstructures for each finite element, calculated according to constraints and the objective function. The Non-Optimal Microstructures NOM method uses a non-optimal microstructure that ensures a certain degree of “fixed” penalty. Finally, the Dual Discrete Programming DDP method uses isotropic microstructures that do not require a penalty [71].

*2.1.3.1.2 The Bubble-method (Topological derivates)*

Topological derivative approaches (also known as Bubble-methods) evaluate the influence of microscopic holes in the design domain. With this method, bubbles are arranged in such a way as to minimise (or maximise) the objective function, thus favouring the creation of new holes. Furthermore, new shapes can be introduced into the initial geometry, overcoming the limitations of the shape derivative. This approach can also be used in conjunction with the level set method [72].

*2.1.3.1.3. Level-set*

It was developed in the late 1980s by Stanley Osher and James Sethian [73]. It is used in various fields such as computer graphics, CFD, computational geometry, optimisation and wherever images are processed. In the field of structural optimisation, the process does not treat the entire volume of the object to be optimised, but only its contours, which are included in a high-order scalar function, called the “level-set function” [74]. With this approach, while the shape and topology of the object will undergo considerable and even complex changes, its contours and thus the level-set function will remain simple. Level-set methods easily manage to make changes to the topology that would be difficult with other methods, such as generating holes, dividing a component into several parts and joining several parts into one. For this reason, they are considered among the most flexible.

The procedure is evolutionary, as in BESO, material is added where stresses exceed a certain percentage of an imposed maximum stress and material is removed where stresses are below another percentage value of the maximum stress. Operating only on the contours of volumes, the operation of removing material results in the creation of holes, conversely adding material results in extrusions [75]. In addition, although the entire volume of the object to be optimised is discretised by means of a cartesian grid, grid node information is calculated only for those nodes present within a certain range from the contour that defines the volume of the solid, thus considerably reducing the computational cost of the process (Figure 5) [76].

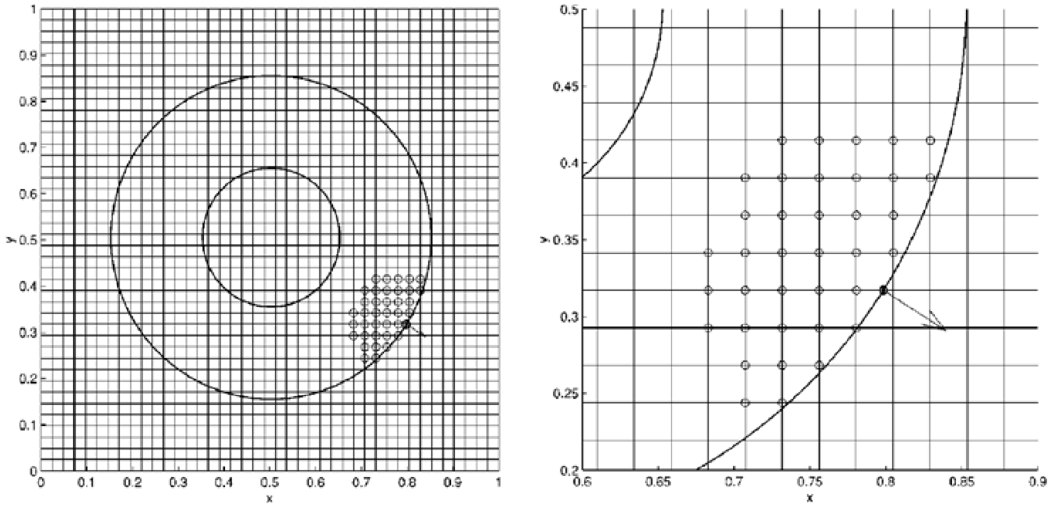



*Figure 5. Cartesian grid and node development in the Level Set approach.*

The level-set approach is now shown.

The scalar function $\Phi$, called the level-set function, used to represent surfaces in 3D space is as follows:

$$S = \{x : \Phi(x) = k\}$$

Where $x$ represents a set of points used to represent an iso-surface. The level-set function can take several values:

$$\Phi(x) > 0 \; if \; x \in \Omega, \quad \Phi(x) = 0 \; if \; x \in \partial\Omega, \quad \Phi(x) < 0 \; if \; x \notin \Omega$$

Where $\Omega$ represents the volume of the object and $\partial\Omega$ its contour. Therefore $\Phi(x) > 0$ for regions included in the volume $\Omega$, $\Phi(x) = 0$ for the contour and $\partial\Omega$ and $\Phi(x) < 0$ for the regions excluded from the volume $\Omega$ (Figure 6).

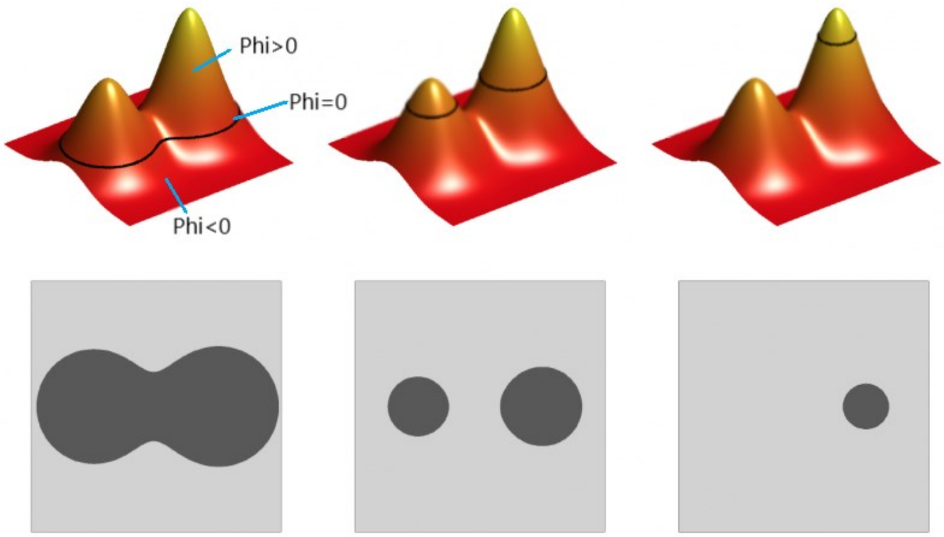



*Figure 6. Example of Level Set function representation.*

Adding the time dependency to determine the variation of $\Phi$ during the optimisation process, the following is obtained:

$$S(t) = \{x(t) : \Phi(x(t), t) = k\}$$

And by differentiating it:

$$\frac{\partial \Phi(x,t)}{\partial t} + \nabla \Phi(x,t) \frac{dx}{dt} = 0$$

Which turns out to be the standard Hamilton-Jacobi equation, where $\frac{dx}{dt}$ represents the velocity with which a point moves on the surface and can be written as $\Gamma(x,\Phi)$ which is the velocity vector of the level-set function.

It then begins to dissect the body to be optimised along a plane, determines its contours and attempts to obtain an optimised version of it with respect to the constraint and objective functions. After that, the velocity vector of the level-set function determines a new plane on which to section the body and the process is repeated until the final optimised result is obtained.

Dealing only with surface contours, if there are no cavities or holes within the volume to be optimised that would increase the surfaces to be analysed, the optimisation process could turn towards a Shape Optimisation problem and it would be difficult to create internal cavities that would vary the topology of the volume by much [77]. In fact, for this reason it is sometimes advisable to pre-generate holes on the starting volume to facilitate the method in varying the topology more efficiently.

*2.1.3.1.4. Phase field*

Phase field methods correspond with density-based approaches with explicit penalisation. Thus, the exponent given to the density value is not discrete but varies continuously according to an explicit function (called "Continuous Density Field"). In this way, smooth surfaces are obtained [78].

**2.1.3.2. Discrete approach**

Discrete approaches use discrete variables. It is necessary to perform a sensitivity analysis, which can often be mathematically challenging, so there is a limit on the complexity of the problem to be solved. Among these approaches, two methods stand out: the Evolutionary Structure Optimisation ESO method [79], and the Bidirectional Evolutionary Structure Optimization (BESO) method [80]. The former is based on the removal of elements with low loads, the latter is an extension of the former in that it offers the possibility of adding elements in overloaded areas. These two methods were rarely used as they often did not converge into an optimal solution. However, in recent years there has been a significant increase in the quality of the core algorithms, making them among the most common. The ESO method operates according to a heuristic procedure, which progressively removes inefficient material from a starting solid by altering its shape and topology, until an optimal result is obtained [81]. After the initial geometry has been discretized into finite elements, a FEM analysis is performed and the value of a parameter, such as the average Von Mises stress $\sigma^{VM}$, is compared within a region of one or more finite elements with a percentage $RR$ (Rejection Ratio) of its reference value, such as the maximum Von Mises stress on the structure $\sigma^{VM}_{Max}$. If the following relationship is satisfied within the region:

$$\sigma^{VM} \leq RR \cdot \sigma^{VM}_{Max}$$

Then it is deleted from the solid. This operation is called "hard kill". At each iteration, the RR parameter is updated, allowing the removal of material in the areas of the solid that are increasingly stressed. The iterative process ends when the efficiency criterion is satisfied in all regions of the solid, decreeing the achievement of a steady state. The $RR$ parameter takes on the following formulation:

$$RR(SS) = A_0 + A_1 \cdot SS$$

Where $A_0$ and $A_1$ are constants and $SS$ an integer counter, initially equal to one, which is incremented by one each time the process reaches a steady state. Based on data gathered from experience, appropriate values for the constants are $A_0 \cong 0$ and $A_1 \cong 0.005$. Then once a steady state is reached, the $SS$ parameter is increased, $RR$ varies and the first relation is verified by repeating the cycle. Another relation added to the previous one is a control on the percentage $RRM$ of the removed volume $VREM$ with respect to the current volume V, this percentage must not exceed a maximum value $RRM_{max}$:

$$RRM = \frac{VREM}{V} \leq RRM_{max}$$

In order to define whether the iterations are proceeding towards a better solution, there are parameters that indicate the quality of the solution. As in Nature, the most efficient structures are those that can minimise the work done by the applied loads, so following this approach, a parameter that defines the quality of the solution is the following Performance Structural Index $PSI$:

$$PSI = \frac{V_0 \cdot W_0}{V \cdot W}$$

where $W$ is the work done by the loads per unit volume $V$ and subscript 0 represents the values referring to the initial configuration [82].

By checking the values assumed by the $PSI$ quality index, it is possible to identify the best solution among the various proposed by the evolution process. Depending on the design requirements, other significant quality parameters can be defined. In addition to these, it is often also useful to monitor certain characteristic quantities of the response, for example to verify compliance with design constraints on displacements or stresses.

Finally, some considerations about the method are given.

Compared to the SIMP method, it requires a very large number of iterations. The Objective Function can obtain local minima or maxima and not global minima or maxima (points *e*, *f*, *d* in Figure 7) and incurs an oscillatory state, unlike the SIMP which has a monotonic trend and therefore the final solution is the optimal one (Figure 8). The design variable that can be used turns out to be only the Von-Mises effort, whereas in the SIMP it is possible to use different types; it lacks appropriate convergence algorithms and criteria that interrupt iterations [83].

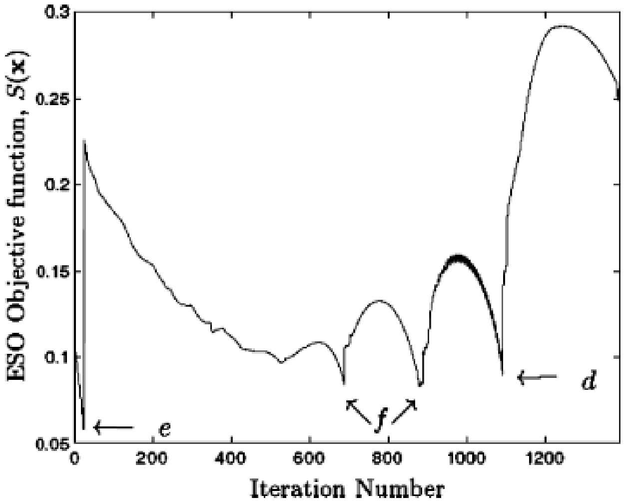



*Figure 7. Objective function trend by means the ESO method.*

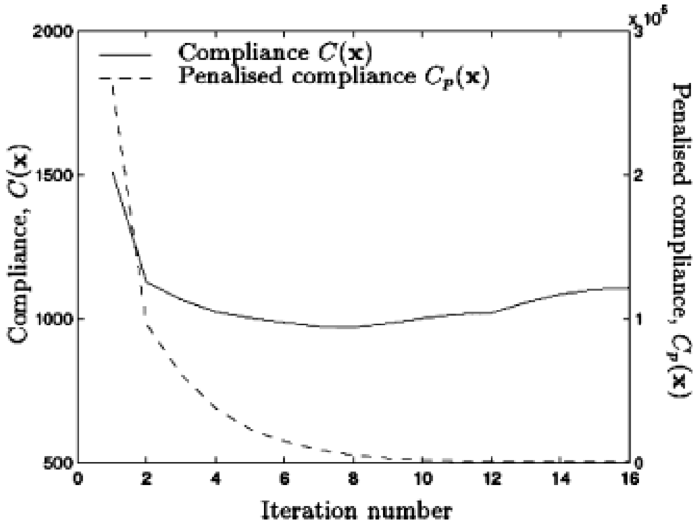



*Figure 8. Objective function trend by means the SIMP method.*

The BESO method is derived from ESO, but with some changes that make it more efficient than its predecessor:

- When material is removed from inefficient areas, material is simultaneously added to the most stressed areas

- It does not require a starting solid that is defined as a volume within which to operate, but reduced volumes on which the loads and constraints of the component to be optimised are applied are sufficient

The areas where it is necessary to add material are determined by the following criterion:

$$\sigma^{VM} \geq IR \cdot \sigma^{VM}_{Max}$$

Where:

$$IR = i_0 - i_1 SS - a_{ir} ON$$

With the constants generally taking the following values: $i_0 = 1$, $i_1 = 0.01$ and $a_{ir} = 0.1$.

$ON$, instead, is a parameter useful for avoiding a state of oscillation in solutions, which occurs when material is removed from elements of the object and then added in the next iteration. To avoid this, the $ON$ parameter is increased by 1 and the iterations are repeated. Figure 9 shows a representation of the process of the BESO algorithm, which is also similar in part to the ESO.

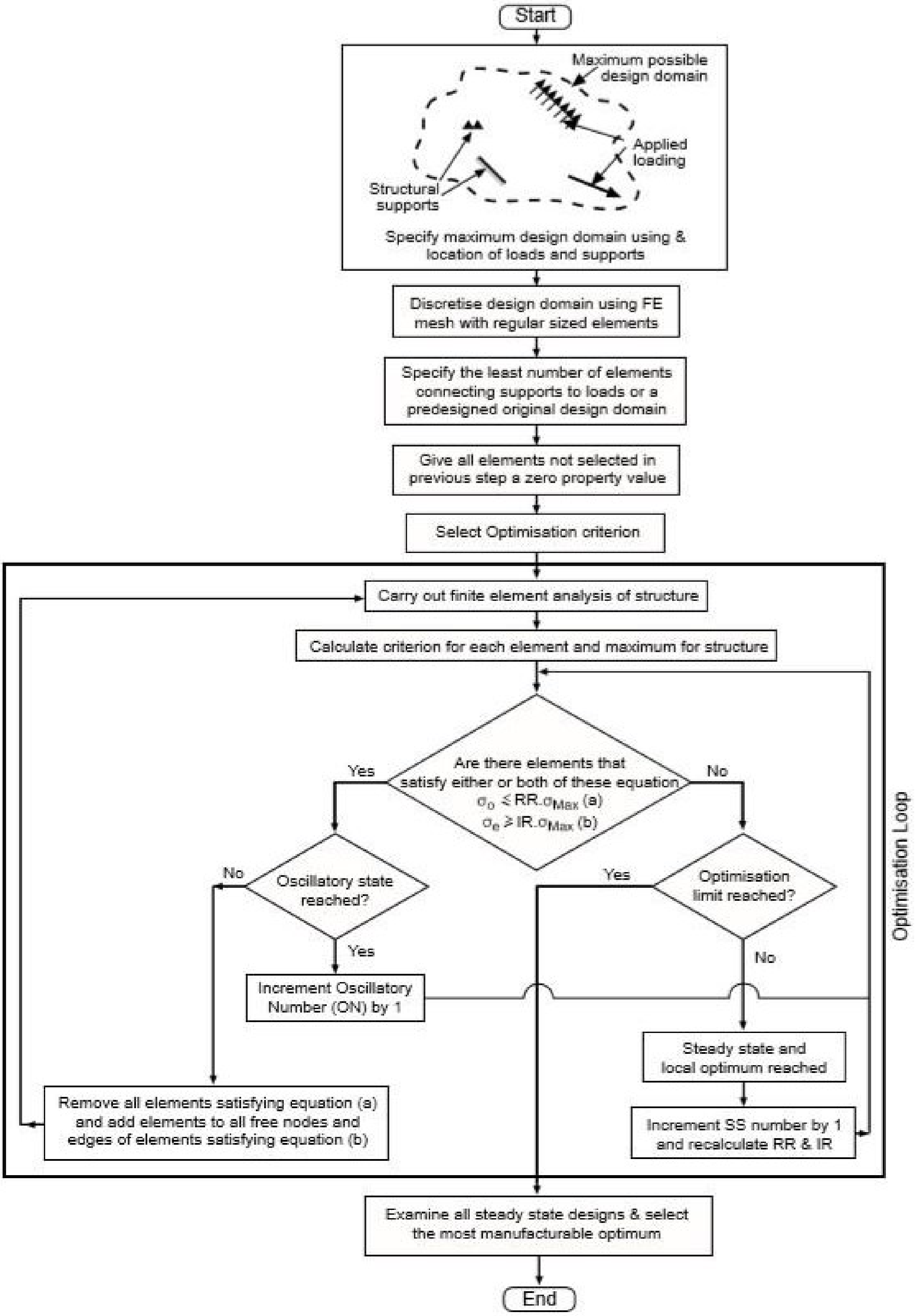



*Figure 9. Workflow of the BESO method.*

Complementary to these two methods is the Additive Evolutionary Structure Optimisation (AESO) method, which is based exclusively on the addition of elements in overloaded zones [84].

#### 2.1.3.3. Combine approach

Combination approaches address the problem holistically, that is, they consider that a complex system is not reducible to the sum of its parts. These approaches include the eXtended Finite Element Method (xFEM) and the Deformable Simplicial Complex (DSC) method. The former uses a fixed mesh that allows surfaces to be represented as smooth and precise, without the need to re-mesh the model (it is often used in conjunction with the level set method [85]. The second uses simplexes to characterise the model (segments, inner tetrahedra, outer tetrahedra) [86].

A summary table of topological optimisation methodologies is shown below in Figure 10.

| Category | | | Approach | Procedure/Description | Strengths | Weaknesses |
|---|---|---|---|---|---|---|
| Element-based | Density-based | | Solid Isotropic Microstructures with Penalization (SIMP) | • Eulerian (fixed mesh) method<br>• Discretization to solid isotropic elements<br>• Remove material<br>• Nested analysis and design approach (NAND)<br>• Minimize the compliance subject to a volume constrain problem via an iterative converge method<br>• 'Soft-kill' penalization method (white: void, gray: fractional material, black: material) | • Homogenization is not a prerequisite<br>• Computational efficiency<br>• Robustness<br>• Adaptive to (almost) any design condition<br>• Freely adjusted penalization<br>• Conceptual simplicity (no higher mathematics required<br>• Available for all combinations of designs constrains | • Intermediate densities<br>• Mesh-dependent<br>• Dependent on the degree of penalization<br>• Nonconvex |
| Element-based | Density-based | | Rational Approximation of Material Properties (RAMP) | • Eulerian (fixed mesh) method<br>• Based on SIMP<br>• Nonzero sensitivity at zero density | • Convex | • Dependent on the degree of penalization<br>• Numerical difficulties in low density |
| Element-based | Density-based | | Optimal Microstructure with Penalization (OMP) | • Eulerian (fixed mesh) method<br>• Based on SIMP<br>• Discretization to optimal nonhomogeneous elements<br>• 'Hard-kill' penalization method (white: void, black: material) | • More information about the isotropic-solid/empty/porous (ISEP) optimum | • Intermediate densities<br>• More computational effort than SIMP<br>• Nonrobust<br>• Advanced mathematics<br>• Nonconvex<br>• Requires homogenization<br>• Dependent on the degree of penalization<br>• Available only for compliance |
| Element-based | Density-based | | Non-Optimal Microstructures (NOM) | • Eulerian (fixed mesh) method<br>• Based-on SIMP<br>• Discretization to nonoptimal nonhomogeneous elements<br>• No penalization | • Available for all combinations of designs constrains<br>• Less variables/element than OMP | • More variables/element than SIMP<br>• Fix and insufficient penalization<br>• Nonconvex<br>• Requires homogenization |
| Element-based | Density-based | | Dual Discrete Programming (DDP) | • Eulerian (fixed mesh) method<br>• Discretization to solid isotropic elements<br>• Remove material | • Penalization is not necessary | • Available only for compliance |
| Element-based | | | Topological derivatives ( 'The Bubble-method') | • Lagrangian (boundary following mesh) method<br>• Special case of homogenization<br>• Remove material<br>• Combine shape and topology optimization<br>• Introduce microscopic hole in order to predict the influence (derivative) and trigger the creation of new holes | • Indirectly include filtering by mapping between nodal and element (or subelement) based on design variables. | • Complex mathematics<br>• It is yet unclear whether the computed derivatives are useful |
| | | | Level set | • Eulerian (fixed mesh) and Hybrid methods<br>• Operate with boundaries instead of local density variables.<br>• Implicit moving boundary (IMB) models | • Flexibility in topological changes<br>• Can be mesh-independent<br>• Can find shape variations for robust design | • Restricted geometry from existing boundaries<br>• Inability to generate new holes at points surrounded by solid material (in 2D) |

| | | | | | |
|---|---|---|---|---|---|
| | | | • Boundaries can form holes, split into multiple pieces, or merge with other boundaries to form a single surface<br>• Boundary of structure = zero level (contour)<br>• Modified density approach (uses shape derivatives for the development of the optimal topology)<br>• Most use ersatz material and fixed meshes | • Formulate objectives and constraints on the interface and describe boundary conditions at the interface | • Starting guess results<br>• Regularization, control of the spatial gradients of the level set function, and size control of geometric features<br>• Must combined with topological derivatives in 2d |
| | | Phase field | • Eulerian (fixed mesh) method<br>• Works directly on the density variables<br>• Smooth the design field by adding the total density variation to the objective<br>• Correspond to density approaches with explicit penalization and regularization | • Total density variation to the objective<br>• Carry out perimeter constrains and represent the surface dynamics of phase transition phenomena such as solid-liquid transitions | • Very slow boundary translation and convergence solution |
| | Discrete | Evolutionary Structural Optimization (ESO) | • Use of discrete variables<br>• Remove material<br>• 'Hard-kill' method (white: void, black: material)<br>• The structure turns into an optimum by repetitively removing inefficient material<br>• The elements with the lowest value of their criterion function are eliminated | • Small evolutionary ratio (ER) and fine mesh can produce a good solution | • Mesh and parameters dependent<br>• Heuristic<br>• Computationally rather inefficient<br>• Methodologically lacking rationality<br>• Tackle only simple 2D problems<br>• Breaks down with rapidly changing sensitivity |
| | Discrete | Additive Evolutionary Structural Optimization (AESO) | • Based-on ESO<br>• Use of discrete variables<br>• Add material (to reduce the local high stresses)<br>• Optimization starts from a core structure that is the minimum to carry the applied load | • Small evolutionary ratio (ER) and fine mesh can produce a good solution | • Mesh and parameters dependent<br>• Heuristic<br>• Computationally rather inefficient<br>• Methodologically lacking rationality<br>• Tackle only simple 2D problems<br>• Breaks down with rapidly changing sensitivity |
| | Discrete | Bidirectional Evolutionary Structural Optimization (BESO) | • Mathematically combination of ESO and AESO<br>• Use of discrete variables<br>• Add and remove material where needed<br>• 0: absence of element, 1: presence of element | • Mesh-independent<br>• Reduction of computational time comparing to ESO<br>• Adaptive shape<br>• Using a small evolutionary ratio ER and a fine mesh can produce a good solution | • Can be dependent on mesh |
| | Combined | Extended Finite Element Method (xFEM) | • Generalized shape optimization<br>• Introduction of a generalized and adaptive finite element scheme which work with meshes that can represent smooth and accurate boundaries<br>• Based on level set. | • Overcome FEM discontinuities<br>• No remeshing is required<br>• Can study large 3D scale industrial problems | • Large errors in the stress estimation |
| | Combined | Deformable Simplicial Complex (DSC) | • Hybrid method<br>• Combine nonparametric shape optimization and introduction/removal of holes | • Robust topological additivity<br>• Topology control natural and simple<br>• Allows for nonmanifold configurations in the surface mesh | • Numerical diffusion<br>• Slower than the level set method<br>• Insufficient mesh quality |

*Figure 10. Summary table of Topological Optimisation methodologies* [68].

#### 2.1.3.4. Advantages of Topological Optimisation

As can be seen from the examples given, the greatest advantage of these tools is the achievement of innovative and complex shapes that could hardly come from the designer's mind. It is now presented how the use of structural optimisation tools influences the product realisation process, compared to a traditional process without such tools.

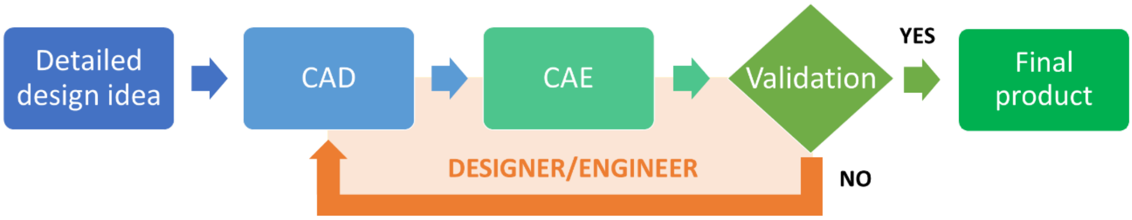



*Figure 11. Traditional product development process.*

As can be seen from the diagram in Figure 11, the traditional process begins by sketching on paper ideas about the design of the new product, in a 2D environment. These are detailed to the point of generally being able to meet most of the required design constraints and are the result of the designer's experience, who is therefore already able to propose geometric solutions that may be better than others. The next step is the translation of the initial idea onto 3D CAD software. Then FEM simulations are performed and, if there are any requirements that are not met, the starting design is modified in the CAD environment and the cycle is repeated until a valid result is obtained. All these procedures are carried out by designers who, based on experience and simulation results, make changes to the product until a valid result is achieved.

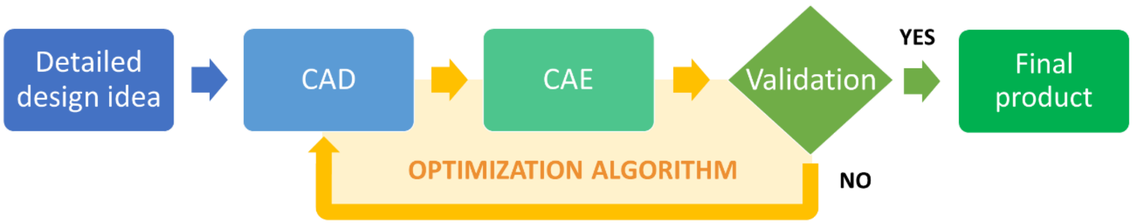



*Figure 12. Product development process by means of optimisation techniques.*

The opposite is the case in a process using optimisation techniques (Figure 12). The starting point is the volume of the known component. It is also possible to add constraints concerning the functional volumes to be maintained, to constrain and stress the structure in those volumes. Next, the idea of the volumes useful for the optimisation process is created in 3D CAD software. At this point, the designer sets structural constraints, material and other parameters in the mesh model translated from the 3D file. The process then reaches the automatic calculation phase, which is completely managed by the optimisation tool, performing multiple iterations. They perform FEM simulations and, based on the results obtained, modify the product design with respect to the stresses present in the analysed mesh elements. The algorithm ends its loop when the results tend towards convergence, resulting in an optimised version of the component.

The main theoretical advantage of a product development process with optimisation in comparison to the traditional one is the saving of time and resources, as the result is a product that meets all requirements and has been developed by means of an algorithm that carries out the steps iteratively and automatically. The individual steps therefore do not depend on communication between professionals from different backgrounds in the technical department, increasing development time. Another advantage that comes with the final product is the complexity of the structures obtained, which on the one hand imply a criticality in managing them, but on the other hand represent solutions that could hardly have been created by the designer [87], [88].

To sum up, structural optimisation can be described as a tool for obtaining innovative, complex and optimised shapes based on design and production constraints imposed by the designer, useful as a support to the latter in exploring new product designs.

#### 2.1.3.5. Topology Optimization limitations

Nowadays, topological optimisation is the most comprehensive structural optimisation technique, as it overcomes the limitations of size optimisation and shape optimisation. Furthermore, depending on the requirements of the problem, a particular approach can be chosen and its potential exploited to arrive at the best solution. A list of the strengths and limitations of each method is given in the Figure 10.

As already introduced, the main issue of topological optimisation problems concerns the possibility of physically realising the proposed final design [89]. Optimisation algorithms may have constraints regarding processing technologies, but they are not so comprehensive as to be able to propose a suitable solution for the chosen production method. Thus, if the design result cannot be produced, it is discarded or must be further modified by a designer, thus negating the innovative aspect of the methodology [90]. In any case, the most suitable machining technique to produce objects derived from topological optimisation, for which sometimes no modification of the final design is even necessary, is Additive Manufacturing, due to its layer-by-layer nature [91]. However, although geometries can be realised with greater freedom in AM, topological optimisation designs may still have such complex shapes that they cannot be produced even in Additive, without major modifications or with support structures that make machining too onerous.

In order to solve this challenge, an improvement of the algorithms underlying TO has been sought in more recent years. Recently, new algorithms have been developed based on the existing algorithms that implement limitations to TO that are able to search for solutions with conventional processing techniques [92]. Another limitation relating TO concerns the role of the designer within the workflow. In fact, the main constraint of the shape optimisation algorithms is the initial volume of the component under study: as an input to begin optimisation, it is in fact essential to already have a starting component with a specific shape. In this case, the designer has the task of defining the initial volumes and those to be maintained as functional for use. The study of loads and constraints is also extremely important, as is the best definition of the mesh from which to start the algorithm computations. At the same time, however, once the assumptions for the algorithm have been set, the designer no longer has control of the process until the convergence of the method in the single solution. His marginal role could be a problem as he has no evaluation of the goodness of the algorithm and its solution, except for the FEM analysis performed on the optimised component at the end of the process.

Also limiting is the individual solution proposed by the optimisation: the designer has no room for intervention except on the further post-optimisation editing to make the component suitable for production. In this step, the designer's experience is limiting because it unintentionally influences the optimisation solution, introducing the psychological inertia of years of traditional design into the development of a product. Topological optimisation, therefore, has the potential to create innovative shapes that are, however, constrained by the presence of a geometry already thought of by a designer according to classical methodologies, and therefore limited by constraints also imposed by design forma mentis less focused on the management of complex shapes and surfaces.

It can therefore be said that topological optimisation concerns the “late stage” of the design phases.

For this reason, Generative Design methodologies were developed to create multiple design solutions depending on the constraints and possible parameters in which the algorithms can operate.

## 1.2. Generative Design

### 1.2.1. Definition

The definition of Generative Design (GD) crosses various disciplines, including architecture, design and ultimately engineering [93]. Before the 2000s, the term 'Generative Design' was never of relevance in scientific publications, although it was first defined in 1975 by Mitchell [94]. In 2001, a new definition was proposed in the field of architecture by Fischer and Herr [95] in which it is emphasised that Generative Design is an approach where the designer does not interact directly with material and products, but through a generic generative system. Afterwards, in 2004 [96] McCormack et Al. described Generative Design as the study of principles for generating complex shapes and structures from simple specifications. This definition follows that proposed by many authors in the literature [97]–[99]. Caetano et Al. observed that Generative Design is a ”*Design paradigm that employs algorithmic descriptions that are more autonomous than Parametric Design*” [93]. In recent years, the software house Autodesk has released its Generative Design tool within Fusion 360, thus highlighting its definition of generative methodology: *“Generative design is a design exploration process. Designers or engineers input design goals into the generative design software, along with parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints. The software explores all the possible permutations of a solution, quickly generating design alternatives. It tests and learns from each iteration what works and what doesn’t."* [100]. It can be noticed that even now the definition of Generative Design is far from being precise and unambiguous, with different definitions for different scientific disciplines (e.g., architecture and engineering) [101].

As a demonstration of the potential of this optimisation tool, Fior Markets estimates an economic growth in the global GD market from $90.08 million recorded in 2017 to a projected $397.49 million in 2025, with an annual growth rate of 19.79%. In fact, several software houses of CAE tools have entered partnerships with the aim of improving GD tools. Artificial intelligence and recently developed machine learning technologies may also contribute to the growth of GD, allowing generative algorithm to better understand how to achieve more efficient results. This trend is described in Figure 13 [102].

It is also interesting to present how Generative Design is technically defined in the literature and on which theoretical and/or mathematical approaches it is based. Even the technical definition, therefore, is not unambiguous as the development of new approaches leads to its continual modification. Some authors associate Generative Design strictly with evolutionary techniques for both the creation and production of design solutions [95], [103]. Others in the literature, however, extend the definition by considering GD as an approach based on algorithms that generate multiple and often complex solutions [94], [104]. In addition, several authors group different approaches within the GD methodology [105]–[107] such as: Swarm Systems [108], Shape Grammars [109], [110], Agent-based Models [111], Evolutionary Methods [112].

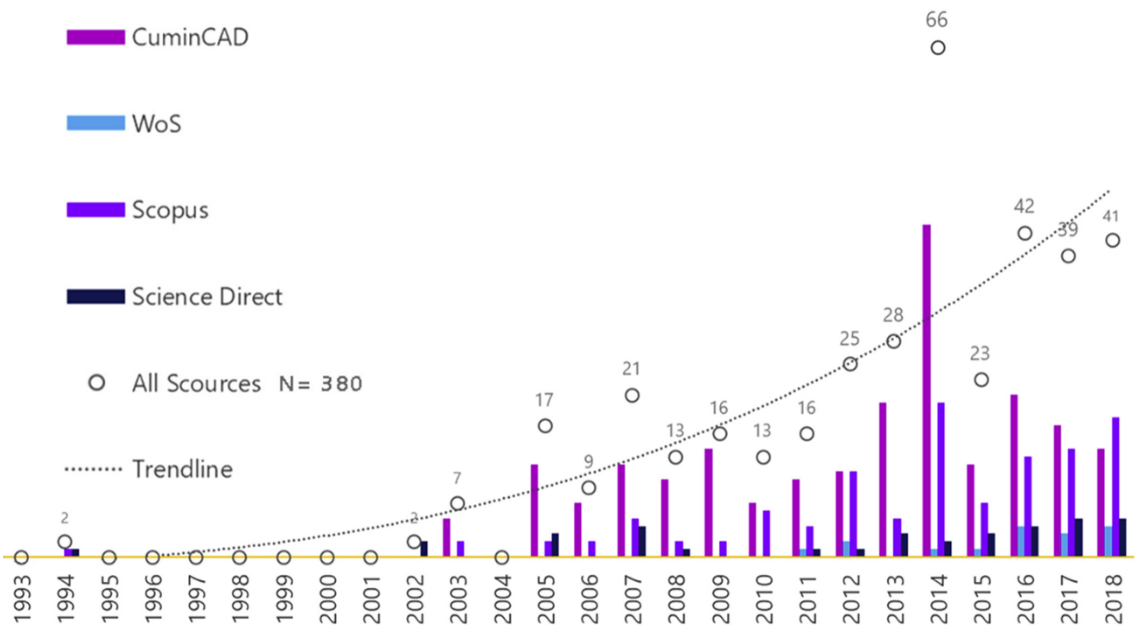



*Figure 13. Number of times the term GD appeared in the different scientific sources between 1978 and 2018 [93].*

Parallel to the studies on GD definitions and algorithms, Performance-based Generative Design Systems (PGDS) were created and evolved. These are applications of GD methods, where a graphical interface allows the designer, in a user-friendly approach, to manage constraints and aims of the generative study to find close solutions to the objective. Some examples for structural design are EifForm [113], Paragen [114] and Project Dreamcatcher from Autodesk, then integrated into the Fusion 360 suite [115].

### 1.2.2. Generative Design theoretical methodologies

The approach most recognised and used in the engineering field for Generative Design is the one that considers Genetic Algorithms [116]. They have been introduced by John Holland [117] and are often used to solve complex optimisation problems. These solution-finding algorithms appear as duals of natural evolution transposed to the artificial world of modern computing [118]. In fact, these algorithms, after creating a group of solutions, evaluate their ability to optimally solve the problem. Each solution is then assigned a 'fitness' rating. Subsequently, the algorithm chooses which solutions are better than the others and brings them into the solution space. As for the worst solutions, these are regenerated, merged or eliminated, in order to recreate a new generation of solutions that are closer to solving the problem than the previous ones [119]. The generative loop is shown in Figure 14.

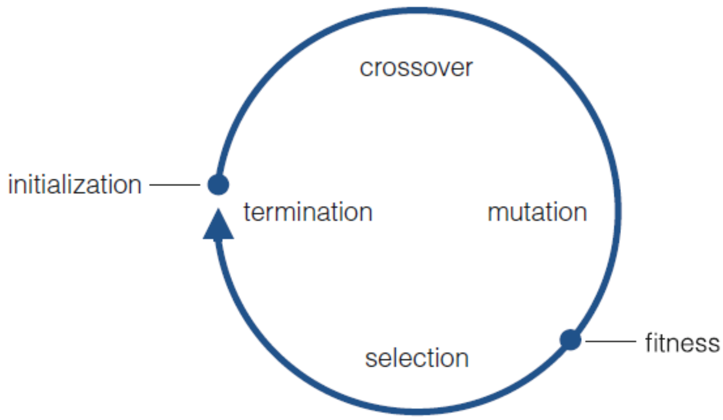



*Figure 14. Cycle of a genetic algorithm.*

The loop continues with a new 'fitness' assessment and thus a division between the optimal solutions and those to be discarded and regenerated. Inspiration from the world of nature is emphasised when the artificial methodology combines or eliminates solutions that are not close to the optimum to create new generations of solutions that are certainly better than the previous ones (Figure 15), as indeed happens with natural evolution [120].

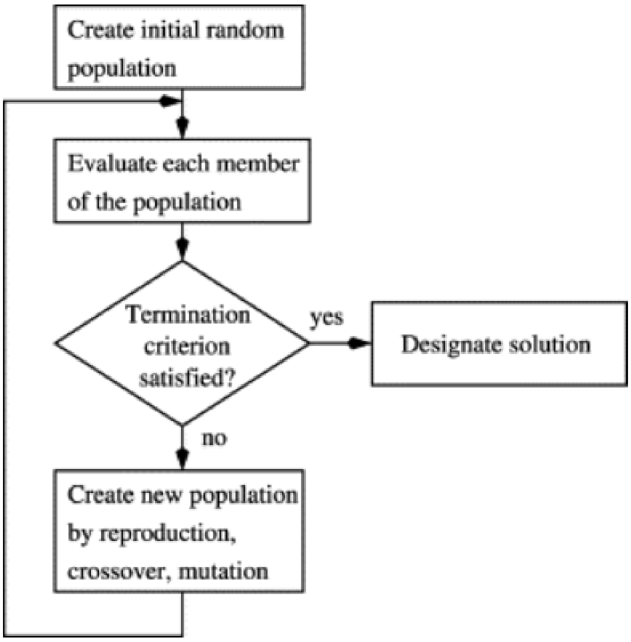



*Figure 15. Genetic algorithm flowchart [120].*

An approach that relies on genetic algorithms to generate design solutions is the Constraint Based Evolutionary Decision Support System (CBEDSS) proposed by Guoyan [121]. The process is based on the optimisation of search patterns and evaluation of the optimal design and is completely designer-driven. This modifies constraints, objective functions and search variables as input. Another design generation concept it uses was proposed by Bentley [122]. The Genetic Algorithm Designer (GADES) is based on the evolution of shapes from "blobs" and is a conventional application of genetic algorithms. This is also used by Krish as a comparison of his method: the Generative Design Method (GDM) [116]. Its method, unlike the others, allows all design steps to be worked on: from the conceptual phase to the detail phase. This is due to its greater flexibility as the designer can vary parameters, constraints, genotypes and filters at each step of the design process. At the same time, it can be implemented directly as a methodology in commercial CAD software. A recent approach for design exploration that combines Topology Optimisation and Deep Learning is proposed by Oh [123]. These two methodologies use cloud computing as a tool, which allows multiple designs to be generated in parallel. The advantage of the methodological basis of Topological Optimisation, and in particular the use of FEA, is to propose not only aesthetically different shapes, but also specific shapes to meet structural engineering problems. Thus, at the same time the OT has both a training function for the generative models and an evaluation function for the design results also created by the generative model. The most important limitation concerns the lack of focus on the production method, which is limited to Additive Manufacturing, compared to all available and more cost-effective manufacturing technologies. Another recent process concerning Generative Design was studied by Dogan et al. [124]. The authors propose a methodology for generating a set of designs similar to an original model through the objectives of diversity, similarity and regularity. The starting step is the selection of simple primitive shapes from the original design. A design space is then created in which to vary the shapes through a selection of control points on the outer surface of the original component. As in previous methodologies, no reference is made to manufacturing constraints in the generation of designs. The approach of Alcaide-Marzial et al. positions itself in a design phase even closer to sketching [125]. Their Conceptual Generative Model (CGM) is a system based on the Grasshoper graphical algorithm [126] able to produce conceptual design sketches comparable to the first design steps made on paper. The entire generation scheme is based on analysing the simple structures of the product used as a model and then merging the solutions of the algorithm to actively allow the designer to select the best shapes from his point of view. By proposing an approach in the first phase of design, this study does not consider the possible constraints of machining the component and does not propose further possibilities for use within methodologies that aim at improving the performance of products. Otherwise, the study made by Caraballo and Fernandez [127] introduces an automatic generative design method that links conceptual and performance design. In fact, the performance of the component, which in this case study is the rear suspension system of a motorbike, is already considered in the early design stages. A multitude of suspension arm layout solutions are then proposed taking into account constraints derived from the motorbike kinematics. This approach guides the algorithm to propose a variety of both innovative and high-performance solutions, unlike classical design where solutions are preferred based on the experience of the designer and conventional designs to minimise risks. In comparison, Gulanova et Al. [128] present a methodology that utilises Generative Design to design surface-based components with an example in the automotive world by modelling class-A surfaces. The method leads to the creation of multiple design variants without human intervention. This approach also improves collaboration between the style centre and the design function in engineering, also leading to a reduction in product development time.

### 1.2.3. Case studies

The applications of the GD are the most varied, which denotes great flexibility and adaptability in various fields of use. Jafferson et Al. [129] propose the generative approach in the fashion industries and particularly in the textile field. They show how GD creates structures that can be flexible and aesthetic with a high possibility of customisation. Also in the textile field, Ricotta et Al. [130] introduce a methodology that uses GD to create flexible textile structures, thus producing them in Additive Manufacturing. Then results are compared with solutions derived from a common CAD: they highlight how GD algorithms overcome many of the drawbacks of parametric design, especially in the field of medical prosthetics. Other articles in the literature expose the GD approach compared with the traditional approach: this is the example of Hyunjin [131] who analyses the GD process in its main steps, stating how the automation of the design process, aided by artificial intelligence, will be one of the cornerstones of the next industrial revolution. There are also articles in the literature showing the methodology for generating new shapes for mechanical components using Fusion 360 software with Generative Design tool. [132]. These are studies concerning the handelbar neck of a bicycle [133] and the gripped arm of a robot [134]. In another case, the software is tested through a case study involving a lifting bracket: the aim is to evaluate the influence of asymmetrical loads in the generation of results by the algorithm [135]. These articles show the difficulty of studying these types of methodologies applied to real cases. Indeed, these are descriptions of standard steps and evaluations of solutions generated by black box software whose algorithms and optimisation models are unknown. At the same time, no emphasis is placed on how the GD can be used as a step, an intermediate step in the creation of innovative approaches where the generative design solution is the means, not the end, to arrive at other more interesting and automated solutions. Another article limited to the search for minimum mass while maintaining performance through autogenetic design theory concerns the optimisation of a bow riser [136]. The authors concluded that this type of approach can reduce the mass of the component by 22% compared to the commercially available product. However, there is no mention of another fundamental issue, which is the manufacturability of the component: Generative Design is often defined as an automatism for finding design solutions in the earlier part of the design process, between the pencil sketch and a drawing by CAD software. This leads to the creation of components whose form is freed from technological production constraints. Some algorithms begin by proposing constraints regarding feasibility for production (i.e., rake angles, tool dimensions, minimum thickness), but without exhaustively detailing the shape for production other than Additive Manufacturing. Interesting, however, is the dualism identified between the solutions provided by the Generative Design approach and biosimilar structures. Stepanyan [137] proposes the combination of various paradigms for the synthesis of new structures and shapes, thus creating algorithms that can be used in industry through Additive Manufacturing. The structures created are similar to tree-like shapes in the blood system. Other biomimetic structures derived from GD approaches are approached by Aversa et Al. [138] concerning green materials and technologies in the medical field of prosthesis. Indeed, by using these innovative tools and adopting sustainable processes, it is possible for the authors to reduce environmental impact and thus also energy consumption. In the automotive field, where lightness and design are two important factors, Briard et Al [139]. proposes a Design for Additive Manufacturing methodology that includes GD for the optimisation of a seatbelt bracket. Subsequently, the design steps were verified through a challenge in which two groups of designers challenge each other in the GD design of a component to be manufactured by AM. Also in the automotive field, studies were presented in the literature for the GD optimisation of a brake caliper [18] and of a double-wishbone suspension assembly [140]. In the first case, there is a theoretical reduction in mass of 21% and in the second case of 52% and 65%. In both cases, the authors emphasised the significant increase in performance due to a significant decrease in mass and an improvement in component stiffness. The production method is limited to AM given the complex and organic shapes derived from the design generation.

As presented, new theoretical and mathematical variants of the Generative Design methodology are exposed in the literature to improve limitations and introduce increasingly effective algorithms. On the other hand, no overview is ever presented that allows the optimisation approach through Generative Design to be modelled to engage it with other technologies and create effective and innovative solutions for real problems, such as in the industrial and medical fields. Indeed, both in marketing for software houses and in scientific publications, the term Generative Design is often used ambiguously and inconsistently, referring to topological optimisation methodologies. The aim of this study is to correctly define the Generative Design approach in order to give it a position among the optimisation tools available to be implemented in innovative methodologies for the development of new products. Subsequently, some of these innovative methodologies are theoretically presented according to the major European and industrial guidelines on issues of high industrial, economic, and social impact. Finally, case studies for the validation of the methodologies are presented.

# Chapter 2
# Generative Design applications

As demonstrated in the literature, there is much confusion regarding the definition and methodologies of GD versus TO. To fill this theoretical gap, articles were analysed, but above all, meetings on optimisation issues were actively attended. In particular, those held at the Kilometro Rosso research facility in Bergamo were chosen, where the general themes of Additive Manufacturing were presented and, in particular, the possibility of implementing TO and GD software and algorithms within the design process. This makes it possible to automate a part of the design process, delegating to the algorithms appropriately prepared to assist the designer in the first conceptual phase of design definition. In these meetings it was often evident that speakers did not differentiate Topology Optimisation from Generative Design: marketing in this case interacts negatively on the theoretical aspect as the term GD is proposed in an identical approach to TO, only to create a strong appeal to the participants. Another shortcoming concerns the production process: components are produced by AM and, if a traditional production method is proposed, these are re-designed manually, without help from software. However, it was interesting to see how, in the last two editions of MECSPE in Parma and Bologna, the attention and presence of start-ups and companies providing design consultancy services in the field of Generative Design and latex structures increased. These companies not only use various generative design software but extend this methodology to their entire work process [141], [142]. In fact, before proposing their solutions, they carry out studies involving nature and natural selection processes that allow them to extrapolate components with innovative designs, as also proposed by genetic algorithms. The same situation was also assessed during the RM Additive Forum in Milan, a conference and exhibition dedicated to issues concerning the development of new products by means of AM, including precisely Generative Design [143]. Knowledge of the various software packages and GD technologies related to them has continued throughout the three years, thanks to participation in webinars and conferences by Autodesk University, nTopology, Desktop Metal, Elise Academy, Ansys. Limited to the possibilities had in recent years, it was nevertheless possible to participate in conferences on the subject of design optimisation and generative methods, in particular: CoCoAM

2019 (Bologna), ADM 2019 (Modena), ASME IMECE 19' 20' 21' (online), JCM 22' (Naples), CAD Conference 2022 (online). Attendance at three international schools [144], [145] provided a further step in understanding technologies but also in approaching the industrial and medical world with a critical eye and at the same time aware of the tools available for research. In the wide range of software featuring TO and GD tools, the most innovative software was therefore chosen: Autodesk Fusion 360 and nTopology. The former offers a complete work environment ranging from design, through CAM simulation, to Generative Design. The second, instead, proposes shape control through functions in which parameters can be varied for the management of lattice structures. The initial studies of the Fusion 360 software were conducted in close collaboration with the developers at Autodesk, so that the behaviour of the algorithm could be analysed according to different inputs and constraints.

## 2.1. Generative Design software: Autodesk Fusion 360

Autodesk's Fusion 360 is one of the most widely used software in research relating to Generative Design methodologies in recent years [132]. Among the various tools available is the Generative Design module. Within it, the designer is followed step by step in the process of choosing constraints and managing all input data to the system. The steps of this module are as follows [146]:

1. Designing or modifying the geometric model in the CAD environment
2. Conversion and refinement of the mesh model derived from the CAD model
3. Definition of Preserve and Obstacle regions and other volume constraints
4. Load and structural constraints allocation
5. Setting manufacturing constraints
6. Determining the optimisation target
7. Materials selection

The starting geometric model differs from case to case. For example, if the objective is the generation of new geometries of an existing product, then the model could be the geometric representation of the product itself. If, on the other hand, there is no product to be optimised, but a new one is to be generated, then the required geometric model would only be functional or characteristic volumes.

In both cases, Preserve and Obstacle regions must be assigned to the geometric model. The former are parts of the model that must remain unchanged during the optimisation process. The latter, meanwhile, are volumes outside the model, which impose where there must be no material generation in 3D working space (Figure 16).

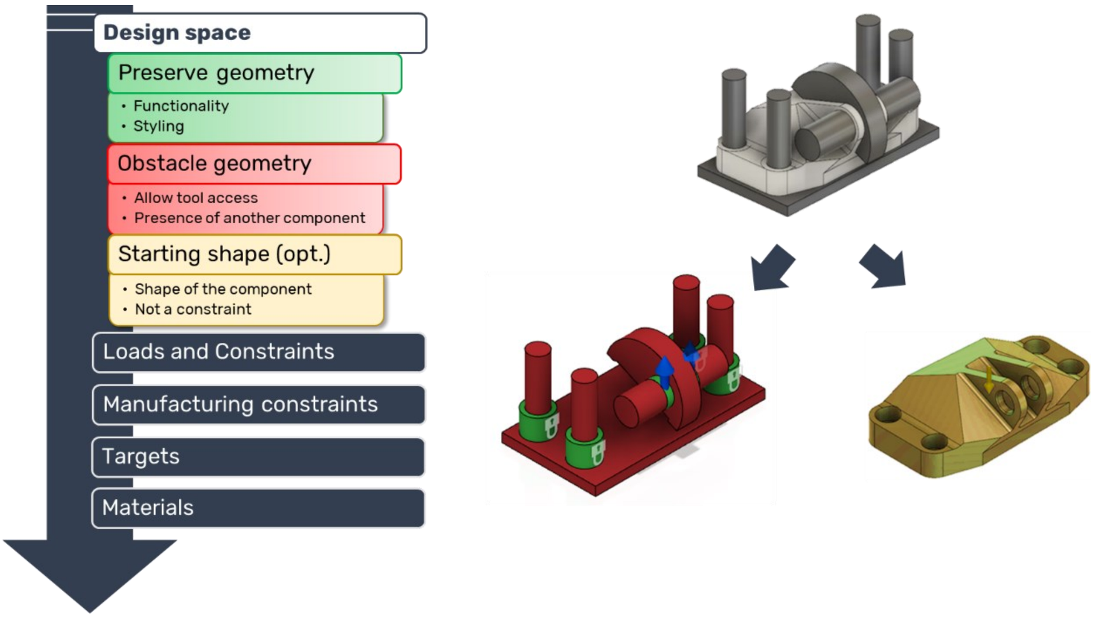



*Figure 16. Autodesk Fusion 360 Generative Design flowchart.*

Examples of Preserve geometry are those portions of the product that interact with other components, which must therefore not be altered to continue their interaction; or are portions of the product of aesthetic importance, which must therefore be maintained. Instead, an example of Obstacle Geometry, is a volume that indicates an access area for a tool, which must therefore be kept free; or a volume that simulates the footprint of another component, with which the generated product must be assembled; or even a volume that includes the movement space of a component with which the product must interact, but which must not obstruct. Returning to the principal geometric model, if it is that of an existing product, its volume could be used as the starting shape. This option allows the algorithm to start the generation loop from a defined shape, but which is not a volumetric constraint as it is in Topology Optimisation, as observed in Figure 17. In fact, the algorithm may proceed to create material even outside the starting shape, which remains a non-strictly constrained input. On the other hand, if the product has a new design, the starting shape is not adequate: the functional or characteristic volumes of the starting model to be used are therefore the Preserve and Obstacle regions.

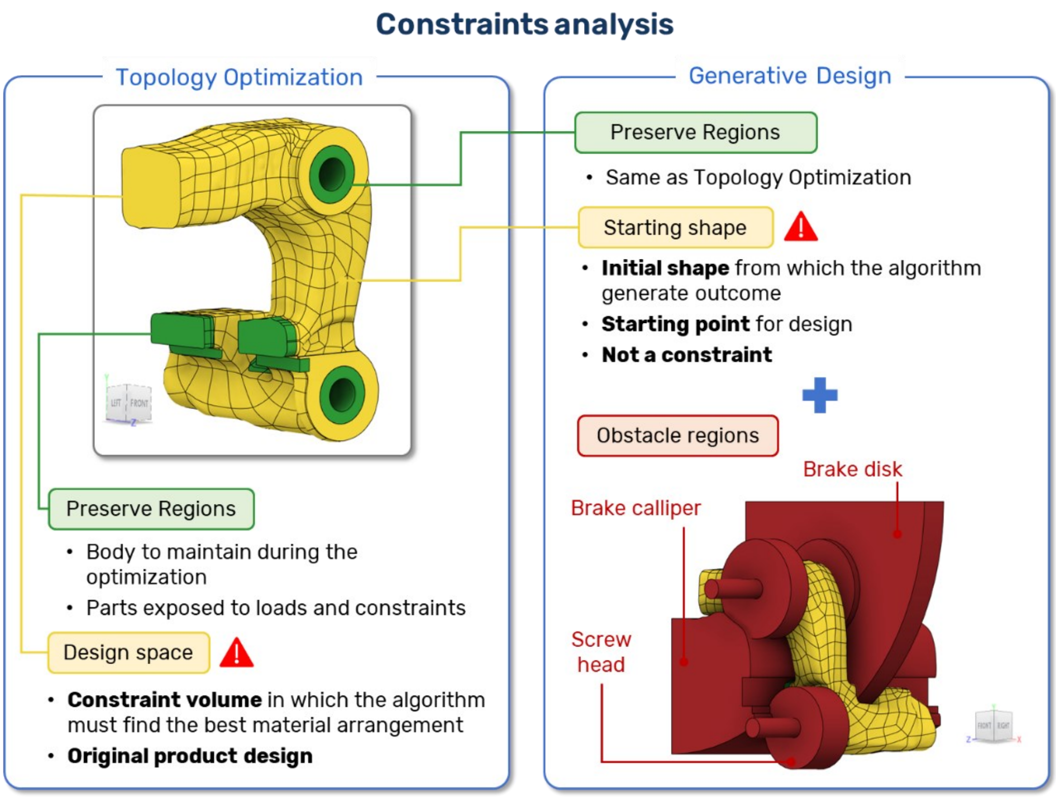



*Figure 17. Analysis of differences between TO and GD.*

Having defined the geometric model and assigned the Preserve and Obstacle geometries, the loads and structural constraints to which the component is subject are assigned. They can only be assigned to Preserve geometries. In addition, in Fusion 360, there is the possibility of creating several load and constraint configurations to generate a single result that satisfies them all at the same time.

Next, one or more materials are assigned to the product, either by choosing them from the library of materials proposed by the software or by manually entering the properties of a material not on the list.

Subsequently, production constraints are established, based on the machining technologies available to produce the product. Fusion 360 has the following constraints:

- *Unrestricted*: no manufacturing constraints
- *Additive*: 3D printing. The minimum feasible thickness and maximum permissible overhang angle can be set, in order not to have to use support structures

- *Milling*: Requires the definition of the number of axes, between 2.5, 3 or 5, the directions of movement and the overall dimensions of the tool
- *2-axis Cutting*: Requires only the direction of the tool movement axis
- *Die Casting*: The mould opening direction, maximum and minimum thicknesses and minimum draft angle are defined

The last step involves defining the optimisation aim. It can be chosen from two: maximising stiffness or minimising mass. For both cases, the assignment of a minimum safety coefficient is required. In the first case, however, a reference mass is also required to be achieved. Recently, with a package called 'Advanced Physics', it is also possible to establish modal frequencies and maximum permitted global or local displacements.

Once all the previous steps have been completed, the GD simulation can be launched, which runs in the cloud, on Amazon and NVIDIA servers. Once the simulation is complete, all results are explored, filtering them by material, product properties, processing methods and cost. Once the best solutions have been identified, the relevant geometric models or MESHs can be exported to perform geometric improvements or further CAE simulations.

## 2.2. Wheelchair frame improved by means Generative Design method

The first case study analysed, given previous experience in biomechanics, was the analysis of a wheelchair frame using Optimisation and Generative Design methods. One of the most frequently encountered problems among those who are confined to a wheelchair for a long time is injuries to the upper limbs, shoulders and neck. To prevent these injuries from occurring, studies have been carried out on the correct pushing technique, thanks to which it has been possible to improve the quality of life of the impaired person, especially by encouraging the use of this technique in adolescence and pre-adolescence to avoid having problems in adulthood. The manufacturers of wheelchairs, aware of the problem, offer a wide range of customised wheelchairs, to try to meet every request of the person with disabilities: at the time of purchase, it is possible to customise one's own wheelchair by modifying the dimensions of every component to adapt the seat to one's physique [147]. In addition to pushing technique, another factor influencing the frequency of injuries concerns the physical effort made to push the wheelchair, or rather the amount of energy expended [148]. It is clear, therefore, that a lightweight wheelchair is better than a heavy one, both in terms of long-term injury and manoeuvrability. To solve the weight problem, wheelchairs have been designed and produced that fit into the category of super-lightweight wheelchairs. The components that have the greatest influence on the weight of a wheelchair are the side rails, the footplates and the frame. The latter is the target of weight minimisation studies: at the moment, wheelchair manufacturers have developed frames that reach a minimum of 11.2 kg for steel frames, 4.4 kg for titanium frames, 3.5 kg for aluminium frames, and 2.1 kg for carbon fibre frames. Therefore, the reduction in frame weight comes exclusively using innovative materials, as the structure remains almost unchanged, except for the section of the tubulars that compose the frame. The aim of this study is therefore to evaluate an alternative way of increasing the performance of the wheelchair, which involves the design of a super-light frame with innovative shapes. Data on the characteristic wheelchair dimensions of 34 patients were used as a starting model. As shown in Figure 18, preservation regions were then defined, i.e., the volumes to be maintained during the automatic generation of the structure, on which both loads and constraints can be applied.

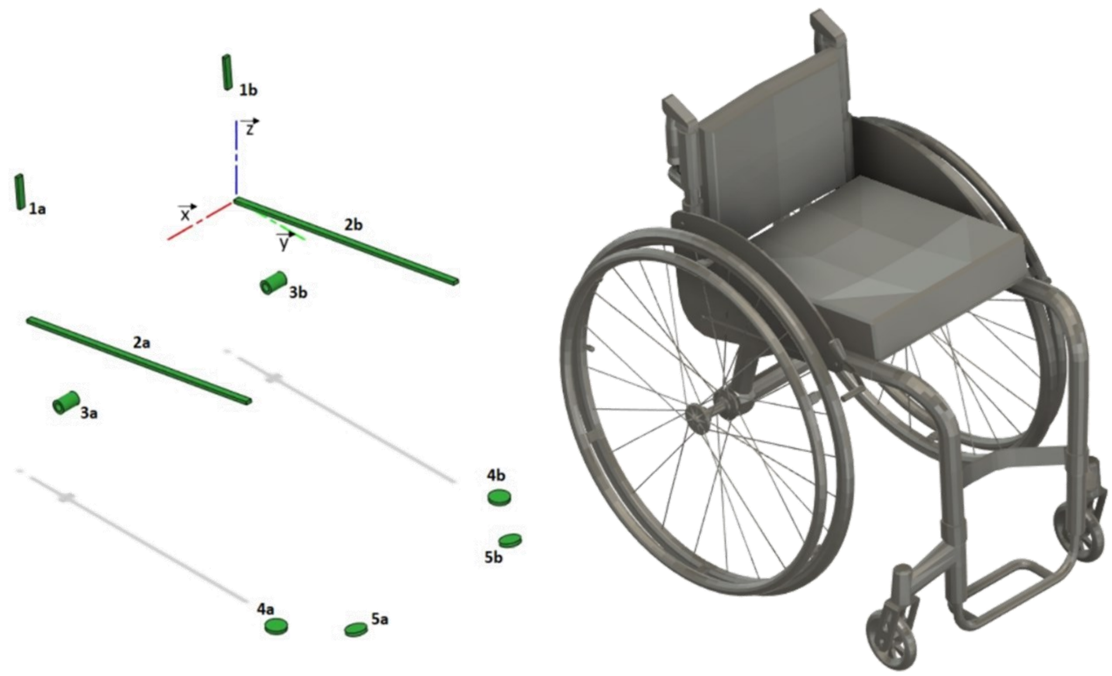



*Figure 18. Preserve regions in relation to a stardard wheelchair.*

Next, obstacle regions are created: i.e., volumes in which no material is allowed to be generated to develop the structure. Normally an obstacle region is inserted in those areas occupied by elements outside the optimisation process (e.g., in the area of the rear wheels) or in the areas where it should not be an impediment (e.g., in the area of front wheel rotation). Figure 19 described the obstacle regions.

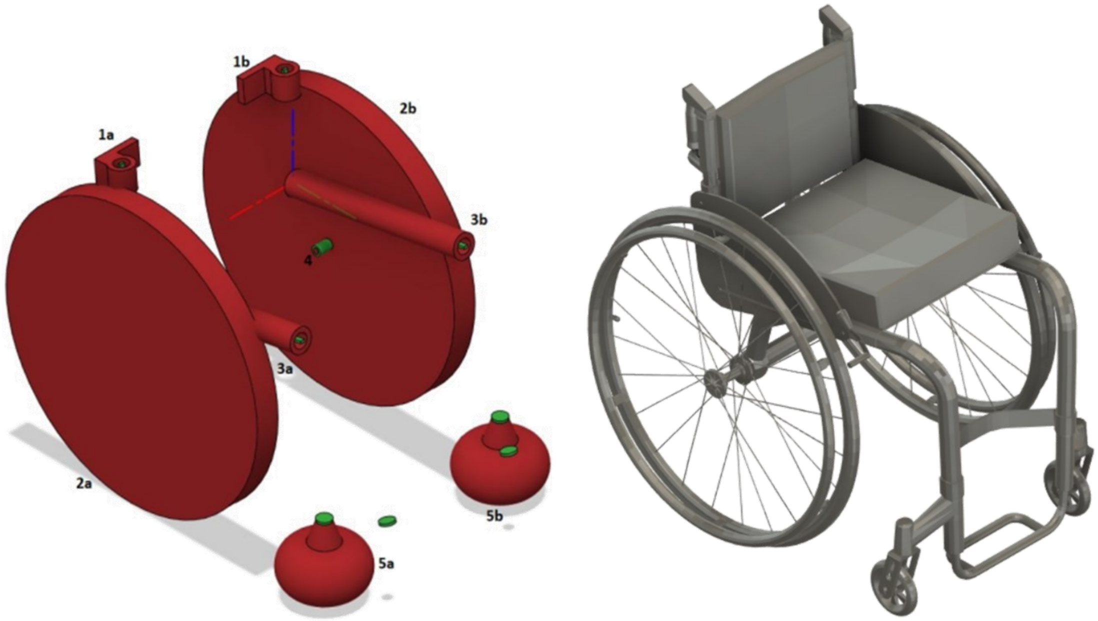



*Figure 19. Obstacle regions in relation to a standard wheelchair.*

The next step is to define the loads and constraints of each load case considered. In Fusion 360, as in most Generative Design and Optimisation algorithms, only static loads are considered. The difficulty therefore lies in identifying the loads that most often stress the chassis, knowing that it is not possible to cover 100% of the loads encountered in the lifetime of a wheelchair chassis. Five main load cases are therefore considered: forces and constraints are studied for each of them, and then imposed in the software GD workflow (Figure 20).

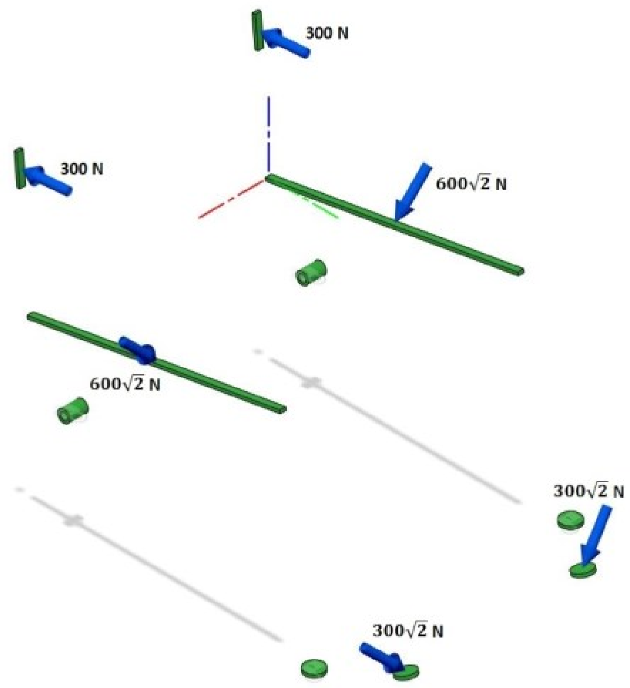



*Figure 20. Example of load case applied to the wheelchair.*

The next step analysed concerns the selection of materials: Fusion 360, compared to most software with Topological Optimisation algorithms, allows more than one material to be selected. This feature is consistent with the purpose for which a Generative Design approach is applied: to independently create innovative shapes in the first steps of product development, which will later be evaluated by a designer.

At this stage, in fact, there is the freedom to consider different materials for the generation of solutions as they are not yet constrained by the restrictions due to production and by the budget allocated for the creation of the final product. Steel, Aluminium, Titanium and Carbon Fiber Reinforced Polymer (CFRP) were chosen for this case study.

One of the most innovative parts of this software and, intrinsically, also of the algorithm underlying the generative study of Fusion 360 concerns the choice of production constraints, as shown in Figure 21. This option allows constraints to be defined that relate to technological parameters of several types of production. The manufacturing technologies considered concern not only AM, as inherently imposed in the various optimisation software, but also 2-axis cutting, die casting, 3 or 5 axes milling and an option for which no constraints are taken into account. The production volume option allows the programme to make a rough estimate of the cost of producing the component.

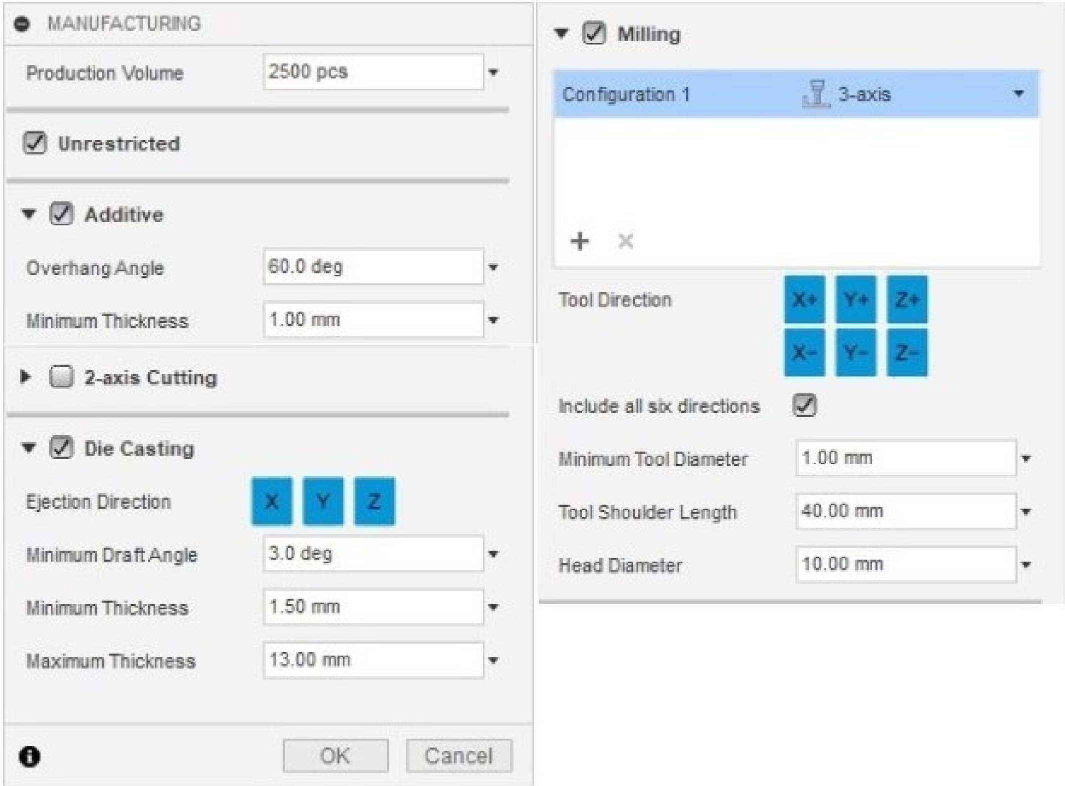



*Figure 21. Autodesk Fusion 360 production constraint options.*

Finally, once all the previous steps have been performed, it is possible to set the parameters of the objective function, as shown in Figure 22. Fusion 360 proposes two possible objectives to set: mass minimisation or stiffness maximisation. In the first case, a limit safety coefficient must be specified. The iterations will tend to reduce the mass by trying to distribute the stresses so that they do not fall below the value of this coefficient. In the second case, it is also necessary to set a mass target, in addition to the safety coefficient already mentioned. In this case, the iterations will attempt to reach the target mass and to distribute the material by increasing the stiffness of the structure, while maintaining an acceptable distribution of stresses, given by the parameters of the set safety factor. In addition to these two objectives, it is also possible to impose limits on maximum permissible deformations, modal frequencies and buckling. In the first case, one may choose to impose a limit on the global or local deformations for each of the three spatial directions, in the second case one may set the minimum value of the first modal frequency, in the third case the 'min first mode frequency' and in the fourth case the limit safety factor for buckling. For the generative study, mass minimisation was set as the objective, with a safety coefficient of 2. The choice of this coefficient derives from the fact that the FEA performed by Generative Design software is not as accurate as the analysis of a specific FEM simulation software: also, for this reason a higher value of the safety coefficient was chosen.

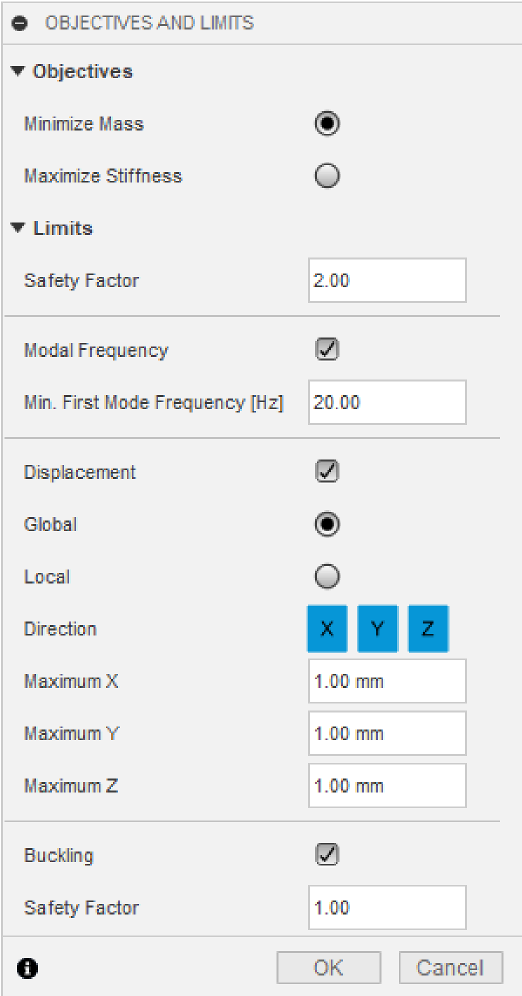



*Figure 22. Autodesk Fusion 360 parameters of the objective function.*

## 2.2.1. First approach in Generative Design study

### 2.2.1.1. Mesh setting

For the generative study, it is also possible to choose the quality of the mesh. There is only one parameter available that generically concerns the resolution of the elements: the mesh control is therefore pre-set to standard values from which to choose. As shown in Figure 23, the choice of mesh ranges from “coarse” to “fine” resolution. Obviously, with a finer mesh, more defined results are obtained but in a long time, while with a coarser mesh, results are obtained in a shorter time but with less definition.

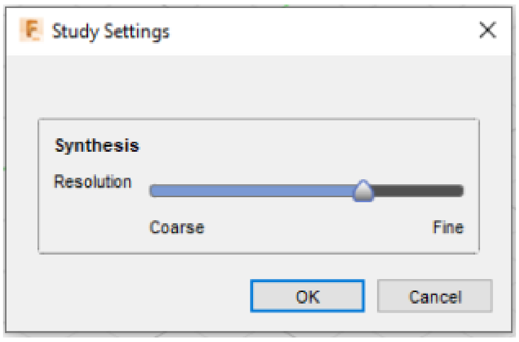



*Figure 23. Parameter for modifying mesh resolution in Autodesk Fusion 360.*

The choice of mesh resolution also influences the type of volume generated by the algorithm. In particular, a fine mesh pattern tends to consider more geometric details of preserves and obstacle regions, and also proposes design solutions with thin surfaces, whereas a coarse mesh tends to create design solutions composed of trusses and tubular elements. This behaviour is also confirmed experimentally: Figure 24 shows three frames resulting from a GD study with different meshes. All frames are made of aluminium and were manufactured using the same production process. The frame in Figure 24c was obtained with as fine a resolution as possible for the success of the generative process (100%), the frame in Figure 24a was obtained with a coarse resolution (33%) and frame in Figure 24b using an intermediate mesh resolution (66%).

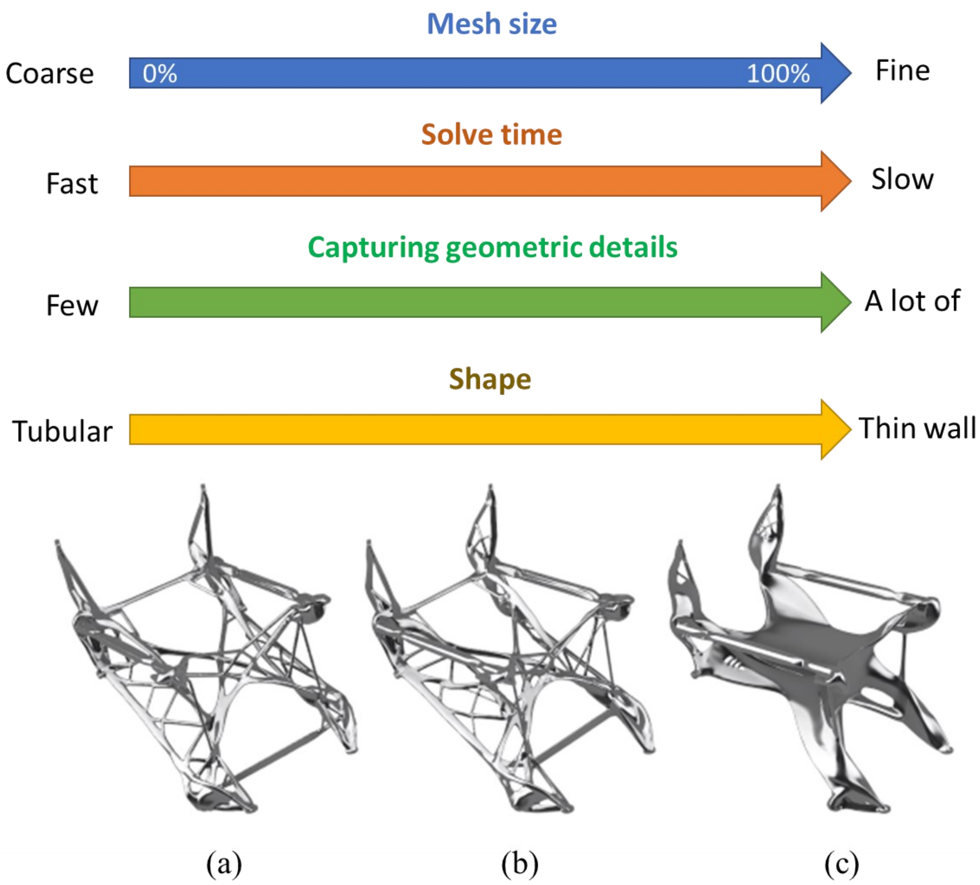
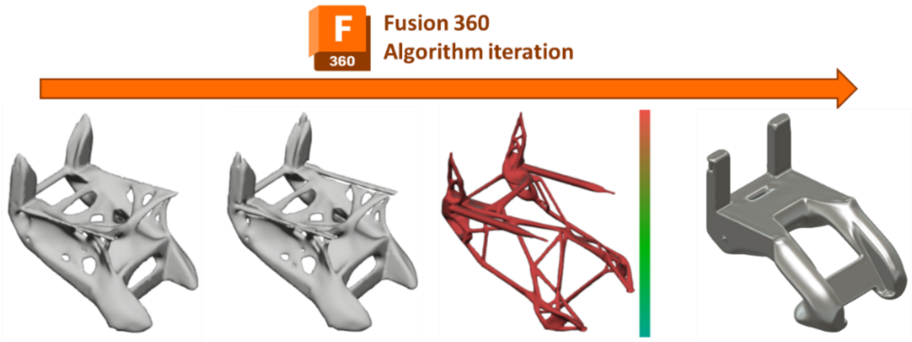



*Figure 24. Design alternatives based on mesh resolution.*

In Figure 24, the case with coarser mesh (0%) is not shown because, during the iterations of the algorithm, singularity cases occurred in the FEA. This means that, at some points in the mesh, sharp intersecting edges are created or point loads are applied to the infinite surface generated after an iteration. This behaviour is evident when, with large mesh elements, the programme is unable to propose continuous surfaces. In these situations, the algorithm, finding in input from the previous interaction a high value of the load at a certain point, starts to increase the mass of the component. This is the classic behaviour of increasing the thickness of a highly stressed area to decrease the maximum stress of the component. All this leads to divergence from the expected result, thus returning a component with a greater weight than that proposed in the first iterations, inadequate in terms of mechanical and form, as shown in Figure 25.

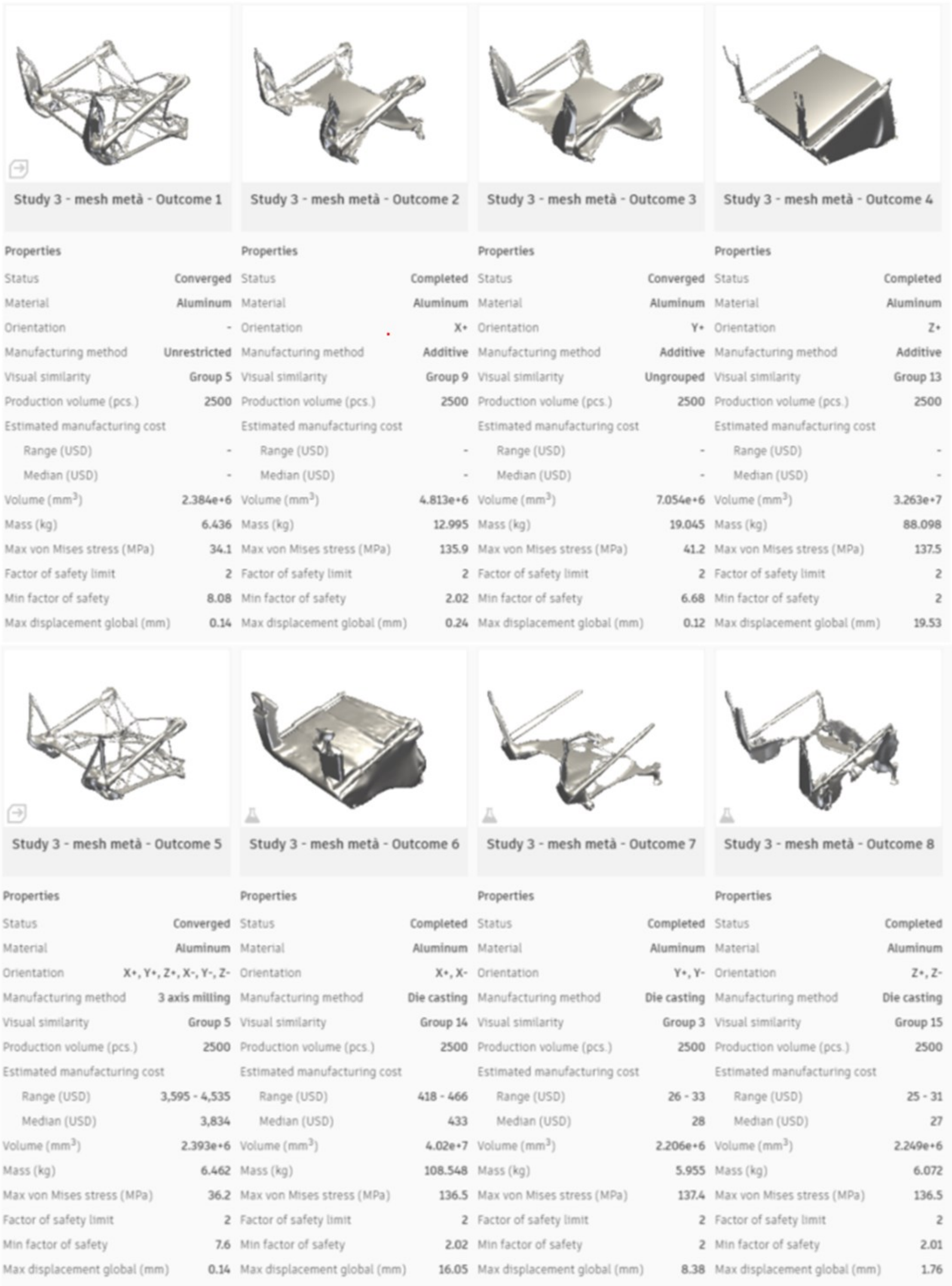



| | | | | |
|---|---|---|---|---|
| **Mass [Kg]** | **31** | **30** | **9** | **70** |
| **Von Mises stress [MPa]** | **2** | **135** | **$2.0\times10^{8}$** | **138** |
| **Safety factor** | **155** | **2** | **~0** | **2** |
| **Max displacement [mm]** | **~0** | **3** | **$1.6\times10^{13}$** | **20** |
| **Outcome evaluation** | Convergence | Convergence | Singularity | Divergence |

*Figure 25. Singularity error in solution generation steps.*

### 3.2.1.2. Manufacturing processes

A second analysis concerns the production processes by which the generated frames can be produced. To perform a correct analysis, it is necessary to refer to the same mesh size (previous paragraph) and the same material. In this case, an aluminium frame with a 33% mesh is considered. The results of the Generative Design study for these conditions are shown in Figure 26.



| Properties | Study 3 - mesh metà - Outcome 1 | Study 3 - mesh metà - Outcome 2 | Study 3 - mesh metà - Outcome 3 | Study 3 - mesh metà - Outcome 4 | Study 3 - mesh metà - Outcome 5 | Study 3 - mesh metà - Outcome 6 | Study 3 - mesh metà - Outcome 7 | Study 3 - mesh metà - Outcome 8 |
|---|---|---|---|---|---|---|---|---|
| Status | Converged | Completed | Converged | Completed | Converged | Completed | Completed | Completed |
| Material | Aluminum | Aluminum | Aluminum | Aluminum | Aluminum | Aluminum | Aluminum | Aluminum |
| Orientation | - | X+ | Y+ | Z+ | X+, Y+, Z+, X-, Y-, Z- | X+, X- | Y+, Y- | Z+, Z- |
| Manufacturing method | Unrestricted | Additive | Additive | Additive | 3 axis milling | Die casting | Die casting | Die casting |
| Visual similarity | Group 5 | Group 9 | Ungrouped | Group 13 | Group 5 | Group 14 | Group 3 | Group 15 |
| Production volume (pcs.) | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 |
| Estimated manufacturing cost | | | | | | | | |
| Range (USD) | - | - | - | - | 3,595 - 4,535 | 418 - 466 | 26 - 33 | 25 - 31 |
| Median (USD) | - | - | - | - | 3,834 | 433 | 28 | 27 |
| Volume ($mm^3$) | 2.384e+6 | 4.813e+6 | 7.054e+6 | 3.263e+7 | 2.393e+6 | 4.02e+7 | 2.206e+6 | 2.249e+6 |
| Mass (kg) | 6.436 | 12.995 | 19.045 | 88.098 | 6.462 | 108.548 | 5.955 | 6.072 |
| Max von Mises stress (MPa) | 34.1 | 135.9 | 41.2 | 137.5 | 36.2 | 136.5 | 137.4 | 136.5 |
| Factor of safety limit | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Min factor of safety | 8.08 | 2.02 | 6.68 | 2 | 7.6 | 2.02 | 2 | 2.01 |
| Max displacement global (mm) | 0.14 | 0.24 | 0.12 | 19.53 | 0.14 | 16.05 | 8.38 | 1.76 |

*Figure 26. Generative Design outcomes based on different materials.*

The results obtained differ in several respects, and not all of them are mechanically acceptable or reasonable in terms of shape. Outcomes 4 and 6 are not acceptable because their mass is too high and the shape indicates a problem in the convergence of the result.

With reference to the Figure 27, the central area is not particularly stressed, while the attachment of the cushion supports to the frame is stressed. The software performs only eight iterations, during which it changes the distribution of material on the supports, while leaving the central zone unchanged. The software stops once a condition of local optimum is reached in the attachment zones, without considering the rest of the volume. This behaviour can be seen in both above outcomes despite having different production constraints.

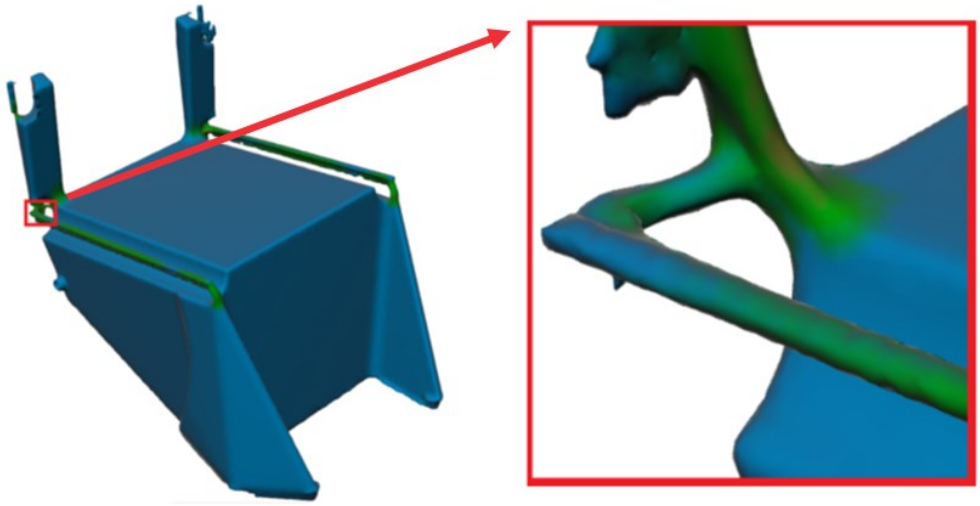
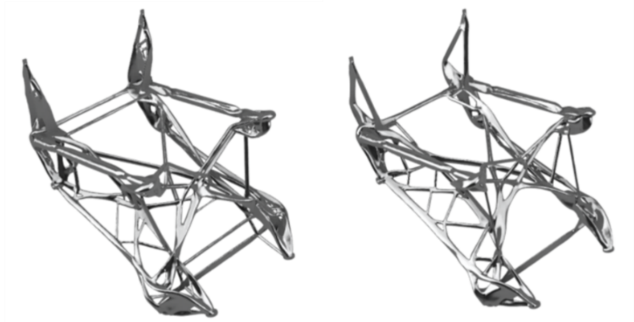


*Figure 27. Problematic Generative Design outcome example.*

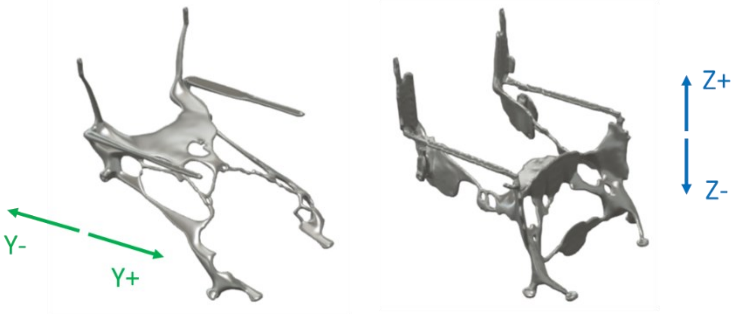
Outcomes 2 and 3, produced in Additive Manufacturing, although acceptable in terms of shape, have twice the mass of the other frames proposed by the software. Frame number 1, shown in Figure 28 on the left, is seen as the optimal outcome of the optimisation process, as it has no limitations given by the manufacturing processes ("unrestricted"): without constraints, the algorithm was able to create a structure with higher performance. Obviously, this outcome has limitations regarding manufacturability due to its complex organic form. The outcome that visually comes closest to the 'unrestricted' frame is number 5, shown in Figure 28 on the right, which can be produced by milling. Being similar to the absolute optimum in terms of both mechanical properties and shape, this frame represents the one with the best stress distribution among those that can be produced.



| Manufacturing Method | Unrestricted | 3 axis milling |
|---|---|---|
| Mass [Kg] | 6.5 | 6.5 |
| Von Mises stress [MPa] | 34 | 36 |
| Safety factor | 8 | 7 |
| Max displacement [mm] | ~0 | ~0 |

*Figure 28. Generative Design outcomes comparison.*

However, this does not appear to be the outcome with the lowest mass, as numbers 7 and 8, shown respectively in Figure 29, have a lower mass. The problem with these two frames stems from the fact that it is necessary to verify that the results obtained can also withstand sudden and dynamic forces, i.e. different from those set during the formulation of the problem. Although no verification has been carried out, it is quite evident that the two frames mentioned above are poorly resistant to forces in the direction of the X axis, as well as having a worse distribution of stresses as they are far from the optimum result. The outcome produced by milling is therefore better at this stage, given the better distribution of stresses and a mass not far from the minimum mass.




| Manufacturing Method | Die Casting Y | Die Casting Z |
|---|---|---|
| Mass [Kg] | 5.9 | 6.0 |
| Von Mises stress [MPa] | 137 | 136 |
| Safety factor | 2 | 2 |
| Max displacement [mm] | 8 | 2 |

*Figure 29. Comparison of Generative Design outcomes with different ejection direction.*

#### 3.2.1.3. Materials chosen

The analysis concerns the differences in mechanical behaviour and design between the frames as the material changes. For a consistent analysis, reference is made to the same mesh quality and the same production process. In this case, frames produced using the milling technique with a 33% mesh are considered. The four results are shown in Figure 30 and their data are summarised in Table 1.

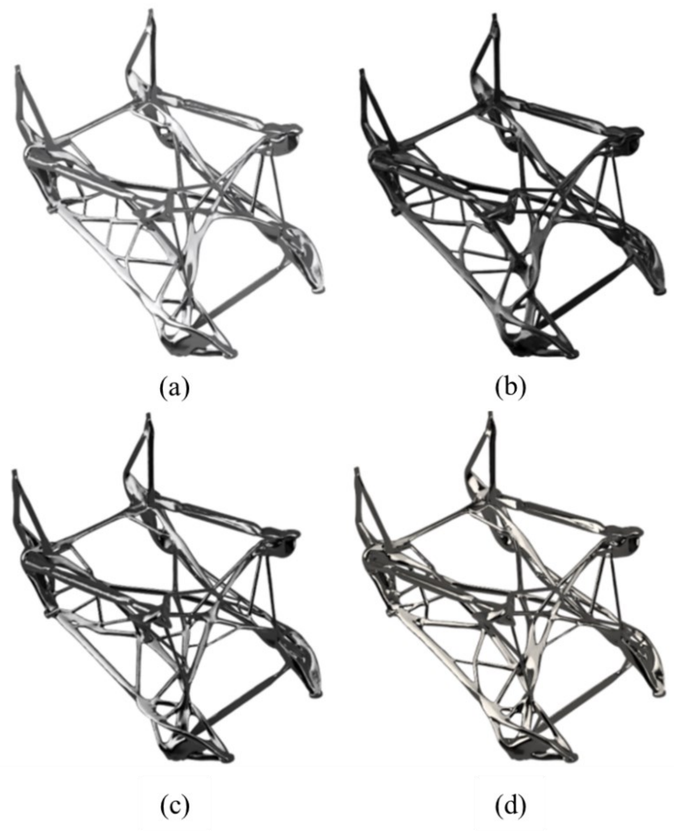



*Figure 30. Generative Design outcomes. Milling with 33% mesh. a) Aluminium, b) CFRP, c) Steel, d) Titanium.*

*Table 1. Proprieties of the GD outcomes in Figure 30.*

| **Materials** | **Aluminium** | **Steel** | **CFRP** | **Titanium** |
|---|---|---|---|---|
| Mass [Kg] | 6.5 | 18.8 | 3.4 | 10.8 |
| Max stress V.M. [MPa] | 36.2 | 35.0 | 35.2 | 38.2 |
| Min safety factor | 7.6 | 5.9 | 8.5 | 7.2 |
| Max displacement [mm] | 0.1 | 0.1 | 0.1 | 0.1 |

Before analysing the difference between the four materials, a clarification is necessary regarding the production processes considered when formulating the problem. The Generative Design software does not consider which of the proposed manufacturing processes as constraints are possible for a given material. The algorithm only handles the parameters of the manufacturing constraints and proceeds to create geometries that are optimal for the given mechanical properties of the materials. It is not uncommon in generative studies to set up manufacturing processes that are not suitable for the chosen materials, to have a wider range of solutions. In these cases, it is necessary for the designer to verify that the frame shapes are feasible with another production process or with catalogue components that come close to the generative shape. The volumes of the four frames are very similar. This characteristic could derive from the fact that the production process of 5-axis milling, with the tool dimensions imposed, does not require any particular limitations. This thesis is supported by the fact that the end results are very similar to unrestricted frames. The maximum stress is also comparable, with a mean square deviation of 4% from the average stress. The main differences lie in the value of the minimum safety coefficient and the mass. Having the same volume, materials with a lower density are lighter; therefore, the material that guarantees better lightness is CFRP, followed by Aluminium, Titanium and then Steel. As far as strength is concerned, it is based on the yield strength of the material. Since the stresses are comparable, again the higher the yield strength of the material, the greater its strength. In this case, although Titanium has a higher yield strength than Aluminium, the Aluminium frame is more resistant because the maximum stress acting on it is less than that acting on Titanium. In any case the values are much greater than 1 and similar to each other, so from the point of view of strength the four frames are comparable. At the same time, the algorithm failed to converge to solutions with safety factors close to those set as limits: this behaviour is probably due to the achievement of other objectives before the safety coefficient or to the difficulty in handling complex geometric constraints.

#### 3.2.1.4. First study consideration

The objective of the case study is to realise innovative, lightweight wheelchair frames by means of Generative Design methods. The expected results are therefore frames with organic shapes and lower masses than those currently on the market.

The minimum weights currently on the market are now listed: 2.1 kg for CFRP wheelchair frames, 3.5 kg for Aluminium frames, 4.4 kg for Titanium frames and 11.2 kg for Steel frames. The results obtained have a weight of 3.4 kg for CFRP wheelchair frames, 6.5 kg for Aluminium frames, 10.8 kg for Titanium frames and 18.8 kg for Steel frames. One possible explanation is that the production processes consider a single manufacturing process for the whole frame, whereas currently wheelchairs are supported by frames that are obtained by assembly. Another possible explanation is the software's inability to consider hollow structures with a larger cross-section instead of solid features. From the software's point of view, this discrepancy is attributable to the behaviour of the optimisation algorithm, which is based on the Level Set method. The iterations decrease the mass of the frame but converge to a minimum that is not an absolute minimum, but a local minimum. A proof of this statement lies in the values of the minimum safety factors calculated from the simulations carried out in the iterative process. All the resulting safety factors values are much greater than 2, the limit imposed on the algorithm. It can therefore be assumed that the absolute minimum is obtained for minimum safety factors close to 2, since if the minimum value were greater, it would be possible to remove material to make the safety factor tend towards the limit. To lower the mass of the frames even further, it is possible to perform a further GD study equal to the one just performed, with the only difference of directing the software towards the solution with a lower mass, giving the model an initial geometry.

## 2.2.2. Second approach Generative Design study

### 2.2.2.1. Boundary conditions

In the second Generative Design study, an attempt is made to go beyond the limitations found in the first analysis of the software, and thus to find alternative working steps to have more performing solutions than those already found. The main modification made to the previous studies is the introduction of a starting shape. This shape is used as a starting hypothesis for the shape of the component. The proposed step could be seen as an approximation to Topological Optimisation approaches, in that the starting shape of the component is provided by the designer, thus limiting the possible innovative solutions proposed by the algorithm. Instead, the proposal of this research presents as a starting shape one of the solutions already provided by the algorithm in the first generative study. To compare the solutions of the two GD studies, the same preserve regions, obstacle regions, loads, constraints, production processes and materials were imposed. For the choice of the starting shape, it was decided to use a design in the middle of the iterative process. This was to avoid imposing shapes influenced by singularity problems as seen previously. As far as the quality of the mesh is concerned, all three element dimensions are considered as done in the previous study: the starting shape was taken from the result with the corresponding mesh. Only one starting shape was chosen for each material, so it was necessary to identify the most suitable starting shape from among those available for the same material and mesh size. The choice opted for the design obtained by the unrestricted method, as this is the result obtained with the least restrictions in the iterative process. This choice will not affect the manufacturability of the final design as the new Generative Design study will still consider the new production constraints.

#### 3.2.2.2. Manufacturing processes

Using the same assessment as in the previous study, it is observed that the best outcomes are those obtained through Additive Manufacturing as their mass is significantly lower than that of all the other outcomes. The difference between the frames is in the material's direction of growth. The mass values are significantly lower than the 3.5 kg reported in the previous paragraph, with a maximum theoretical reduction of 57%. The values of the safety factor are also close to 2, so that, unlike the first GD study, it can be concluded that the minimum achieved by the algorithm is very close to the constraining minimum imposed by the designer.

#### 3.2.2.3. Materials

In order to be able to correctly analyse the results, it is necessary to refer to the same production process, and as seen in the previous paragraph, the frames closest to the optimum are those that can be produced in Additive Manufacturing. All directions of material's growth (X, Y and Z) and mesh quality considered previously (33%, 66%, 100%) are therefore considered. The data for the four proposed materials will be analysed below.

The aluminium frames currently on the market have a minimum mass of 3.5 kg, while the results of the GD process, have an average mass of 2.1 kg, so it can be concluded that the second Generative Design process generated theoretically better results than the frames on the market (Table 2), but above all with innovative geometries shown in Figure 31. In this the average reduction is 40.5%.

*Table 2. GD aluminium frame proprieties.*

| **Mesh Resolution** | **Growth Direction** | **Mass [Kg]** | **Mass Reduction [%]** | **Volume [$10^5$ mm$^3$]** | **Safety Factor** | **Displacement [mm]** |
|---|---|---|---|---|---|---|
| 100% | x | 2.19 | 37.6 | 8.09 | 2.1 | 0.6 |
| | y | 2.26 | 35.5 | 8.36 | 2.8 | 0.5 |
| | z | 2.18 | 37.6 | 8.10 | 2.2 | 1.0 |
| 66% | x | 1.99 | 43.1 | 7.37 | 2.0 | 0.8 |
| | y | 2.05 | 41.4 | 7.60 | 2.0 | 0.7 |
| | z | 2.03 | 42.1 | 7.51 | 3.4 | 0.7 |
| 33% | x | 1.99 | 43.1 | 7.37 | 2.0 | 1.6 |
| | y | 1.98 | 43.3 | 7.34 | 2.0 | 0.7 |
| | z | 2.07 | 40.8 | 7.67 | 2.0 | 0.6 |

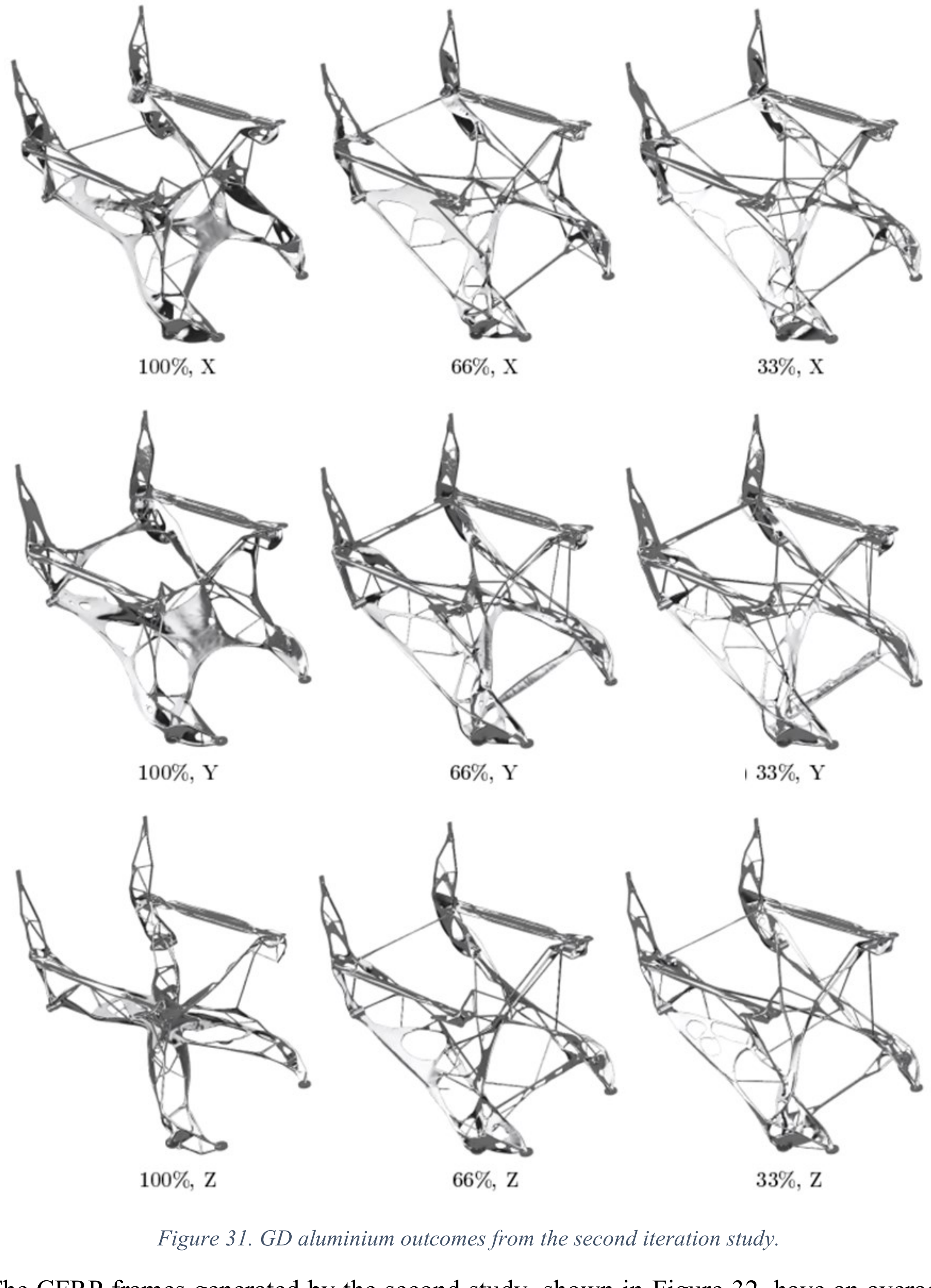



*Figure 31. GD aluminium outcomes from the second iteration study.*

The CFRP frames generated by the second study, shown in Figure 32, have an average mass of 1.1 kg compared to the commercially available minimum of 2.1 kg, so again it can be said that the results found are better than those already existing (Table 3). However, it must be remembered that the production process used to generate the CFRP solutions (i.e. Additive Manufacturing) is difficult to be applied. The percentage reduction in mass is 46.6%, slightly higher than the aluminium frames.

*Table 3. GD CFRP frame proprieties.*

| **Mesh Resolution** | **Growth Direction** | **Mass [Kg]** | **Mass Reduction [%]** | **Volume [$10^5$ $mm^3$]** | **Safety Factor** | **Displacement [mm]** |
|---|---|---|---|---|---|---|
| 100% | x | 1.16 | 44.6 | 8.14 | 2.0 | 0.3 |
| | y | 1.20 | 42.8 | 8.41 | 2.0 | 0.3 |
| | z | 1.17 | 44.5 | 8.15 | 2.0 | 1.3 |
| 66% | x | 1.06 | 49.3 | 7.44 | 2.0 | 0.4 |
| | y | 1.08 | 48.8 | 7.52 | 2.5 | 0.4 |
| | z | 1.08 | 48.5 | 7.57 | 2.1 | 0.3 |
| 33% | x | 1.13 | 46.2 | 7.90 | 2.0 | 0.7 |
| | y | 1.10 | 47.5 | 7.72 | 2.1 | 0.3 |
| | z | 1.11 | 47.1 | 7.77 | 2.4 | 0.5 |

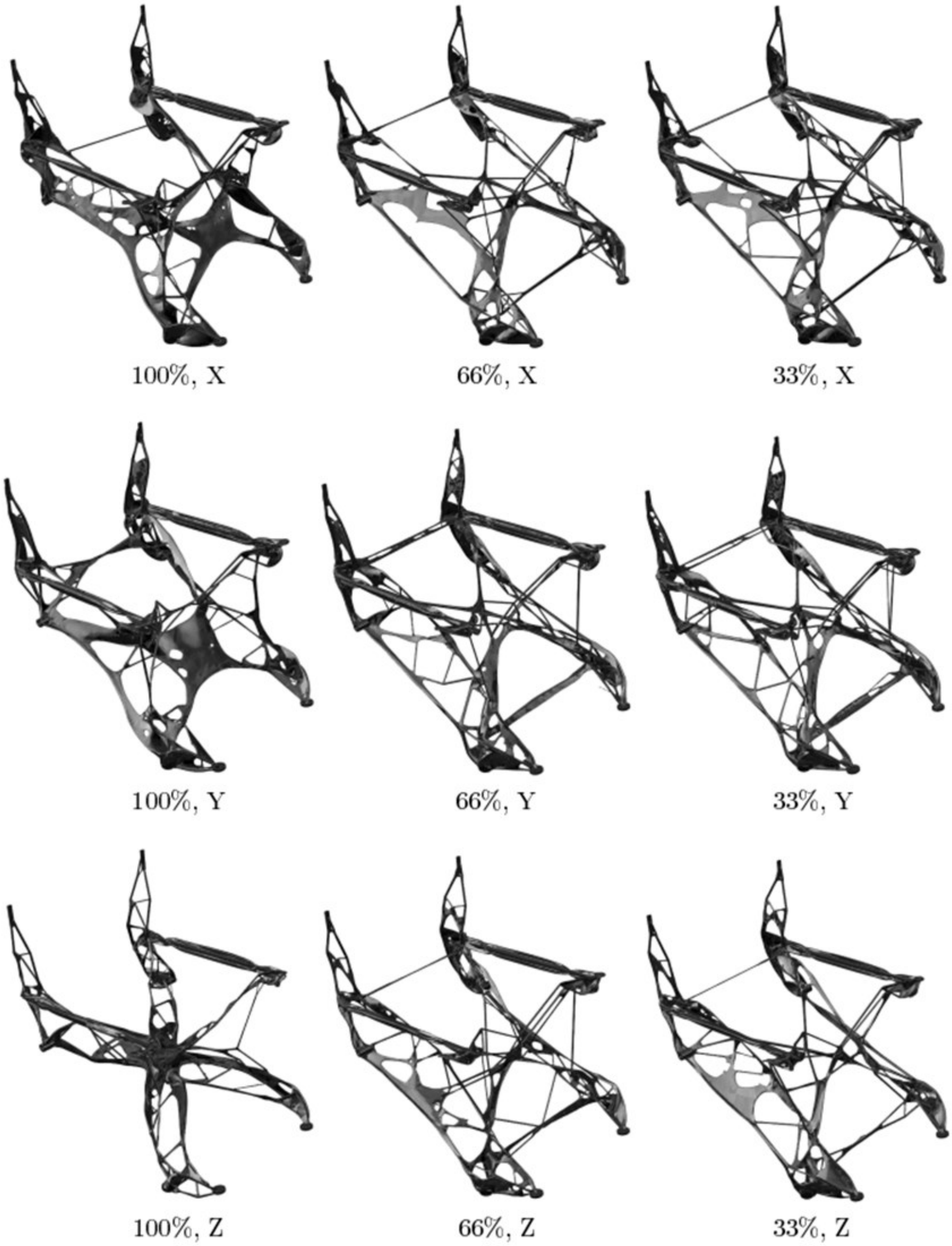



*Figure 32. GD CFRP outcomes from the second iteration study.*

Steel frames are not suitable for the design of super-lightweight wheelchairs, as the lightest Steel frame on the market is 11.2 kg. However, the application of Generative Design methods gives steel frames a chance to enter this category, as the values generated, shown in Figure 33, average 6.1 Kg (Table 4). The percentage reduction is 46.6%, the maximum deformation is less than a 1 mm and the safety factors are close to the imposed limit.

*Table 4. GD Steel frame proprieties.*

| Mesh Resolution | Growth Direction | Mass [Kg] | Mass Reduction [%] | Volume [$10^5$ $mm^3$] | Safety Factor | Displacement [mm] |
|---|---|---|---|---|---|---|
| 100% | x | 6.57 | 41.3 | 8.37 | 2.0 | 0.2 |
| | y | 6.43 | 42.6 | 8.19 | 2.2 | 0.2 |
| | z | 6.48 | 42.1 | 8.30 | 2.0 | 0.8 |
| 66% | x | 5.98 | 46.6 | 7.62 | 2.0 | 0.4 |
| | y | 5.85 | 47.8 | 7.45 | 2.0 | 0.2 |
| | z | 5.85 | 47.8 | 7.46 | 2.0 | 0.3 |
| 33% | x | 5.91 | 47.2 | 7.53 | 2.0 | 0.3 |
| | y | 5.96 | 46.8 | 7.59 | 2.0 | 0.2 |
| | z | 5.80 | 48.2 | 7.39 | 2.0 | 0.3 |

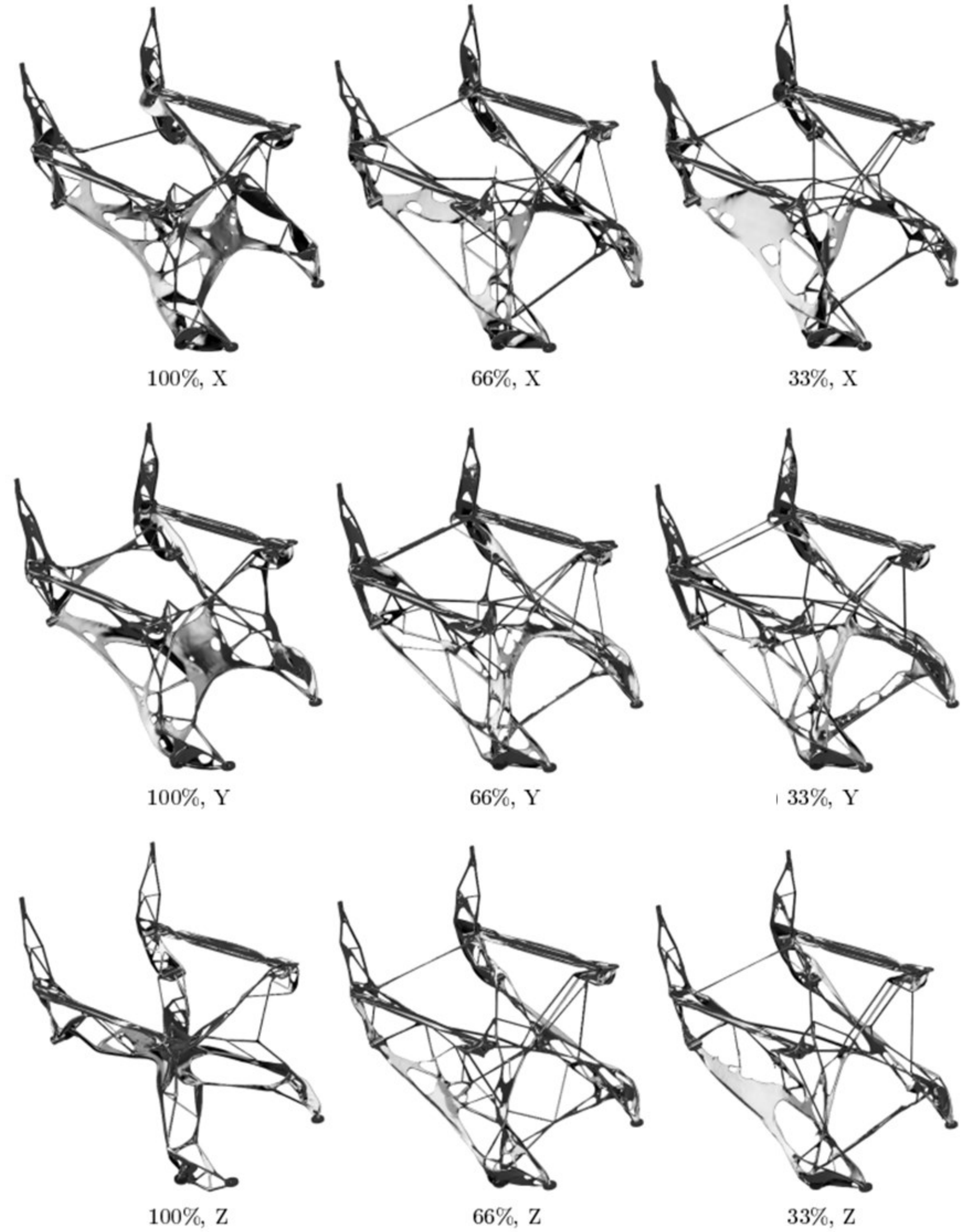



*Figure 33. GD steel outcomes from the second iteration study.*

Titanium frames on the market have a minimum weight of 4.4 kg, while the Generative Design study, in Figure 34, showed frames averaging 3.6 kg. The figure that differs from the three materials analysed above is the percentage reduction value, averaging 19.1%. This figure is half that of Aluminium, Steel and CFRP, so the application of optimisation methods on Titanium frames is less impactful, but still valid. Titanium frames also have other characteristics that differentiate them from others, the value of the safety coefficients, as shown in Table 5. In fact, although they are all close to two, on average they are higher. The only frame with a coefficient of two has a maximum deformation of 7.3 mm, higher than all the other deformations shown with other materials.

*Table 5. GD titanium frame proprieties.*

| Mesh Resolution | Growth Direction | Mass [Kg] | Mass Reduction [%] | Volume [$10^5$ $mm^3$] | Safety Factor | Displacement [mm] |
|---|---|---|---|---|---|---|
| 100% | x | 3.80 | 13.6 | 8.29 | 2.6 | 0.5 |
| | y | 3.78 | 14.0 | 8.43 | 2.2 | 0.3 |
| | z | 3.65 | 17.2 | 8.08 | 2.0 | 7.3 |
| 66% | x | 3.51 | 20.3 | 7.77 | 2.4 | 0.5 |
| | y | 3.39 | 22.9 | 7.53 | 2.1 | 0.6 |
| | z | 3.51 | 20.3 | 7.77 | 2.8 | 0.5 |
| 33% | x | 3.51 | 20.3 | 7.77 | 2.4 | 0.5 |
| | y | 3.39 | 22.9 | 7.53 | 2.1 | 0.6 |
| | z | 3.51 | 20.3 | 7.77 | 2.8 | 0.5 |

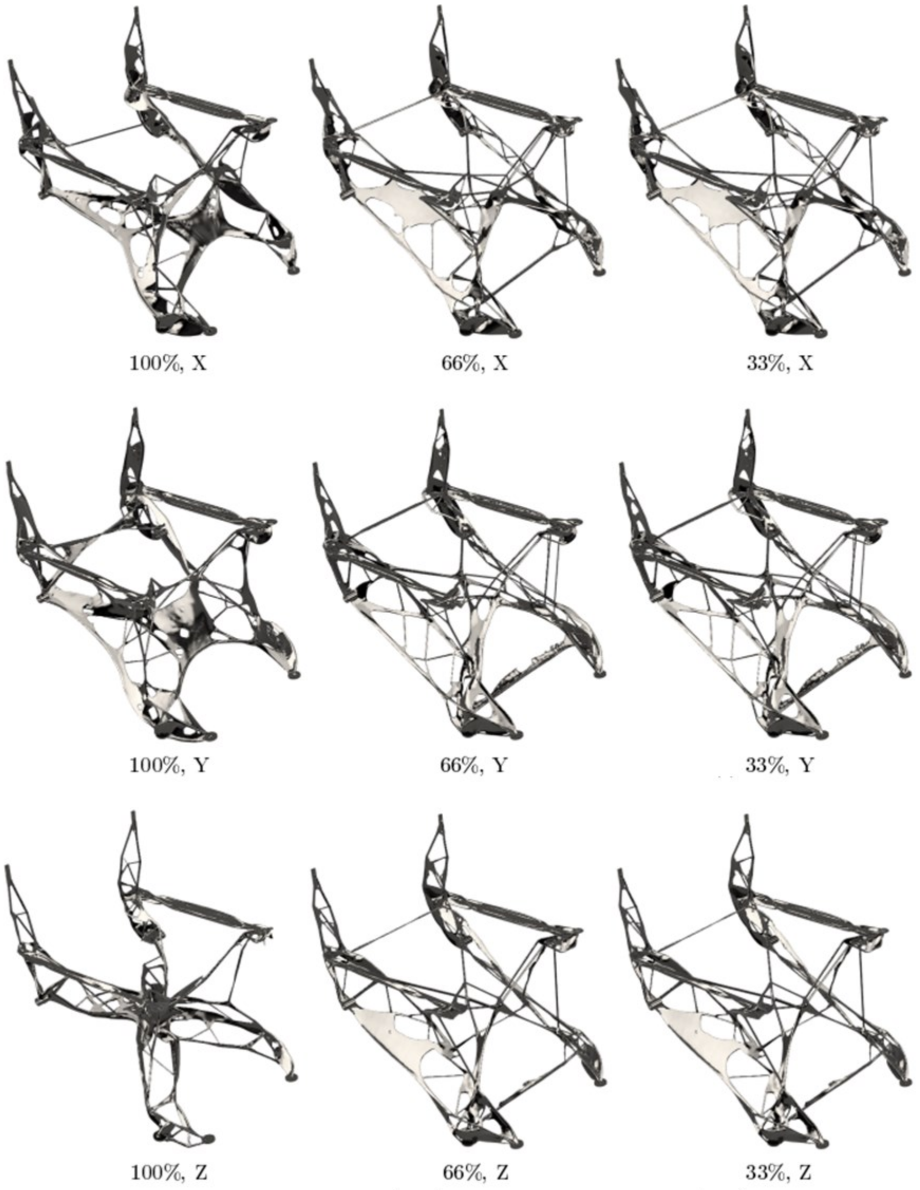



*Figure 34. GD titanium outcomes from the second iteration study.*

#### 3.2.2.4. Comparison of the design results

The last analysis concerns the comparison of all frames that can be produced using Additive Manufacturing regardless of material, mesh quality and direction of material growth. All the frames shown in Figure 35 have designs with some peculiarities in common and other aspects characteristic only of the specific result.

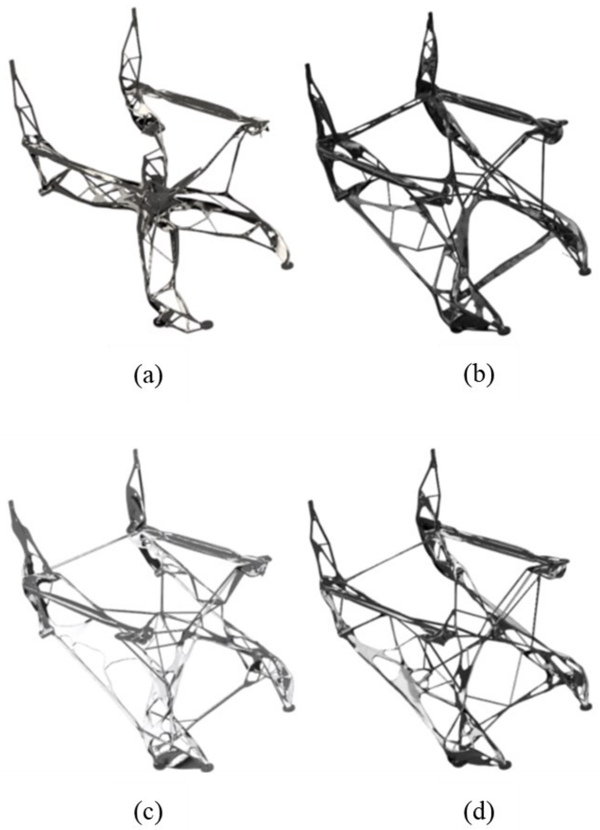



*Figure 35. GD best outcomes with different materials, mesh quality and growth direction. a) Titanium, 100%, Z, b) CFRP, 66%, Y, c) Aluminium, 33%, X and d) Steel, 66%, Z.*

Frames with a 100% fine mesh and Z direction of growth are the most different from the others, regardless of the material chosen. Their X-shape converges towards the centre in a feature, shown in Figure 36, through which the load paths pass.

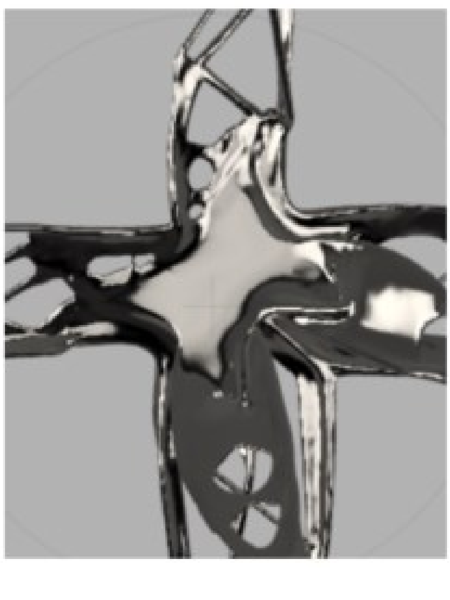


*Figure 36. Central features proposed by GD outcomes.*

The other frames considered do not have a central zone of union, but the loads pass through the frame according to a rectangular shape inclined along the Z axis, highlighted in Figure 37. The two sides facing the X direction are much thinner than the two sides facing the Y direction. This characteristic could be problematic since, a high load not expected in the case studies on one of the two thin sides could break the frame.

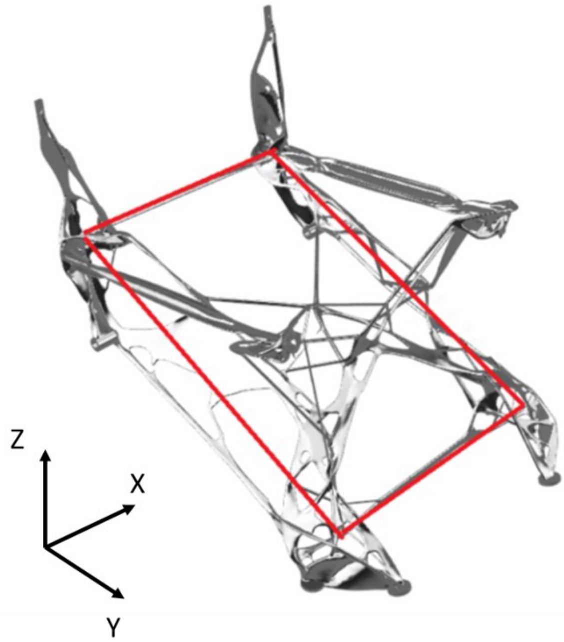



*Figure 37. Rectangular shape proposed by GD outcomes.*

An interesting observation concerns the shape of the frame in its entirety, with particular focus on the structure connecting the cushion supports, the rear wheel hubs and the sections at the front wheels and footrest. Depending on the quality of the mesh and the direction of growth, it is possible to identify areas formed by thin surfaces (Figure 38a) and areas formed by numerous features resembling the structure of a truss (Figure 38b). This arrangement of material allows for good strength along all directions and, above all, good rigidity, as triangles are theoretically non-deformable elements. Furthermore, these structures are interconnected and form a truss macrostructure that connects all the preserve regions. In this way, the entire structure has greater strength and greater stiffness.

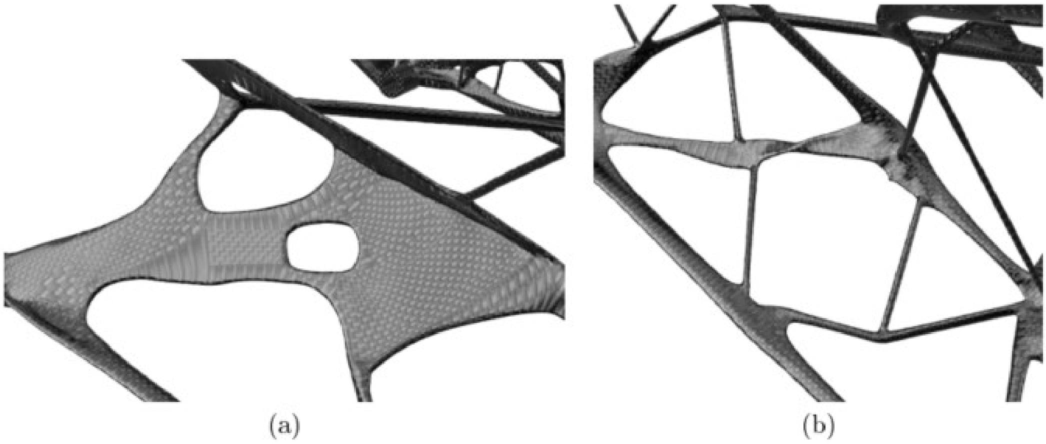


*Figure 38. Details of shape feature proposed by GD outcomes. a) Thin geometries and b) Truss structures.*

The most interesting comparison remains with the wheelchair frames currently on the market. Figure 39b shows a model of a super-lightweight wheelchair. Compared to the Figure 39frames obtained through Generative Design methodology (Figure XXSOTTOa), the entire structure is more streamlined. In fact, the generated frames present a structure with multiple interconnections between finer elements, which would allow loads to discharge in all directions. In this way, it is possible to bear a greater load with the same mass, or as in this case, it is possible to support the same load with a lower mass.

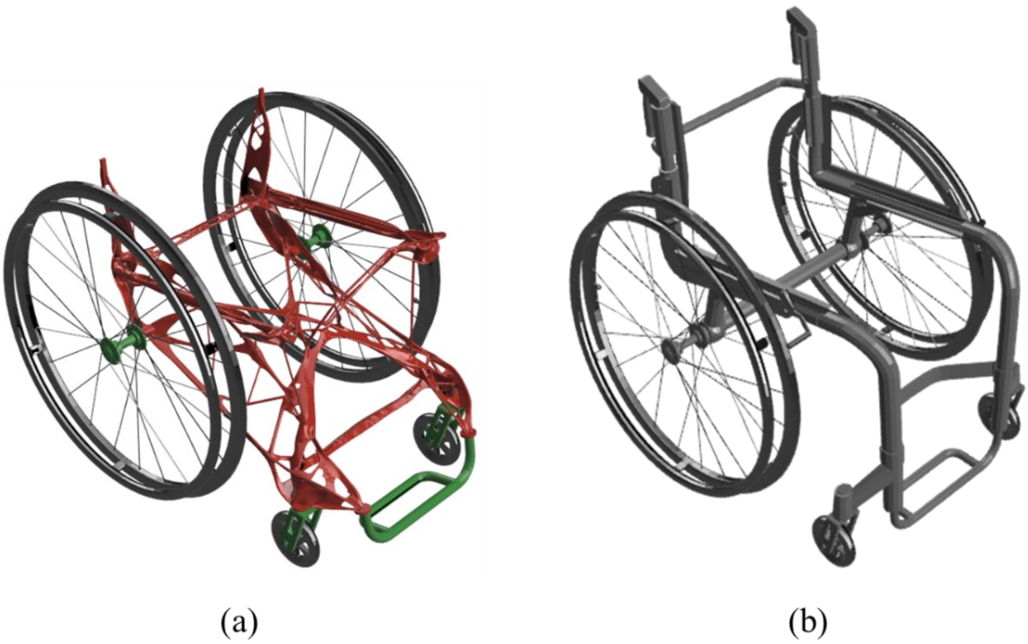


*Figure 39. Comparison between innovative wheelchair frame by means GD approach and commercial wheelchair frame.*

### 2.2.3. Assessment of the Generative Design approach for wheelchair frame

The Generative Design approach starts with the definition of input geometries, whether they are to be preserved or obstacles. It has been noted that Fusion 360 has problems handling thin surfaces under load, especially if these geometries are only cylindrical. This is probably due to the handling of either finite elements in the algorithm calculation or surfaces that tend to infinitesimally contact each other, especially if they are tangent to circular section geometries. In fact, experimental tests have given a value of 5 mm as the minimum acceptable thickness. To overcome this problem, in the study of the wheelchair, some cylindrical geometries to be preserved have been replaced by elements of rectangular cross-section. This obviously also involves approximations in the calculation of stresses by the algorithm, to be evaluated by in-depth FEA once the design solution has been found.

Also important is the impossibility of considering time-varying or cyclic loads, thus neglecting the phenomenon of fatigue. Similarly, the case of corrosion of structures is omitted. This reiterates a second in-depth study using specific software of all those stresses other than the static mechanical case.

The parameters characteristic of this software and most impacting on the number of solutions are undoubtedly the production processes. These constraints are one of the major differences to Topological Optimisation, even though there are important limitations in their use. For large structures, such as the wheelchair, the production processes considered in Fusion 360 are all to be discarded. In fact, the part consolidation approach of design for Additive Manufacturing implies the production of components as a whole. The solution to this limitation could be to study each individual component with a generative approach, thus losing the possibility of having new overall geometries of the structure. However, it must be remembered that, by definition, the GD methodology is used in one of the first designs stages and therefore implies further modifications by the designer to reach the final product. In this sense, GD is an excellent tool to move the designer away from classic and lack of innovative structures.

Another point of possible development concerns the actual manufacturability of a component based on the selected material. Optimisation mathematics considers the mechanical and physical characteristics of the material and relates them to the engineering parameters of each production process. This approach produces a wide theoretical choice of generated geometries, but at the same time does not consider that materials are incompatible with certain production processes.

Also concerning the iterative process, but more directed towards the result, is the software's inability to consider hollow surfaces. In fact, many structures to be studied propose solutions in which tubular features of various sizes and sections are present. This possibility is not considered in the algorithm, which then generates solid components and uses complex geometries to create specific structural behaviour.

## 2.3. Generative Design to solve video entry phone stiffness problem

This case study aims to analyse the performance of the Generative Design algorithm in the industrial field. More specifically, the subject of the study is a video entry phone. It presents critical issues in terms of stiffness relating to a support plate made of polymeric material, which constitutes a load-bearing element of the product. In particular, the portion of the plate is where the handset is housed: the problem concerns the deformation of the plate after several uses of the handset. In fact, the cornet transmits a tearing force to the plate each time it is used, which deforms the structure (Figure 40). The aim is to re-design the product, using the Generative Design module of Fusion 360, with a view to improving the rigidity of the backplate while improving the aesthetics and perceived quality of the product.

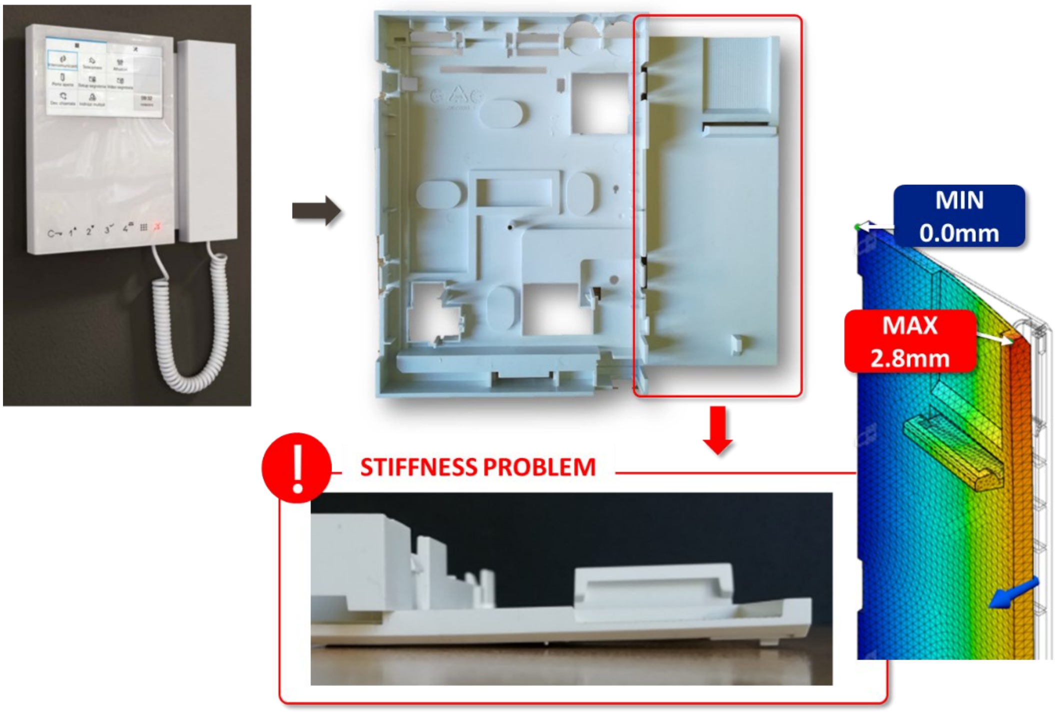



*Figure 40. Stiffness problem of the video entry phone.*

During the study, several models of the video entry phone frame were analysed and developed: the former cover the entire product, while the latter consider only the plate where the handset is housed. Of both, versions supplied directly by the company were used, with detailed and complex features. For this reason, a detailed preserve, obstacle geometry and starting shape configuration was used, considering the overall dimensions of all the components to be assembled with the plate. In fact, all those elements considered useful for the assembly of the internal electrical components, the fixing of the frame to the wall, the support of the handset and the improvement of the aesthetic side of the device were considered as preserve geometry (Figure 41a). On the other hand, the volume of the handset and the plane simulating the wall where the video intercom will be positioned were chosen as obstacle geometry, as shown in Figure 41b. No other geometries were used as it was decided to include a starting shape (Figure 41c) representing the entire frame among the geometric constraints. This choice was made because the walls of the frame are very thin and the GD algorithm, in this case, would be unlikely to generate material in highly constrained areas with little margin, as in thin walls.

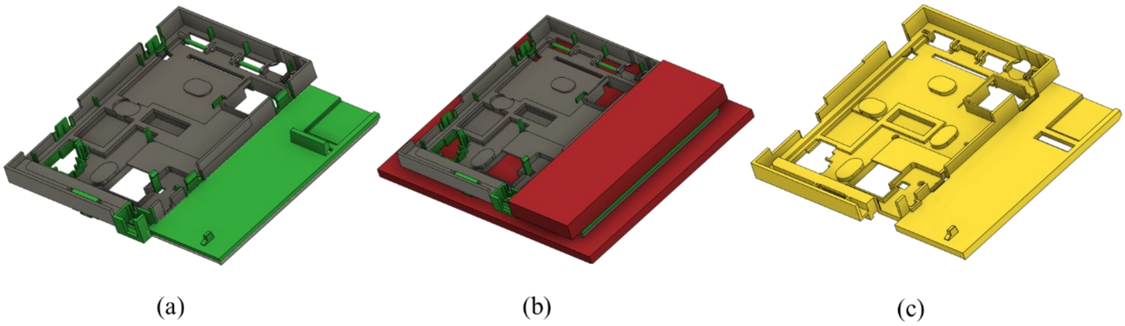



*Figure 41. Constraint regions chosen for GD study. a) Preserve regions, b) Obstacle regions and c) Starting shape.*

It was therefore decided to place a force of 50 N perpendicular to the support plane of the handset, with a safety limit imposed at 1.2. Another limit imposed by the company concerns the material: ABS polymer with precise mechanical and physical specifications was applied. Die casting, Additive Manufacturing and unrestricted are used for manufacturing methods.

One of the results proposed in Figure 42, which is very similar to all others in the same process, denotes the strong similarity to the company's designed chassis. At the same time, the iterations of the algorithm are limited and do not converge. After various analyses, it was discovered that the problem lies in the complexity of the constraint geometries. For each shape, the algorithm collects a large amount of information on geometric constraints, this large amount of data is not adequately supported by a good volume of action in which the software can generate mass. On the other hand, to guarantee the assembly of the plate with all other components without modifying them, the use of such a detailed configuration is obligatory.

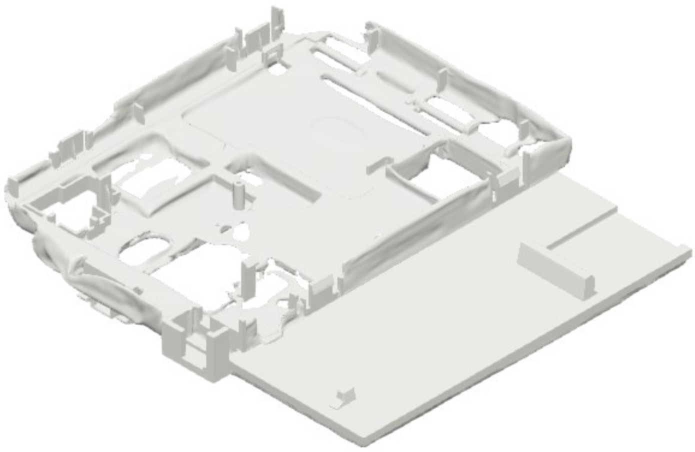


*Figure 42. Example of outcome proposed by first GD study.*

To solve this problem, an attempt was made to reduce the form constraints by studying only one part of the frame: the plate holding the handset. The validation of this choice was made through a FE analysis of the entire frame, in which it was noted that the part stressed by the loads is always the handset plate and not the frame housing the electronic part. The focus then shifts to the handset plate, which must increase its rigidity compared to the current one. In this way, the other portion of the plate, not being altered, will continue to ensure assembly with the other components. With respect to the boundary conditions, the material and manufacturing methods have been retained. Instead, the weight target, which is now 20 g, and the constraint geometries have been modified. As can be seen in Figure 43, a preserve region was placed on the outer plate for design reasons and on the handset attachment. Subsequently, only one obstacle region was created, which does not allow the algorithm to generate material where the complete frame is already present.

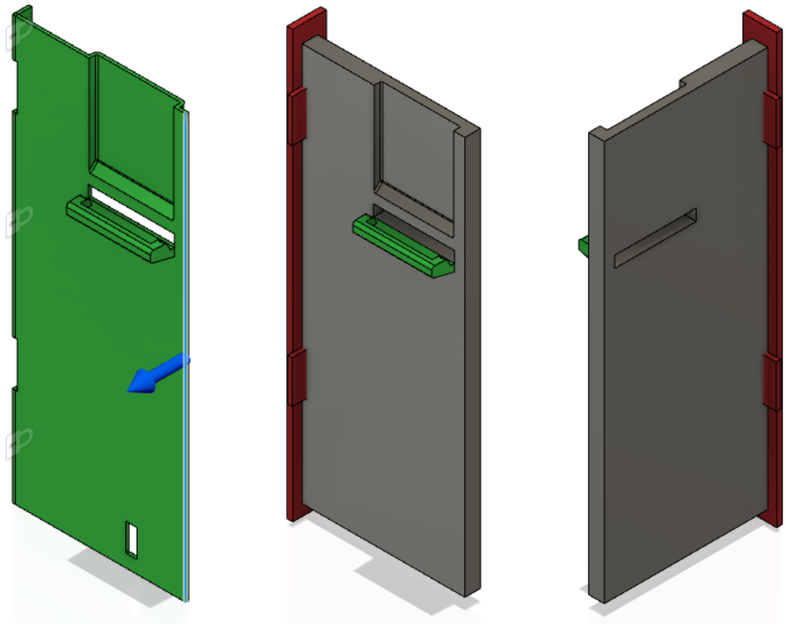


*Figure 43. Preserve (green) and obstacle (red) regions chosen in the second GD study.*

Observing the shapes generated in Figure 44, one can see the presence of ramified structures that tend to hold the outer edge to prevent the plate from buckling under stress. At the same time, complex structures resembling trusses are present in the central part of the plate, which help to increase its rigidity.

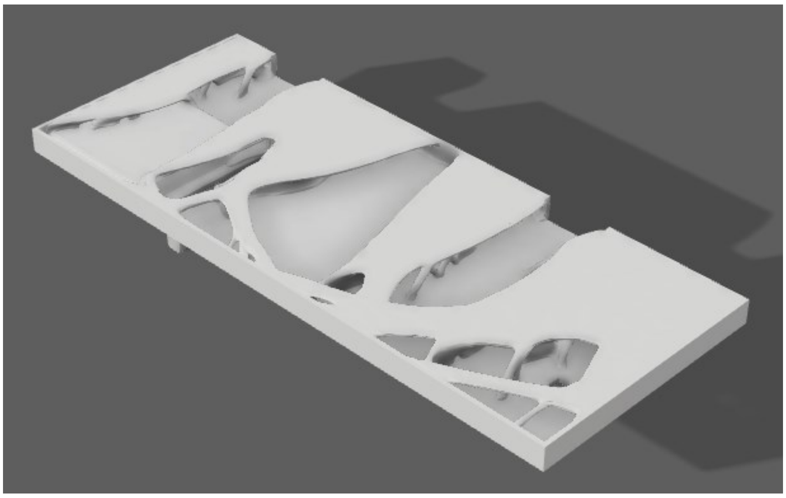
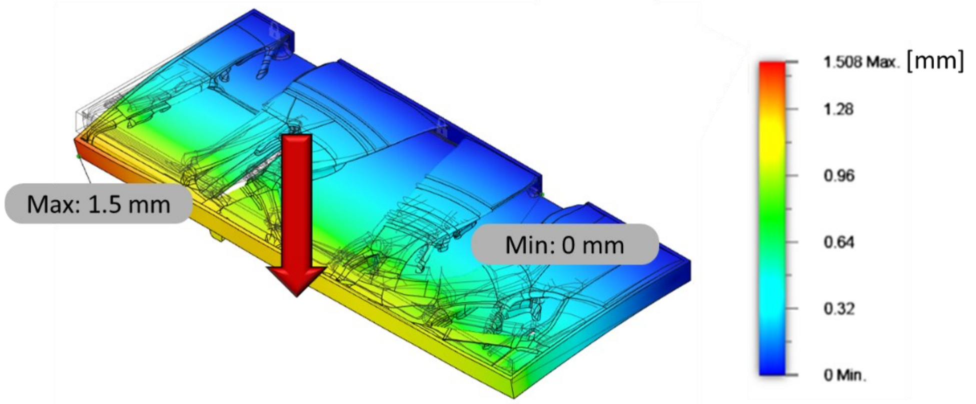


*Figure 44. One of the shapes generated in second GD study.*

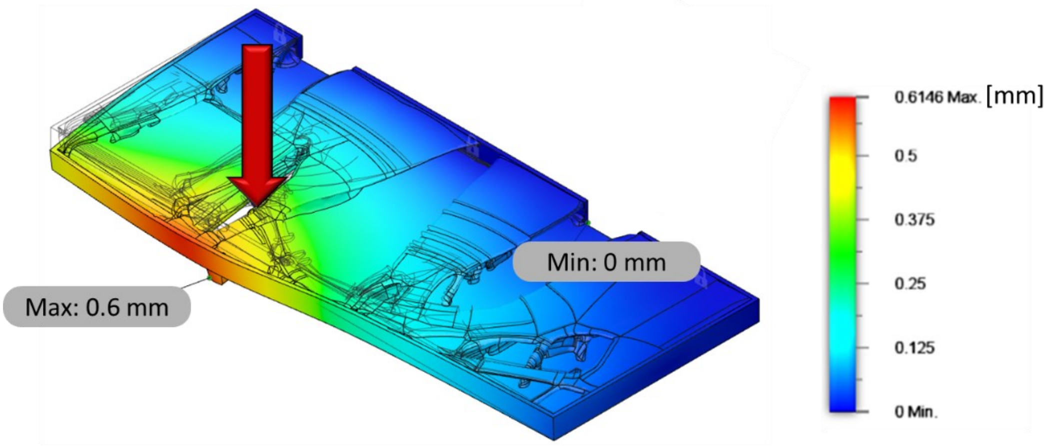
From the FE analysis carried out on the loads studied, it can be seen that:

- In the case of the load applied at the end of the plate (Figure 45a), the maximum displacement of the plate is approximately 1.5 mm i.e., theoretically 46% less than the plate configuration on the market

- In the case of the force applied on the handset support (Figure 45b), the maximum displacement of the plate is approximately 0.6 mm i.e., theoretically 51% less than the commercially available plate configuration.




(a)




(b)

*Figure 45. FEA of GD outcome in different load cases. Force applied a) at the end of the plate and b) On the handset support.*

Although the product on the market is manufactured by injection moulding, an "unrestricted" outcome was chosen as the result (Figure 46). Indeed, this form provides the best performance for the same weight. However, this does not imply that this result cannot be realised with different production technologies, such as Additive Manufacturing. Of course, such complex shapes limit the possibility of using traditional and more profitable production techniques for large volumes.

These methodologies are not developed to generate products ready to be mass produced and marketed. Therefore, it is right that various constraints are included to limit the generation of shapes, but they only help to better direct the development of the new product, rather than to ensure manufacturability in all its details.

In this case study, the possibility of multiple results has not been fully exploited. The biggest constraint lies in the fact that the frame is a component that has already been developed and tested to support and contain many components that increase its complexity with thin thickness. So, from a defined and complex starting shape, the algorithm started out very limited in its results. To improve the process, we recommend starting from a design step closer to the pencil sketch, and then adapting the shapes proposed by the GD to all the design and packaging problems of the internal components. In any case, GD's algorithm proved to be a valid tool for increasing product performance through an innovative approach ready to disrupt the classic and limited solutions proposed by the designers' experience.

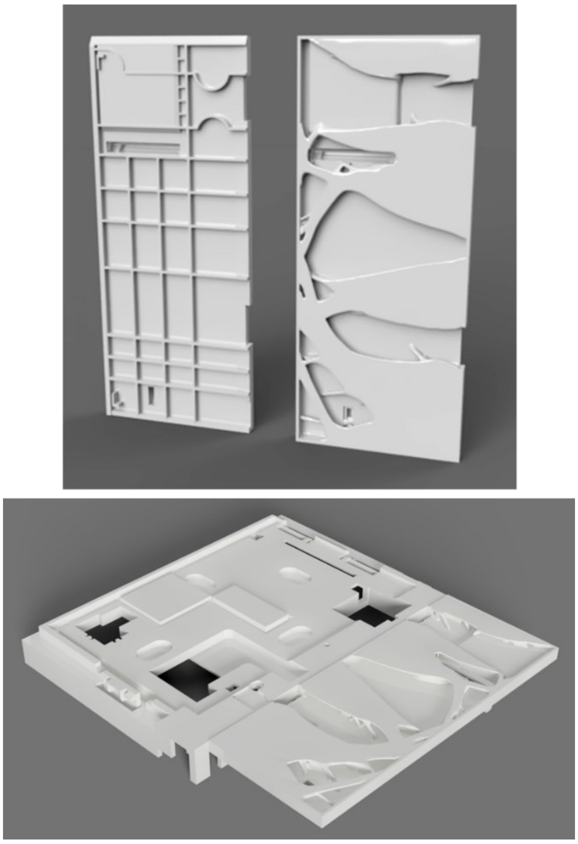


*Figure 46. Definitive shape of the handset attachment in the video entry phone.*

## 2.4. Generative Design for video entry phone: change material, change shape

The subject of this case study is the design, using Generative Design methodology, of an innovative frame for external video door entry systems. The diversification in material and geometry is evaluated, researching through various simulations the strengths and weaknesses to elaborate new, more economical prototypes, while maintaining the strength characteristics. In fact, to reduce production costs, two new design solutions are to be evaluated: in the first case, an attempt is made to reduce the mass of the existing Zamak 15 frame, and in the second, a possible change of frame material is evaluated, using ABS polymer. The Generative Design process is fundamental to this analysis: the creation of new geometries with different materials leads to a direct comparison between the existing frame and alternative solutions generated by the GD methodology.

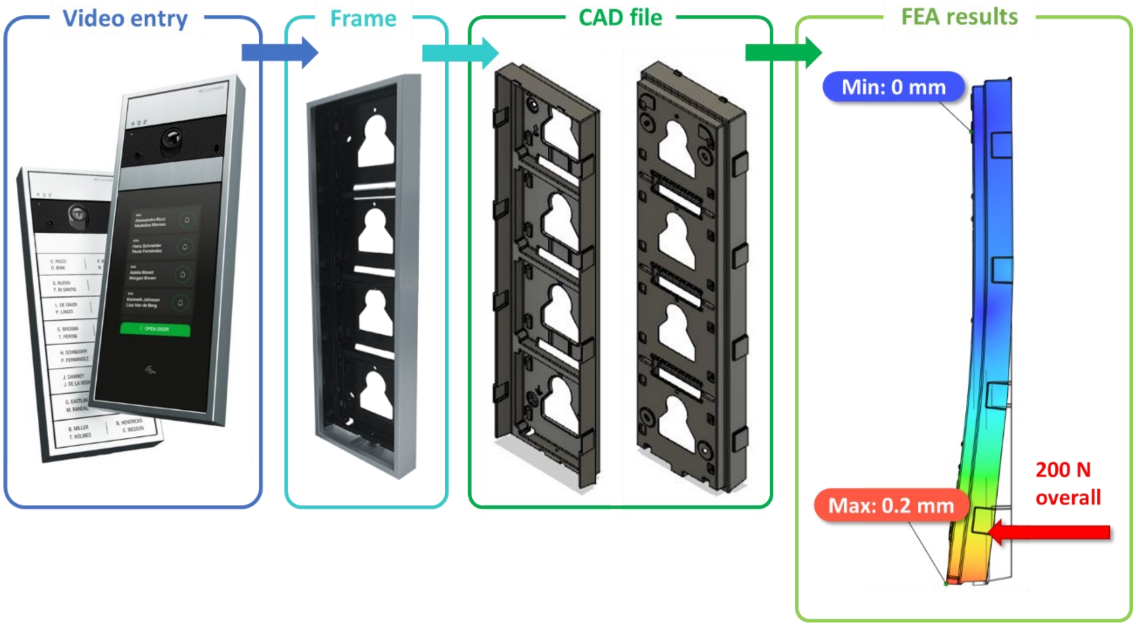



*Figure 47. FE analysis of the commercial video door entry frame.*

Given the structural function of the frame, to which the modules for use and an external design frame must be added, the aim of reducing mass is linked to the component's stiffness (Figure 47). In fact, the low interlocking tolerance for inserting the video intercom modules and the frame require an in-depth analysis of the displacements in addition to the mass reduction.

As already seen for the other case studies, preserves and obstacle regions are defined first. The former refers to parts of the frame that are functional both for wall mounting and for housing and locking the electronic modules, such as the pins (Figure 48a). The obstacles were defined as the module insertion spaces and the external frame, so that the external and internal components did not have to be redesigned as well (Figure 48b). Regarding materials, the company limited the study to a prototype made of Zamak 15, the same material as the frame on the market, and ABS for the frame designed from the beginning.

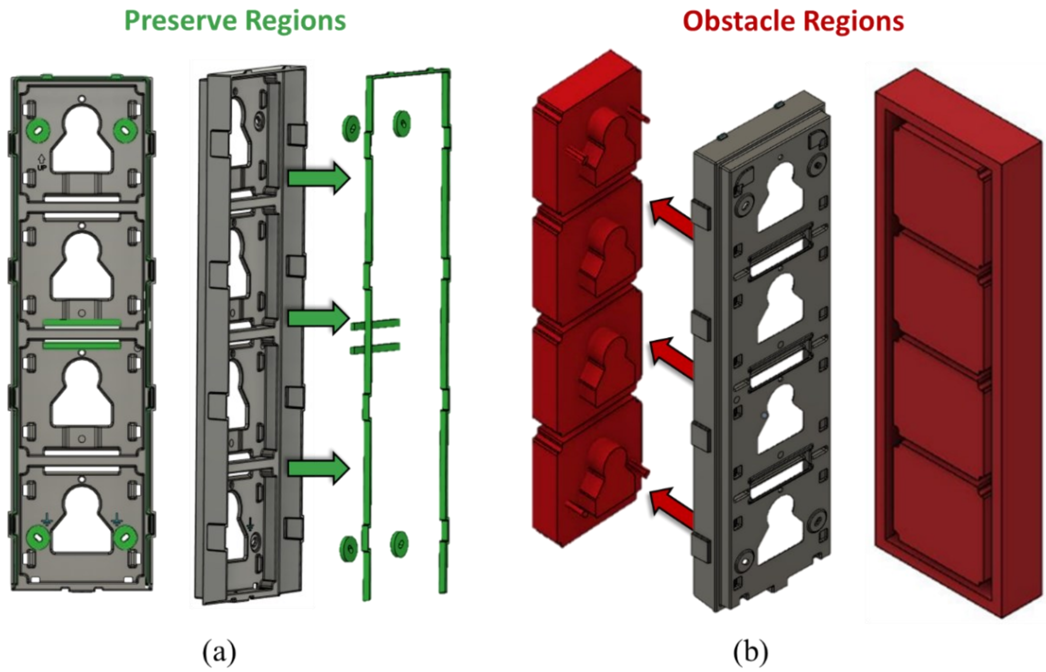



*Figure 48. Constraint regions chosen for GD study. a) Preserve regions and b) Obstacle regions.*

The frame is subjected to static loading conditions. The forces acting on the frame are the weight force, which is negligible, and the loads related to fixing the frame to the wall using dowels. According to the company's R&D team, two forces of 100 N each are considered to simulate the maximum fixing capacity of the dowels. The forces are applied to the prepared surfaces through contact between the screw head and the frame.

Regarding the constraints to be considered, the most severe operating condition has been considered. An uneven wall surface or a different tightening of the screws may cause the frame to tilt. The chosen boundary condition has two forces acting on the surfaces prepared for the housing of the corresponding two screws, two interlocking constraints on the surfaces prepared for the housing of the other two screws and a sliding constraint on the central supports of the frame in contact with the wall (Figure 49). In addition, a further constraint inherent in the maximum permitted displacement of 5 mm in the load application zone is considered.

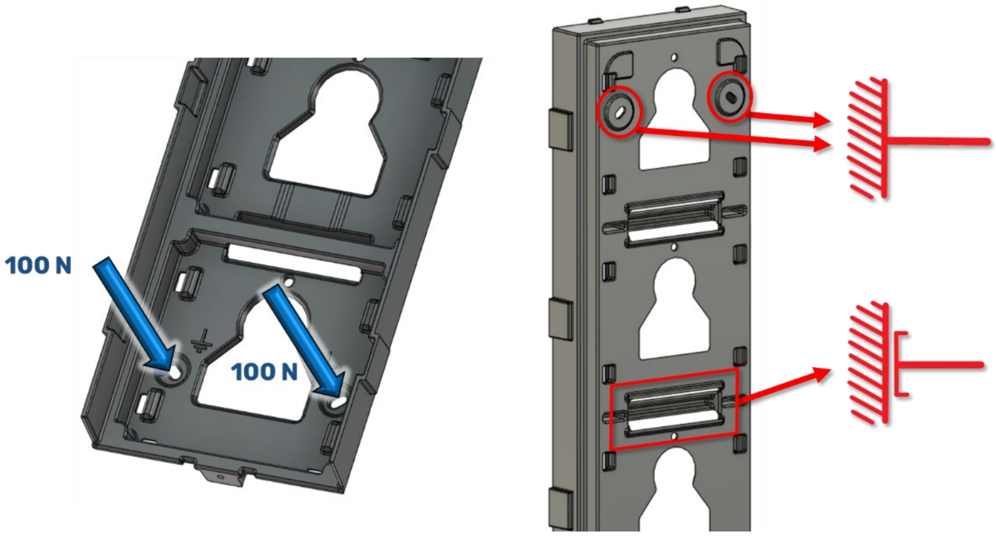



*Figure 49. Loads and constraints chosen for GD study.*

Furthermore, together with the company's engineers, it was decided to apply a safety factor of 1.2 and as an objective to achieve both mass minimisation and rigidity maximisation with both materials.

The original chassis is made using a die-casting process. The production process for the Zamak 15 material is therefore the same as the one used in Fusion 360. For the ABS polymer, on the other hand, the aim is to obtain a prototype frame using an AM process (Table 6).

*Table 6. Production constraints and aims of the GD study.*

| **Materials** | **Case Study** | **Aim of the study** | **Manufacturing Methods** |
|---|---|---|---|
| Zamak 15 | 1.1 | Min. Mass | Die Casting<br>Unrestricted |
| | 1.2 | Max. Stiffness | Die Casting<br>Unrestricted |
| ABS Polimer | 2.1 | Min. Mass | Additive |
| | 2.2 | Max. Stiffness | Additive |

The results obtained for the Zamak 15, shown in Figure 50, have shape features that are common to all generated models. Therefore, the structures of the new frame will be based on these shared features.

Firstly, one of the recurring structures is the 'H' shape: in some it is more evident, as in Figure 50b and Figure 50c, in others it is intrinsic to the truss structure, such as the frame in Figure 50a. This geometry is fundamental because it shows the possibility of eliminating the slots for the cable passage, making the structure in the central area much simpler than the original model.

From the truss structures present for all the cases performed, an innovative geometry can be derived in the first place, the only limitation of which is that of physical realisation using traditional production methods (Table 7). From these results, there is also a key element for the design of the prototype: the structure must maintain the connections between the frames on the Y-axis, with different geometries depending on the case.

Following these considerations, a prototype will be developed that recalls these characteristics and is actually feasible using the traditional production processes associated with the Zamak 15 material. This further step will also make it possible to add the pins useful for interlocking the electrical modules.

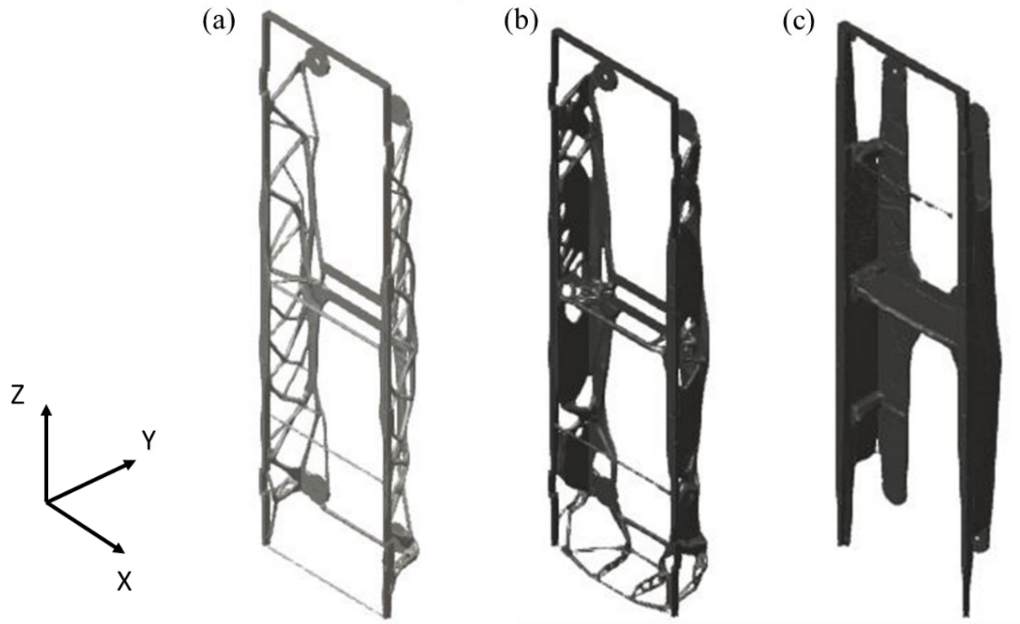



*Figure 50. Outcomes proposed by GD study for Zamak 15 frame. Manufacturing method: a) Unrestricted, b) Die casting Y+ and c) Die casting Y-.*

*Table 7. Constraints for Zamak 15 frame outcomes shown.*

| | | | |
|---|---|---|---|
| **Manufact. Method** | Unrestricted | Die Casting Y+ | Die Casting Y- |
| **Aim of the study** | Min. Mass | Mass assign | Min. Mass |
| **Max. Displacement** | 0 mm | 5 mm | 5 mm |

The results obtained for the ABS polymer (Table 8) also present common features for all generated models. The geometries for the development of the new prototype will be based on these.

The slots for the cable routing, even when using ABS polymer, can be more extended than in the basic model of the frame, so less material will be present in the central area of the frame (Figure 51c). The 'H' structure of the frame is retained; however, it is also necessary to integrate the intermediate cross members connecting the outer frames between the different modules.

Compared with the frame generated with Zamak 15 material, the algorithm, to compensate for the lower bending strength of ABS, does not present truss structures, but resorts to important and extended ribs in which the material is placed on the main frame tension lines Figure 51a and Figure 51b.

As a result of these considerations, a prototype will also be developed for the ABS frame that recalls these characteristics and is realisable by means of AM processes.

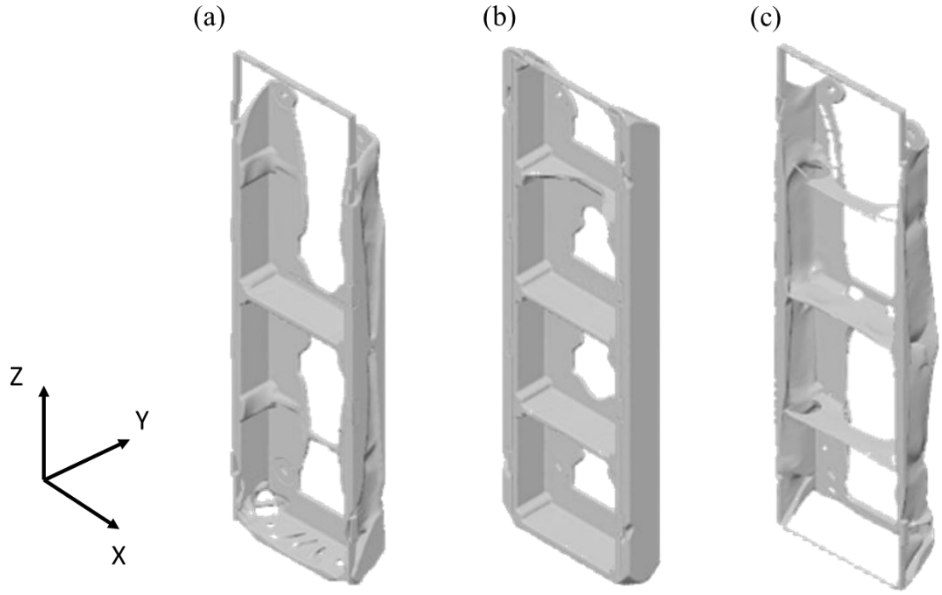



*Figure 51. Outcomes proposed by GD study for ABS frame. Manufacturing method: a) Unrestricted, b) Die casting Y+ and c) Die casting Y-.*

*Table 8. Constraints for ABS frame outcomes shown.*

| | | | |
|---|---|---|---|
| **Manufact. Method** | Unrestricted | Die Casting Y+ | Die Casting Y- |
| **Aim of the study** | Min. Mass | Mass assign | Min. Mass |
| **Max. Displacement** | 0 mm | 5 mm | 5 mm |

The next study focuses on the downstream design step of the Generative Design methodology. The difference between the commercially available solution and the solution influenced by the solutions of the generative algorithm will then be assessed. The advantage of having no experience in the field, but relying on pure engineering and mathematical rules, allows the algorithm to propose innovative and complex solutions, which deviate greatly from the characteristic structures of classical design. At the same time, the system does not yet can find solutions to mathematical problems that may be created by meshing complex structures. Very often the conflict results when singularities occur due to the approximation of articulated shapes with finite elements. In these cases, the experience of a designer allows these problems to be avoided.

## 2.4.1. Metals outcomes by means Generative Design approach and designer experience

Figure 52a shows the prototype developed for the material Zamak 15. The structure was defined by comparing the results obtained from the GD models illustrated previously. The geometry has the same overall dimensions as the original frame (Figure 52b), so that it can be adapted to the elements connected to it. The positions of the module attachments, both inside and outside, have been retained. The attachment point of the outer shell is retained in the lower area of the frame. The support areas and screw attachment points remained in the same positions, consistent with the simulations carried out in the Generative Design environment.

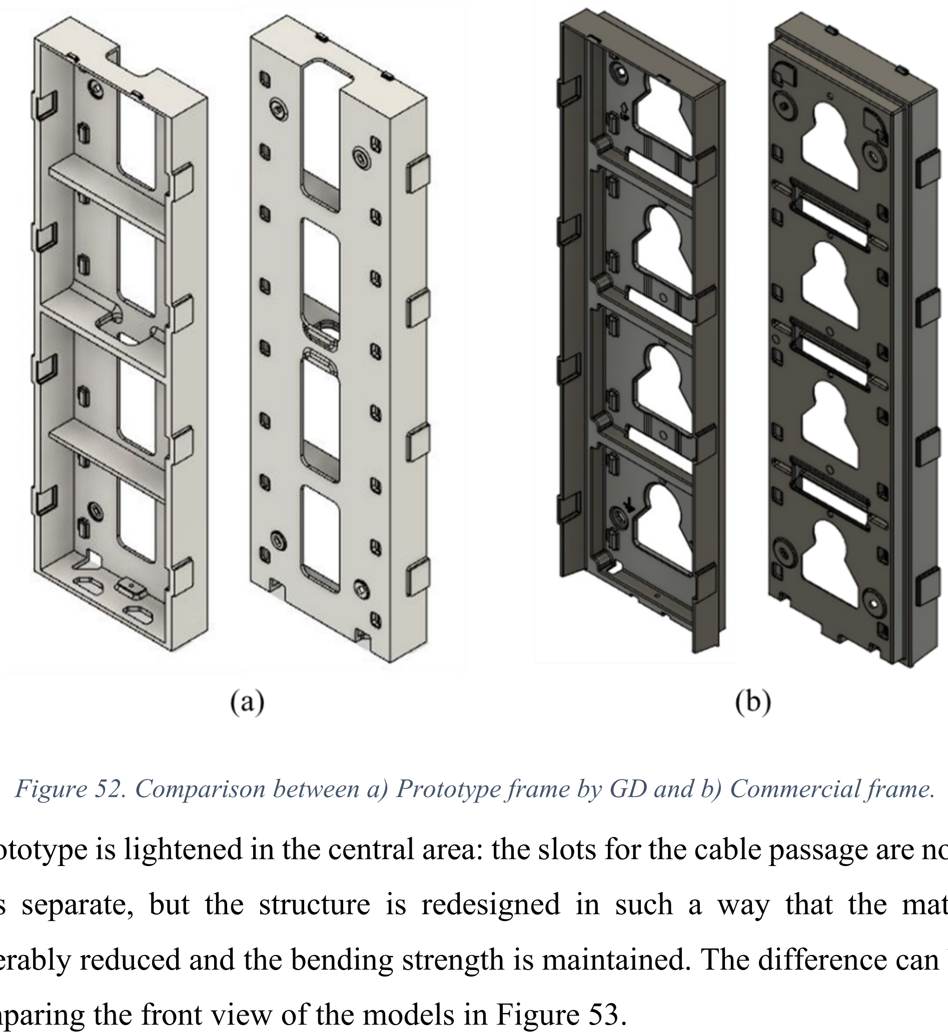
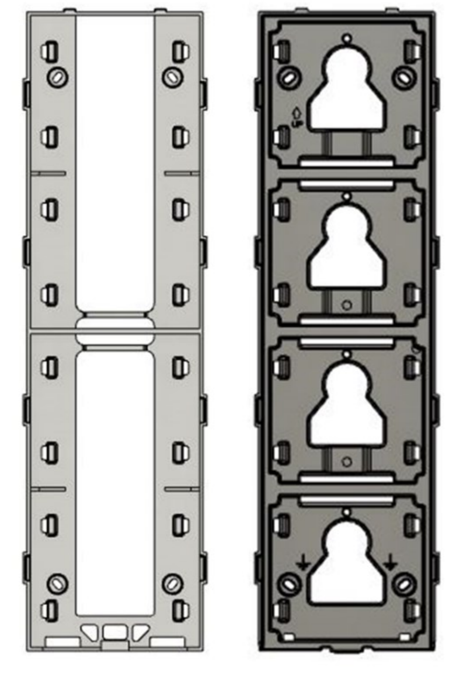


*Figure 52. Comparison between a) Prototype frame by GD and b) Commercial frame.*

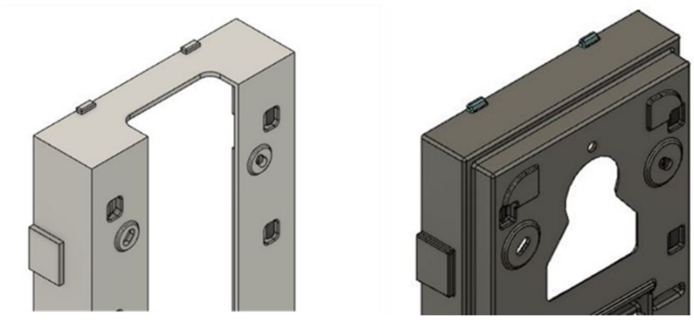
The prototype is lightened in the central area: the slots for the cable passage are no longer seen as separate, but the structure is redesigned in such a way that the material is considerably reduced and the bending strength is maintained. The difference can be seen by comparing the front view of the models in Figure 53.



(a) (b)

*Figure 53. Front view of a) Prototype frame by GD and b) Commercial frame.*

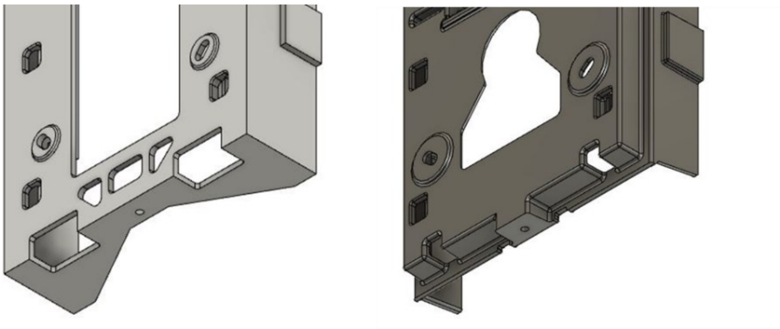
The connection between the lateral frames is ensured in the upper, middle and lower zone of the frame. The upper zone is designed to obtain a cut-out since in many simulations this is a zone without material, as in Figure 54.



(a) (b)

*Figure 54. Detail of the upper part of a) Prototype frame by GD and b) Commercial frame.*

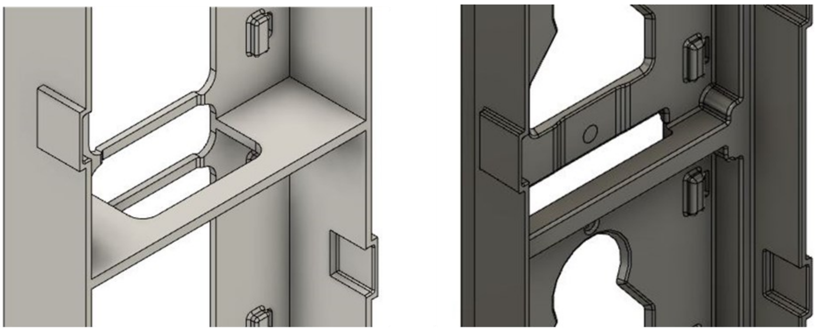
The lower area is designed to achieve both a useful geometry to locate the screw for attaching the outer shell and to remove material where it is not needed, as shown in Figure 55.



(a) (b)

*Figure 55. Detail of the bottom part of a) Prototype frame by GD and b) Commercial frame.*

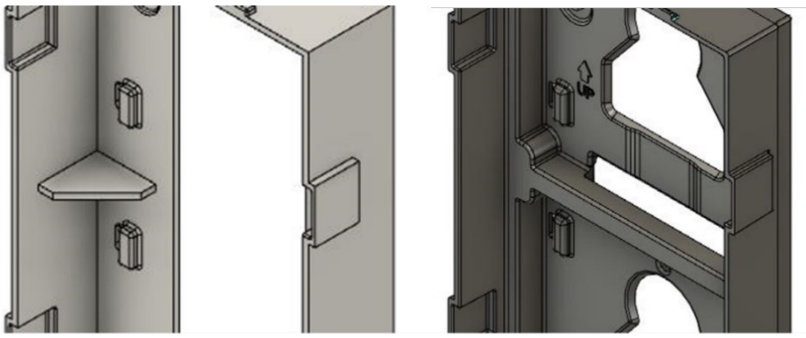
The central area has a crossbar connecting the lateral frames and two smaller crossbars that also act as supports on the wall, as shown in Figure 56.



(a) (b)

*Figure 56. Detail of the central part of a) Prototype frame by GD and b) Commercial frame.*

The ribs assumed in the areas between the upper and middle crossbeams and between the lower and middle crossbeams are designed to stiffen the structure in areas where crossbeams were previously present (Figure 57).



(a) (b)

*Figure 57. Detail of ribs of a) Prototype frame by GD and b) Commercial frame.*

As shown in Table 9, the developed prototype has a mass of 0.66 kg, approximately 0.14 kg less than the original model, with an increase in maximum stress while keeping the displacement value unchanged.

*Table 9. Specs comparison between GD prototype and commercial frame.*

| Frame | Commercial Frame | Prototype from GD |
|---|---|---|
| **Material** | Zamak 15 | Zamak 15 |
| **Mass [Kg]** | 0.80 | 0.66 (-18%) |
| **Max. Stress [MPa]** | 78 | 114 (+46%) |
| **Max. Displacement [mm]** | 0.2 | 0.3 |

### 2.4.2. Polymer outcomes by means Generative Design approach and designer experience

The prototype in ABS polymer, shown in Figure 58, presents many features already highlighted in the prototype in Zamak 15 material, thickening some surfaces to maintain adequate strength. The positions of the attachments of the different modules, both in the central area and on the sides of the frame, have remained unchanged, as have the screw positions with reference to what was done in the simulations in the Generative Design environment.

The slots for the cable routing are modified and enlarged compared to the chassis on the market, but unlike the prototype in Zamak 15 they are not completely eliminated. There is again the central crossbar and the wall bearing points in the central part of the frame.

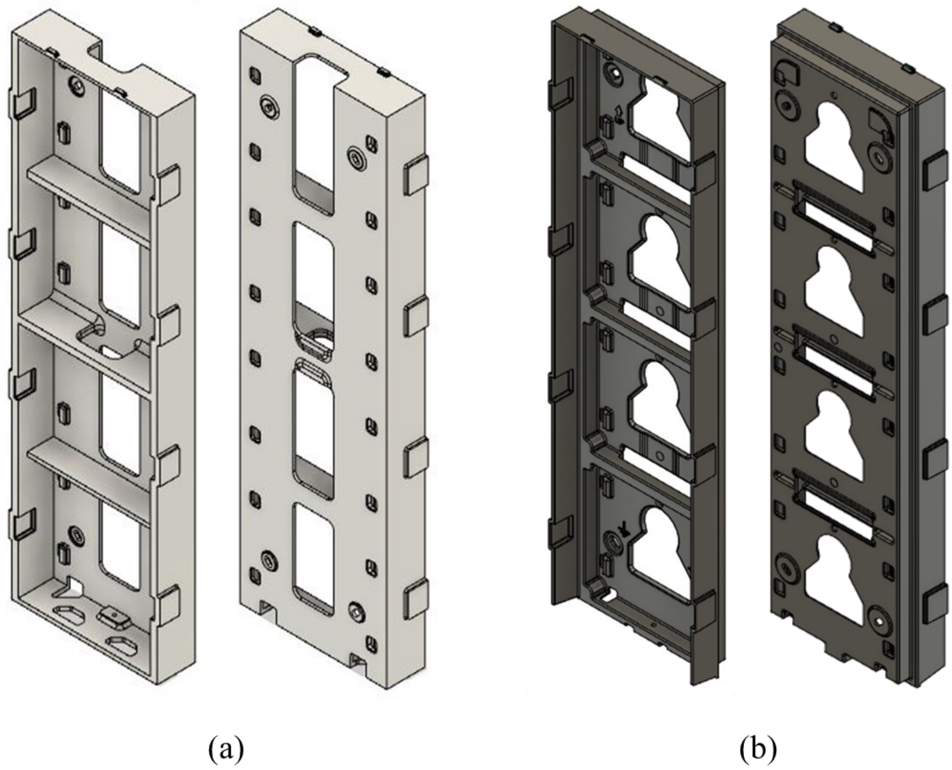
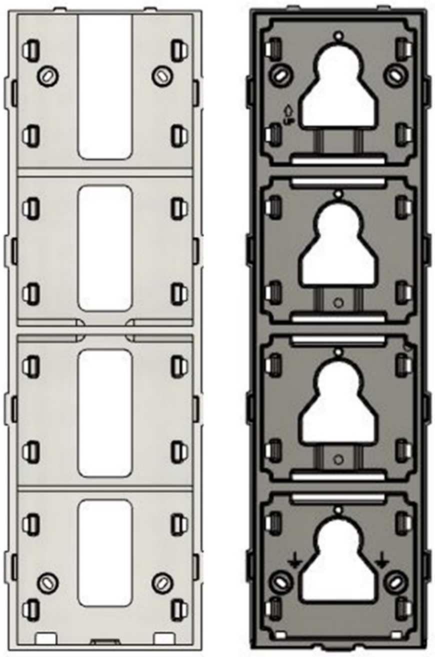


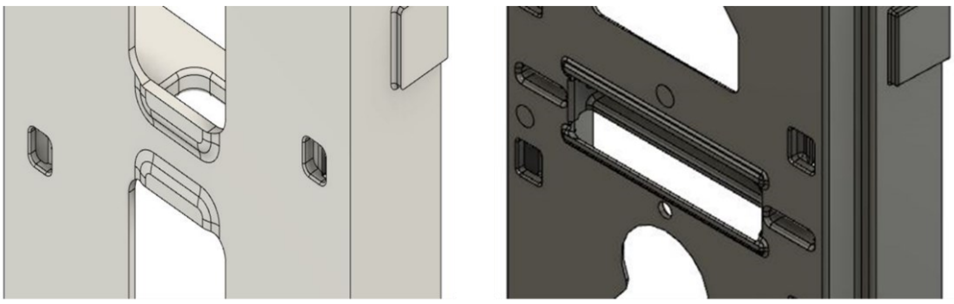
*Figure 58. Comparison between a) ABS prototype frame by GD and b) Commercial frame.*

Figure 59 shows a comparison with the initial geometry of the central area of the frame, while Figure 60 shows a detail of the support points with a new geometry.



(a) (b)

*Figure 59. Front view of a) ABS prototype frame by GD and b) Commercial frame.*



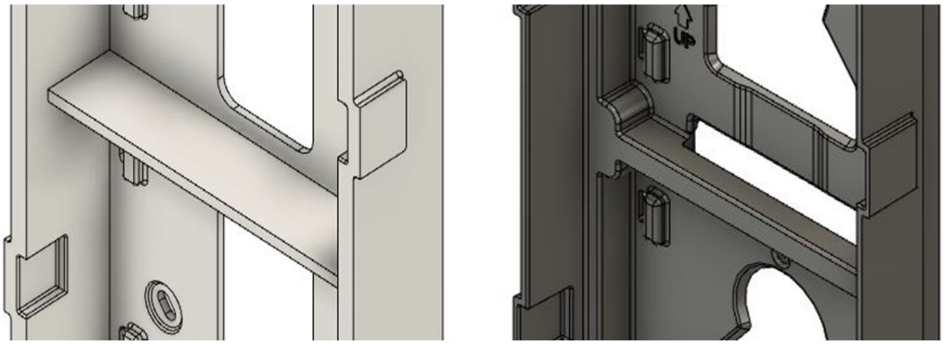
(a) (b)

*Figure 60. Detail of supports of a) ABS prototype frame by GD and b) Commercial frame.*

The support areas and screw positioning areas were changed because of the FE analysis: this detail was not detected by the Generative Design algorithm.

In general, it was necessary to impose a larger radius than for the Zamak 15 material to avoid critical points with reduced strength. A larger radius was also imposed in the central crossbeam to reduce the stress values.

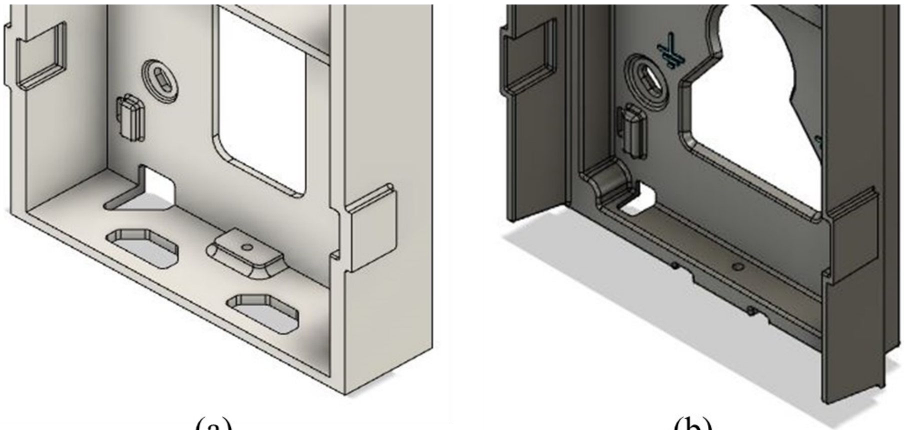
Another important consideration concerns the intermediate cross-members: these are remodelled for the new prototype since, for the ABS polymer cases generated, they played a key role in the structure. They are compared with those in the initial model in Figure 61.



(a) (b)

*Figure 61. Detail of the central part of a) ABS prototype frame by GD and b) Commercial frame.*

The lower zone presents, as before, the attachment point of the outer shell by means of a screw and has some slots to reduce the material but maintain rigidity based on the geometries obtained from the simulations in the GD environment. Figure 62 compares the lower zones of the prototype and the original frame.



(a) (b)

*Figure 62. Detail of the bottom part of a) ABS prototype frame by GD and b) Commercial frame.*

The results obtained from the FE simulations make it possible to assess the strengths and weaknesses of the two proposed prototypes. Although to be considered at an early stage, the two models present certain characteristics that can lay the foundations for the in-depth development of an optimised frame model.

Table 10 shows the mass, stress and deformation data of the two prototypes compared with the characteristics of the commercial frame.

*Table 10. Specs comparison of commercial, Zamak 15 and ABS frame.*

| Frame | Commercial | Zamak 15 prototype | ABS prototype |
|---|---|---|---|
| **Mass [Kg]** | 0.80 | 0.66 | 0.22 |
| **Max. Stress V.M. [MPa]** | 78 | 114 | 53 |
| **Max. Displacement** | 0.2 | 0.3 | 11 |

As for the prototype in Zamak 15, the result respects all the limits imposed by the Generative Design methodology. The mass is lower than the original model: 0.66 kg compared to the initial 0.80 kg, a reduction of approximately 18%. Considering slightly higher stress and deformation values, but still acceptable, the Zamak 15 prototype was identified by the company as a possible base frame to obtain an alternative to the existing model.

Considering the ABS polymer prototype, the maximum stress is well above the material's yield strength limit of 20 MPa. Having created a redesign more consistent with classical production methods for polymer components has effectively negated the advantage of the solutions proposed by Generative Design. This is despite having defined constraints within the algorithm concerning the production technology. It can therefore be seen that the production parameters managed as constraints are still at the beginning of their evolution within the GD approach. In fact, the presence of certain parameters in Fusion 360 does not however allow the generation of geometric solutions that are always feasible, relegating Generative Design to an early state of design that cannot take the place of a designer, but helps him to evaluate complex alternatives, but above all innovative and attractive to the market.

## 2.5. Generative Design versus Topology Optimization

Another fundamental point for establishing Generative Design within the DfAM methodologies was the study and comparison with Topological Optimisation. The juxtaposition of the two approaches made it possible to find similarities and differences that lead to defining two different design methodologies in terms of workflow and use within the design phase. Topological Optimisation is used in the design when one already has prior experience in the design of the study component. This is essential because the component already has a well-defined form from classical design practices, aided by CAD methodologies. In fact, the design of components using CAD software restricts the arrangement of material according to well-defined functions such as extrusions of known shapes, cut-outs, standardised holes and so on. The OT takes as input a set of geometric and mechanical parameters already well defined by CAD software and translates these as constraints. In fact, all software that proposes this methodology has the initial 3D shape of the component as a geometric constraint, and from this the algorithm begins to remove material where there are regions of low load, i.e. where stress is lower, through iterations that include FE analysis. For this reason, one of the most important aspects is the resolution of the mesh elements: if the number of elements is high, the quality of the solution improves, but increases the number of iterations and thus the computational time. These approaches do not allow the creation of material outside the volumetric constraint. Few research has been done on the introduction of production constraints, which have always remained on the side-lines of the TO treatment, compared to the search for new mathematical approaches for the OT. Another characteristic of the TO is the proposal of a unique geometric solution: this is because the algorithm has the component geometry as its main input and constraint, which is then considered as the domain of the optimisation problem. The result is therefore a single geometry defined within the starting geometry, as shown in Figure 63.

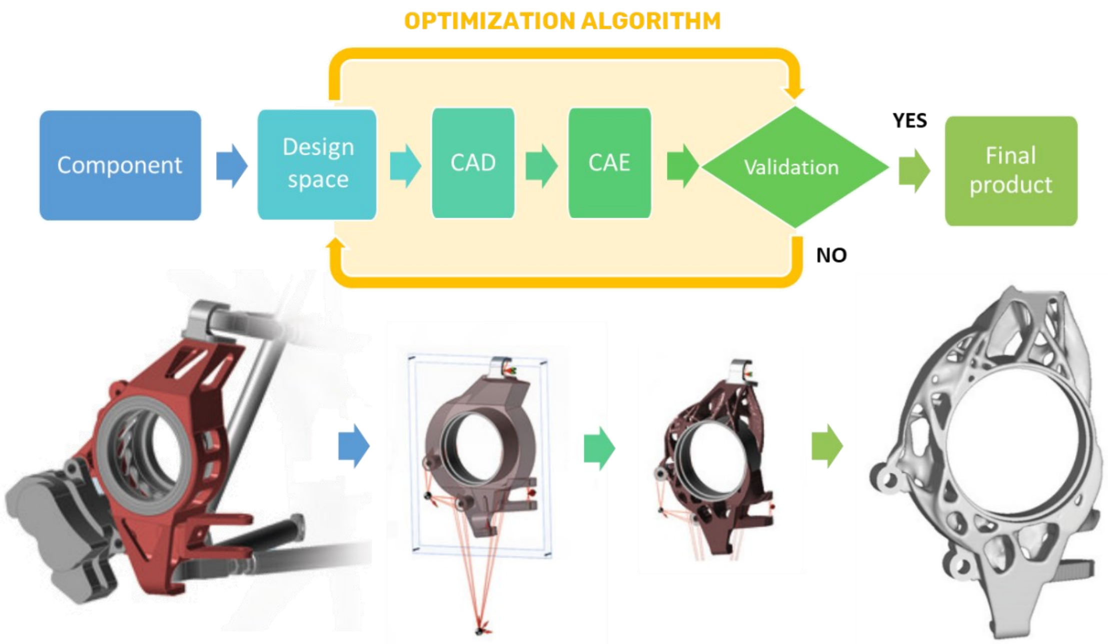



*Figure 63. Workflow of the optimization approach.*

Generative Design, on the other hand, makes its main contribution in the initial phase of component design (early-stage design), when only the functionality of the object is known, but not a previous, already designed form. In fact, in the GD, the input data mainly concern the obstacle volumes (geometries belonging to other components connected to the one to be optimised or volumes that are not accessible because they are used for assembly or for the movement of the component) and to be preserved (geometries that are essential for the correct functioning of the component in the assembly, including man). Also very important is the integration of certain parameters inherent to manufacturing constraints into the GD algorithm, bringing a major innovation that is still in its infancy: that of bringing innovative DfAM methodologies closer to classical manufacturing technologies. Another difference from TO, which creates a single form solution, is the GD's ability to generate multiple design solutions. In fact, the GD algorithm allows multiple input constraint options to be selected, so that multiple shape solutions can be generated from which the designer/engineer can choose according to the needs of the project. These different form solutions differ in the material chosen, the manufacturing technology, loads and constraints, and finally in the type of optimisation objective (maximising stiffness, minimising mass and buckling). Thus, the GD allows better integration between the workflow of the mathematical/optimisation part and the designer. In fact, with the use of the GD, the designer is assisted in the initial design of the component and his or her position remains central in the design steps: he or she chooses the starting and obstacle geometries, loads and constraints, and then moves on to materials and design technologies. In a second step, after the software presents the results, the designer must choose the best aesthetic and functional compromise, and then begin modelling the result to be manufactured. Figure 64 shows the workflow of the Generative Design methodology.

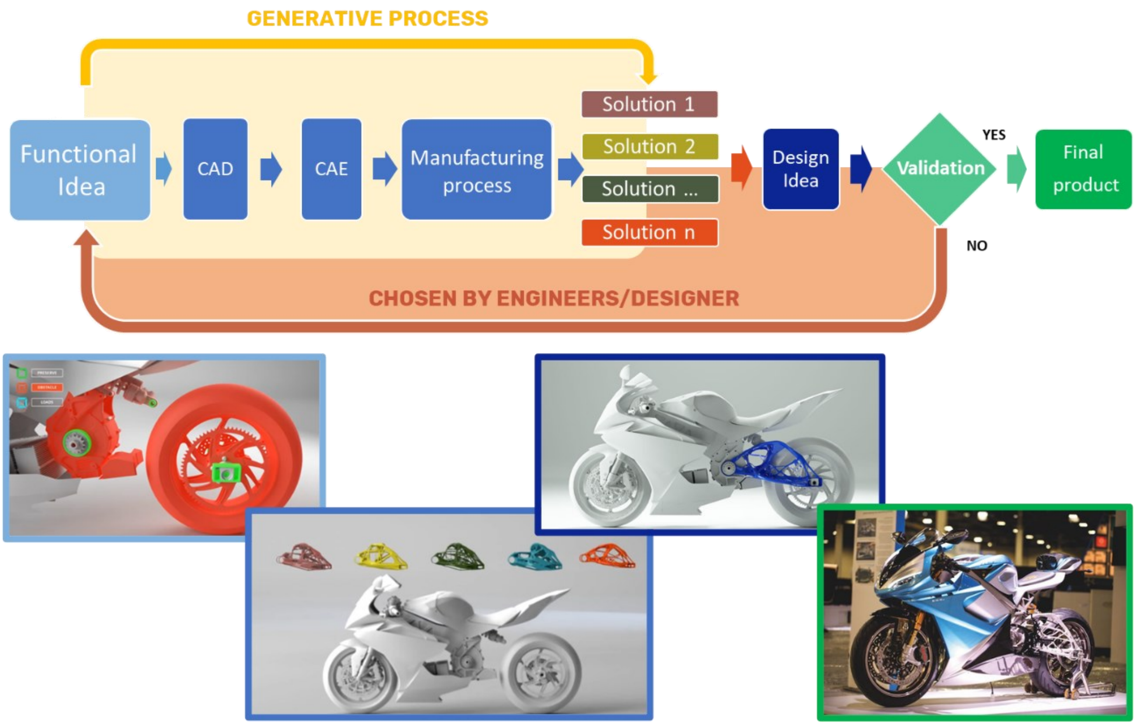



*Figure 64. Workflow of the Generative Design approach.*

The meeting point between the two methodologies is mathematical theory: in fact, optimisation is implemented according to various mathematical approaches (SIMP, Level set, ESO, BESO and so on). OT and GD base their algorithms on the same mathematical foundations, while varying in the input data, the information processing workflows and the form solutions generated. In fact, GD's algorithms are based on bioinspired geometry selection processes: designs are processed and compared with each other according to evolutionary logic, in which the best design 'survives' in the environment of design hypotheses by approaching the optimum more than the others, which are then discarded. In a practical view of the methodologies, the OT takes as input the geometry of the component and that remains as a constraint from which it cannot extend further; on the other hand, the GD starts from a numerous series of random solutions which are then evaluated and if necessary, eliminated because they are not compatible with the environment of hypotheses created by the designer.

The lack of such considerations of current product optimisation tools in the literature therefore led to the writing of the article 'Generative Design and Topology Optimisation of Disk Brake Floating Carriers' for the ASME 2020 International Mechanical Engineering Congress & Exposition IMECE 2020 November 15-19, 2020, Portland, Oregon, USA. In this paper, the major differences between TO and GD are presented and analysed through the case study of a brake caliper carrier. The objective of the research was to generate innovative solutions through the two methodologies of GD and TO and then evaluate the two design processes and their solutions. On a theoretical level, the solutions of both approaches lead to an important decrease in weight, while also proposing innovative and never considered designs, as shown in Figure 65.

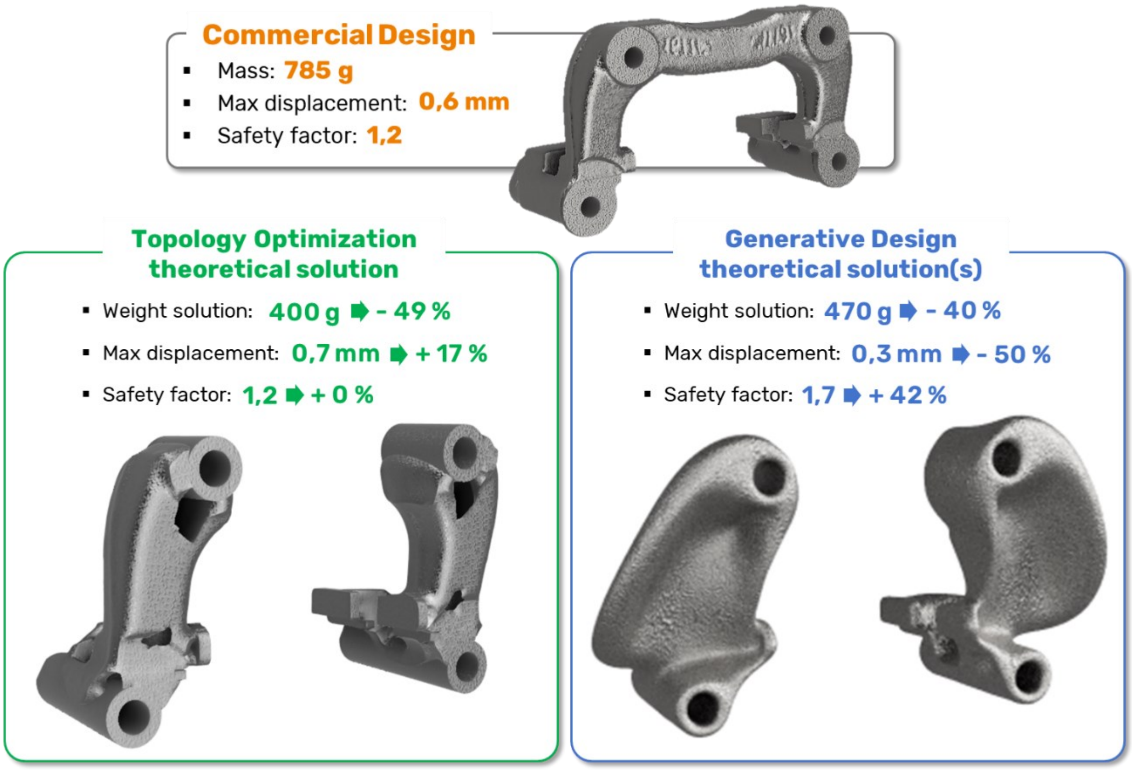



*Figure 65. Comparison between commercial design, Topology Optimization and Generative Design outcome.*

However, these form results present problems with the mounting of the component on the steering knuckle. These problems are easily solved with the addition of simple rails: an economical post-processing considering the significant material savings. This innovation of form also allows a step forward in the area of environmental sustainability. The complex geometries, however, tie production only to AM, which is a technology that is not feasible with the huge quantity of components to be produced at low cost, as can be seen in Figure 66. In this case, a future development could be the alteration of some secondary geometries to allow the use of more suitable manufacturing technologies and post-production processing. In this context, the figure of the designer, who is able to make the component more manufacturable by combining his skills with the purely numerical evaluations carried out by the algorithm, returns in importance.

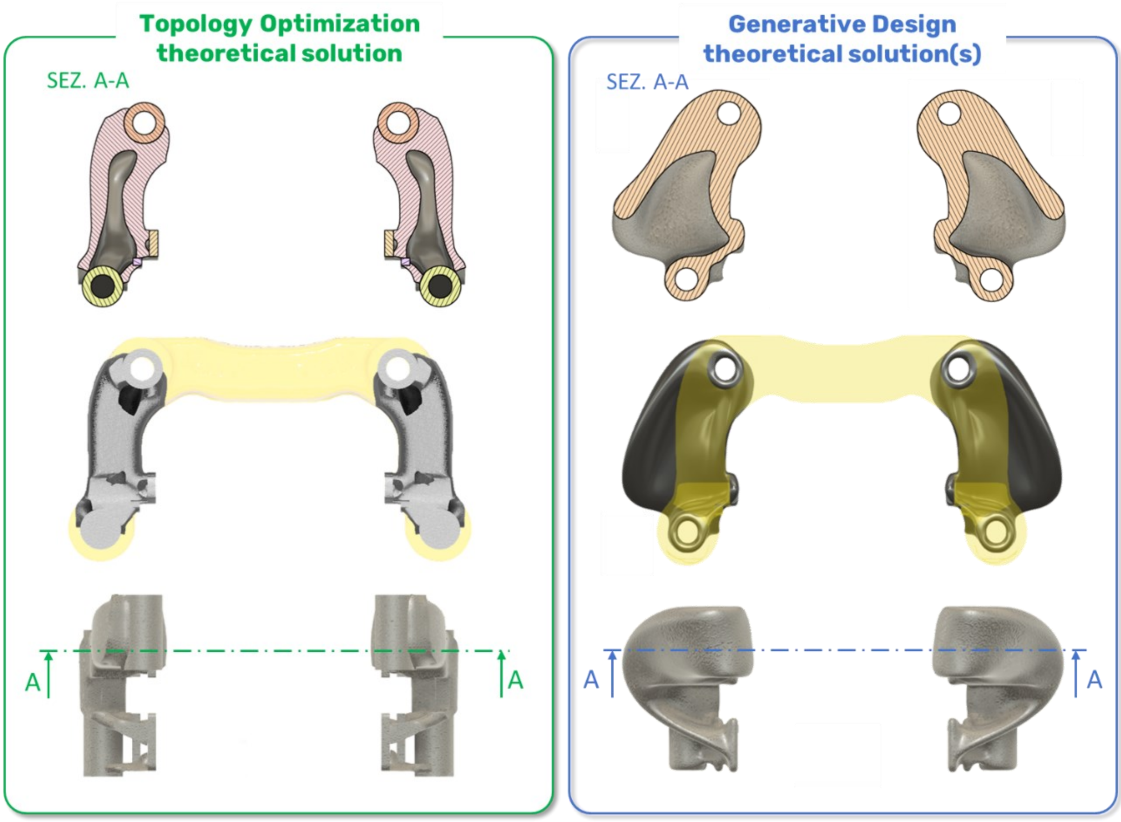



*Figure 66. Design comparison between GD and TO outcome.*

Equally importantly, differences were found between the classic and Generative Design methodology about the design workflow. In fact, as shown in Figure 67, in the case of classic design, each industrialisation step is sealed off: each professional only communicates with his colleague before and after his work step. Each professional has to evaluate the work of the previous steps, with the option of modifying the project and returning it to a previous work step. This action can be done several times by several professionals, uniquely and iteratively, wasting a great deal of time. In contrast, with the Generative Design workflow, already in the initial design creation phase, all professions are called upon to work multidisciplinary together. This is because the Generative Design process needs initial constraints and assumptions that include all aspects of design and industrialisation: from constraint geometries to production constraints. Similarly, the same professions will be called upon simultaneously to make a compromise choice for product validation. This new workflow makes it possible to train multidisciplinary professionals who have a complete view of the design and industrialisation process. In this way, downtime is reduced and the multidisciplinary of professionals is increased.

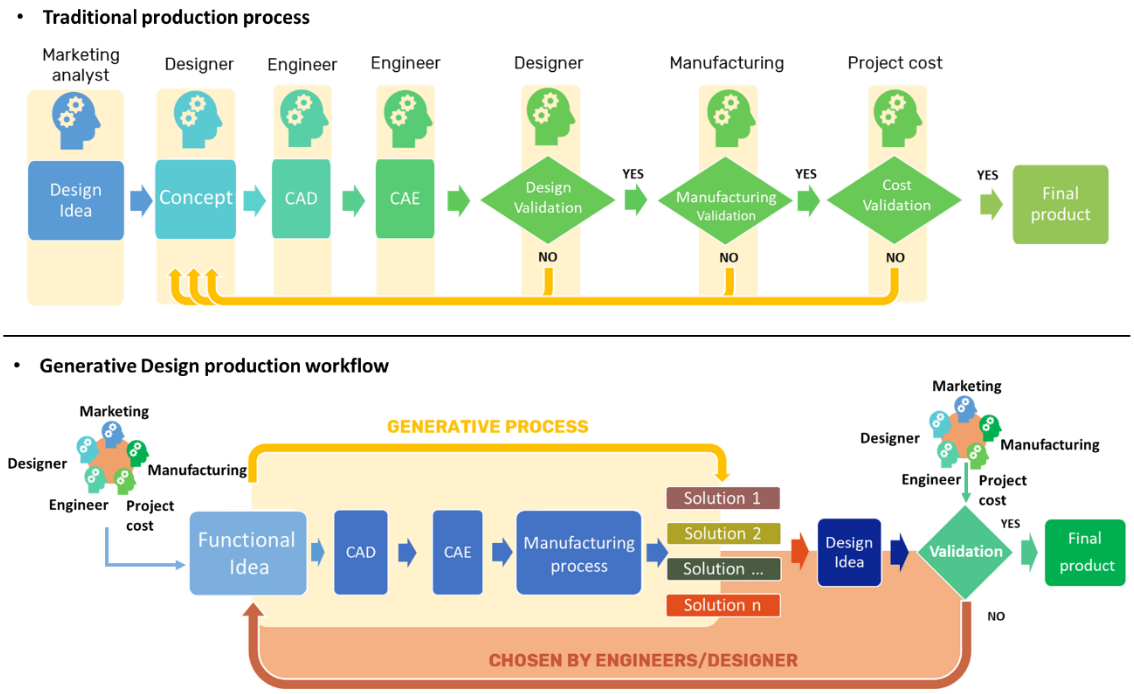



*Figure 67. Workflow comparison between traditional production process and GD production process.*

Thus, the GD tool, in addition to the advantages of the OT, allows to:

- Reduce design time even further, thanks to the possibility of proposing multiple results in a single simulation, as well as the presence of geometric and production constraints
- Increase the exploration of product design through the possibility of multiple results
- Obtain innovative, high-performance shapes, as the starting design is a non-binding option for the analysis
- Obtain results that can better meet production requirements through more detailed constraints

A schematic comparison within assessment of both the methods is shown in Table 11.

*Table 11. TO and GD schematic comparison.*

| **Property** | **Topology Optimization** | **Generative Design** |
|---|---|---|
| Set-up complexity | Medium: Starting from an existing product, the working volume is already present. The finite element analysis needs a high proficiency about mesh theories. | Medium: Starting from an early stage of design without an existing product as baseline. Mesh quality is managed by the software. Volume constraints are defined by the designer. |
| Execution speed | Low: In general, FEA is computed in local. So, the single solution creation depends on computer performance. | High: Because multiple solutions are generated, often GD algorithms work using cloud high computing. |
| Post processing complexity | Medium: The model must be remodelled using the mesh solution as a reference in most situations. | Low: Solutions are already parametrized also in solid model, easy to modify. |
| Multiple boundary set-up complexity | Medium: The load cases can be split in separate solutions and then redesigned to find the definitive shape. | Low: Multiple set up are quick to be solved but must be composed afterwards. |
| Implementing Creativity | Low: The tool depends completely on the starting volume derived from an existing component. | High: The number of solutions, given the proper conditions, can be high, thus proposing new designs never considered before. |
| Availability | High: There are several CAD software with an optimization workspace (compared to GD). | Low: There are few CAD software implementing this tool (compared to TO). |
| Versatility | High: With proper knowledge of the tool and the FE theory, many solutions can be found if the starting volume is varied from the existing product. This is not a Black-box workflow. A correct mesh definition allows complex and close-to-reality solutions. | High: Even when the starting volume is fixed the software can generate viable solutions working on the internal stress path, thus solving even incorrect starting shapes. When used for exploring new ideas, the tool gives its best offering a wide range of possibilities already considering other aspects, such materials, machining technologies, costs, that TO cannot. |
| Limitations | The tool is incapable of producing more than one single solution. The starting volume should also be able to be simplified, otherwise the tool is pointless. Manufacturing constraints aren't considered, so the design solution, sometimes, is impossible to produce. | The availability of the tool and the different way of thinking to implement the methodology are the biggest limitations. Some solutions are too complex for the chosen manufacturing method. The inability to manage mesh parameters, in some cases, limits the convergence of solutions. |

However, it is believed that the role of the designer is fundamental and even more important is the understanding that the proposed GD methodologies are to be used in the first design phase, to explore new forms and solutions. By combining the designer's experience and awareness of analysis with a fast and completely memory-free tool on the classic CAD design canons, it is possible to innovate with a new methodology and propose highly competitive products on the market with production advantages, as shown in Figure 68.


*Figure 68. Advantage of matching GD approach and technical experience.*

## 2.6. Compliant mechanism by means Topology Optimization approach

After addressing the study and evaluation of optimisation methodologies in the first research phase to give a definition to the Generative Design approach, these methodologies are applied in the industrial and medical fields. The aim of this research phase is to apply optimisation methodologies within more complex approaches for the design of innovative components. This is to investigate the possibility of optimising products and their mechanical behaviour through Design for Additive Manufacturing methodologies. All without resorting to changing materials or adding mechanisms or components.

In detail, methodologies were developed to propose products with different and specific characteristics and behaviour depending on the situation encountered. In particular, in the article "Design Innovation of Bicycle Frames Exploiting Topology Optimisation" in ASME International Mechanical Engineering Congress and Exposition, an advanced application of OT is studied. The case study comes from the contradiction inherent in MTB bicycles and which has created a strong demand from users and therefore attention from the market: maintaining high performance and comfort regardless of the type of terrain to be overcome: off-road or on road. Nowadays there are in fact only two frame morphologies on the off-road bike market to increase comfort and riding efficiency on rough terrain, with no middle ground. The first, to which the Hard Tail bikes (HT) comprise, has a single suspension system on the front fork. The second, to which the Full Suspension bikes (FS) belong, also features a kinematic mechanism that allows the chain stays to move in relation to the rear wheel. HT bikes have a rigid, lightweight frame that ensures low dispersion of the muscle power introduced. But at the same time, they have limited comfort where vibrations and impacts due to uneven terrain are transferred to the rider.  FS bikes, on the other hand, are more effective in isolating from the roughness of off-road tracks, but they dissipate a substantial part of the pedalling energy in the movement of the kinematics. Figure 69 describes the two frame configurations just mentioned.

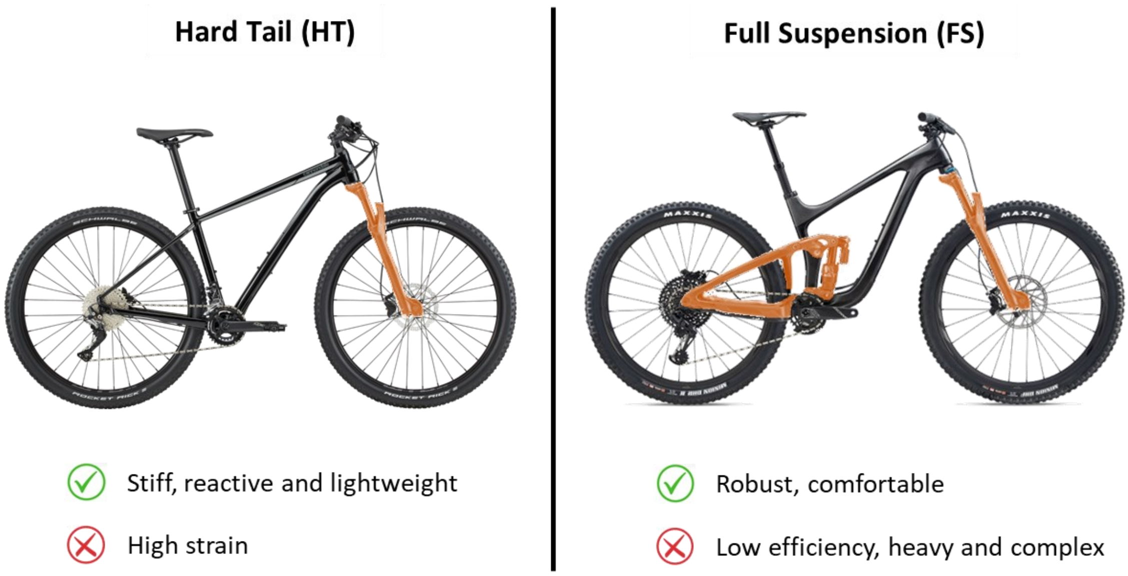



*Figure 69. Main MTB frame and suspension configuration*

In order to combine the positive characteristics of the two MTB types in a single mountain bike frame, it was necessary to study existing geometries, collect data from load simulations defined in the literature and develop a methodology with OT as the innovation tool. As a first step, a frame with characteristic geometries common to several models on the market was modelled using 3D CAD software. The reproduction of the operating behaviour of the frame is conducted by means of the FE method and with first-order beam elements. The 6 load cases with the greatest relevance and accuracy in the literature and industry were then chosen for the analysis of MTB frames, where an example of off-saddle pedalling is shown in Figure 70.

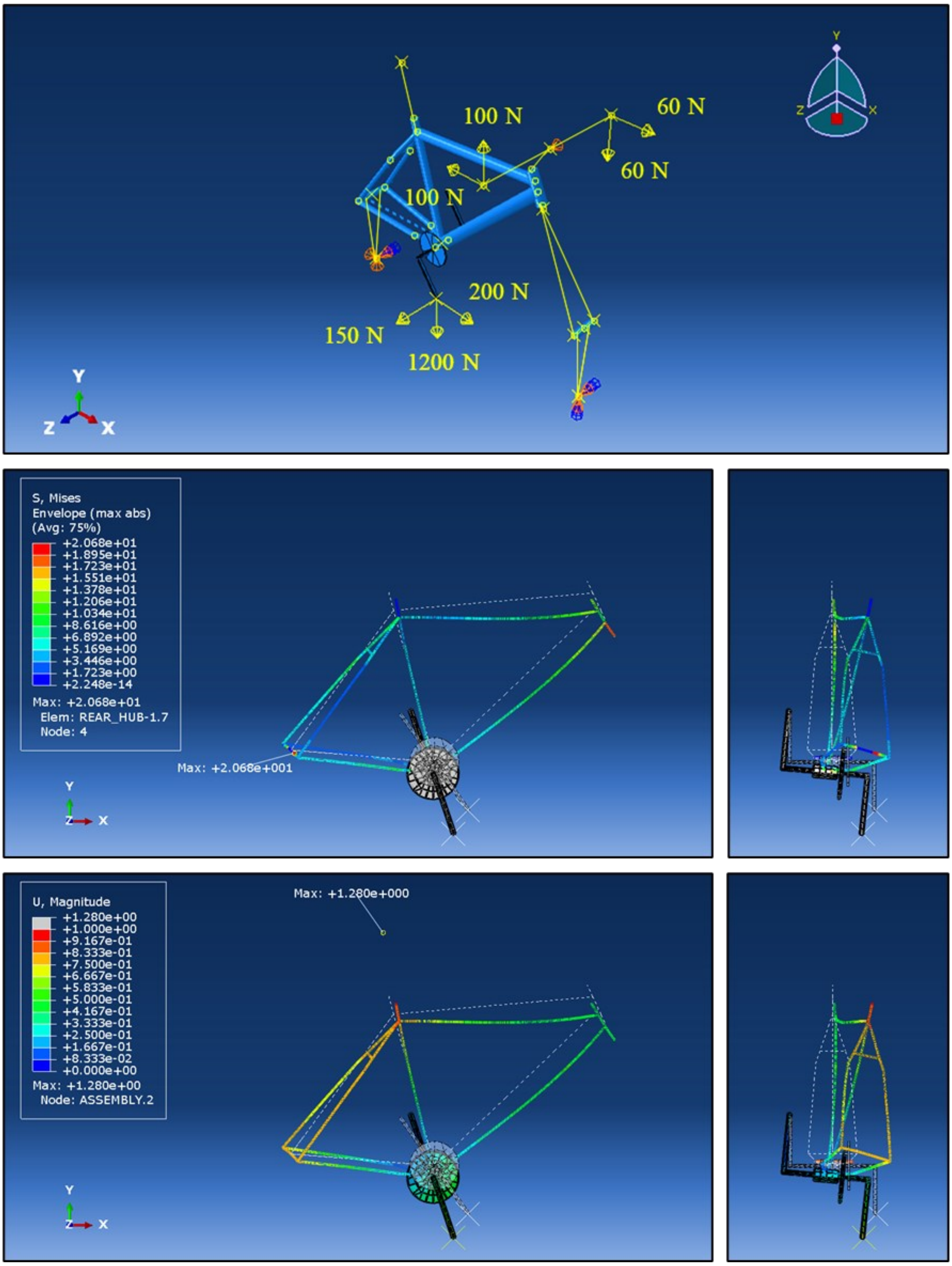



*Figure 70. Example of off-saddle pedalling FE analysis.*

Several external factors have been excluded due to their low influence on the overall system. These forces include the rolling resistance of tyres, the effect of air friction and tyre deformation. In contrast, the inertial loads resulting from the accelerations of the rider's centre of mass and the frame were not neglected. In the various Load Cases (LC) they took the form of multiplying factors for the forces involved. Without representing complex dynamic situations, it was thus possible to model static tests and derive stress and deformation indices to which subsequent simulations could easily refer. The main problem with this simplification lies in the fact that the control of vibration propagation and damping is precluded. As a result, the reliability of the structure in terms of the distance between natural frequencies and induced vibration modes cannot be identified.

Having the knowledge of working on a reliable model, it was possible to proceed with a local optimisation, which is much more manageable than studying the entire structure. The frame, therefore, was divided and analysed into several characteristic parts, as shown in Figure 71.

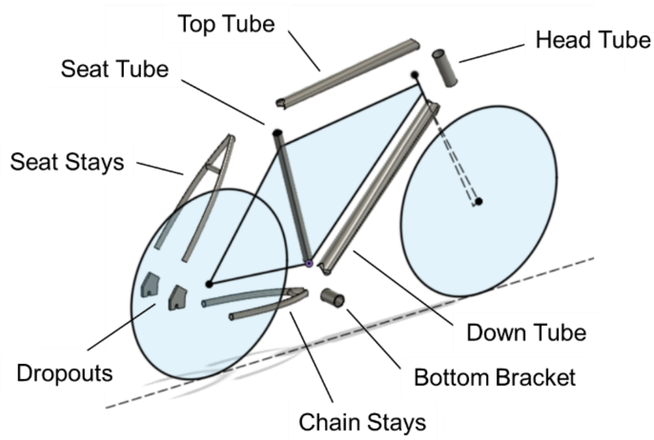



*Figure 71. Bicycle main component considered.*

In order to identify the part to be improved, it was necessary to take into account deformation characteristics, internal stress distribution and the way loads were applied. It was therefore necessary to have an indicator that incorporated all these properties, avoiding the directionality of stiffness. Taking a cue from the literature, it was decided to analyse each frame constituent in terms of strain energy. It represents the ability for an element of the frame to store elastic energy (i.e. the stiffer the element, the less the storing capacity). Knowing that the vector of the applied forces [F] and the vector of the displacements [X] are related through the stiffness matrix the [K] (Eq. 1), the strain energy is defined as in Eq. 2.

$$[F] = [K][X] \tag{1}$$

$$E = \frac{1}{2}[F][K] = \frac{1}{2}[X]^T[K][X] \tag{2}$$

The effects of each load condition were then compared in percentages (Figure 72).

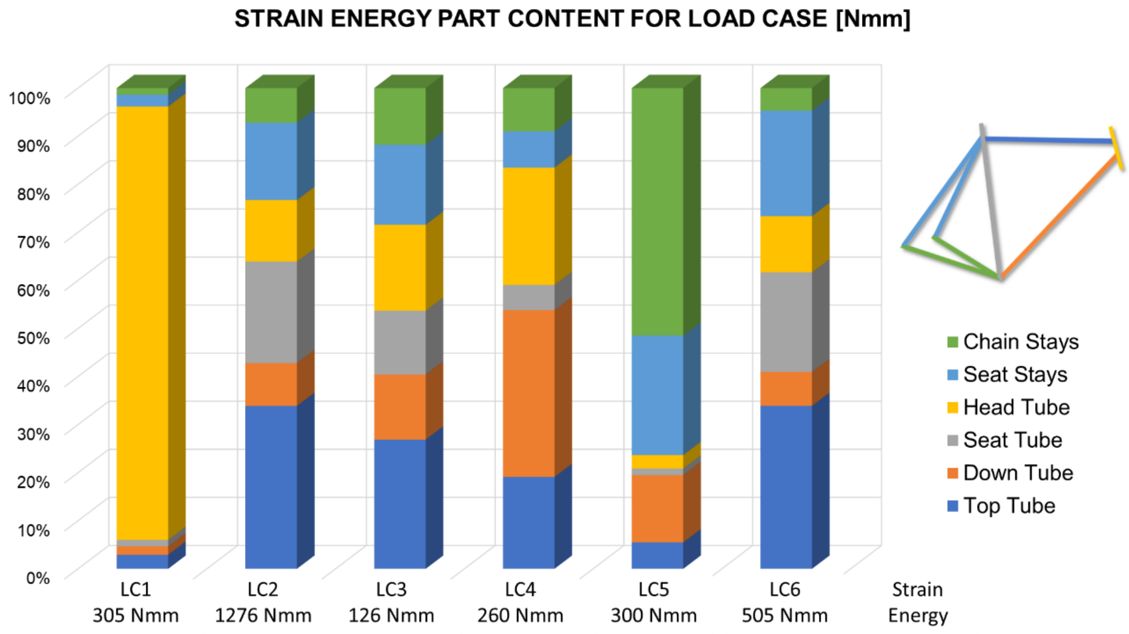



*Figure 72. Diagram of strain energy quantity for each load case considered.*

The required component will have the task of improving the performance of a standard frame, aiming at the benefits offered by the suspension systems without excessively reducing the overall stiffness. The component will therefore be able to absorb most of the deformation energy induced by shocks and show little flexibility during pedalling. Considering these considerations, the seat tube was chosen as the element to be optimised. In fact, observing the histogram in Figure 72, the features of this component are those that most closely align with the required specifications. The chosen element has a high extension and connections with other components that hinder its total optimisation. For this reason, the entire length of the vertical tube was divided into segments of 10 mm each and analysed, like the frame assembly, because of the deformation energy. Based on the preceding considerations and analysing the seat tube element with the same methodology, the region to be optimised was found to be 270 mm from the bottom bracket and had an extension of 80 mm, as shown in the graph in Figure 73.

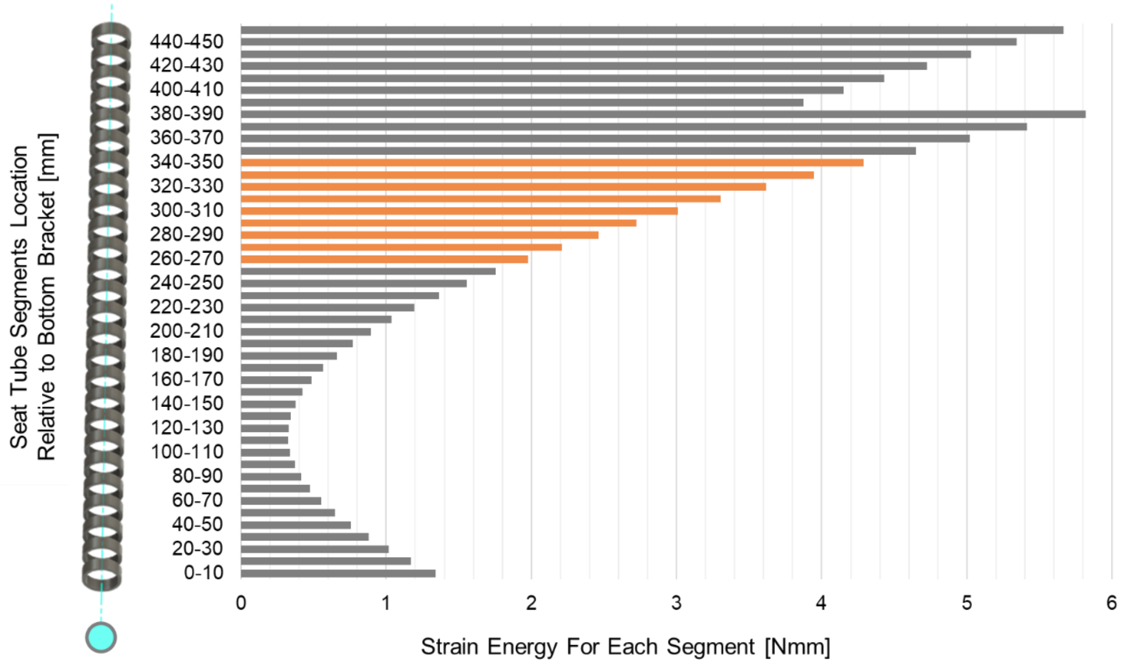



*Figure 73. Diagram of the strain energy for each segment considered.*

The internal presence of the seat tube gives rise to an increase in the resistance characteristics, the source of the graphic discontinuities in Figure 73. The same trend has been observed for the other load cases.

At this point, the optimisation of the component part was performed. The first step was to evaluate the use of GD or OT. The choice was the latter as its algorithms allow component optimisation according to the specifications input by the problem (strain energy, VM stress) and the fact that this optimisation could be iterated manually until component characteristics were achieved. In fact, the developed methodology allows new features for the frame to be created iteratively, increasing the number of elements to be analysed and optimised to achieve the goals. This process is not permitted in the GD due to its high degree of automation, which does not allow the iterations of the algorithm to be changed at different volumes.

Abaqus' Tosca optimisation suite was used for this study. Then an optimisation task was developed with SIMP algorithm and penalty factor p=3, a value recommended to produce robust results in static problems [149]. Compared to available alternatives focusing on strain energy and node stress, this technique offers the greatest operational flexibility and the possibility of setting up non-ordinary design variables on isolated regions.

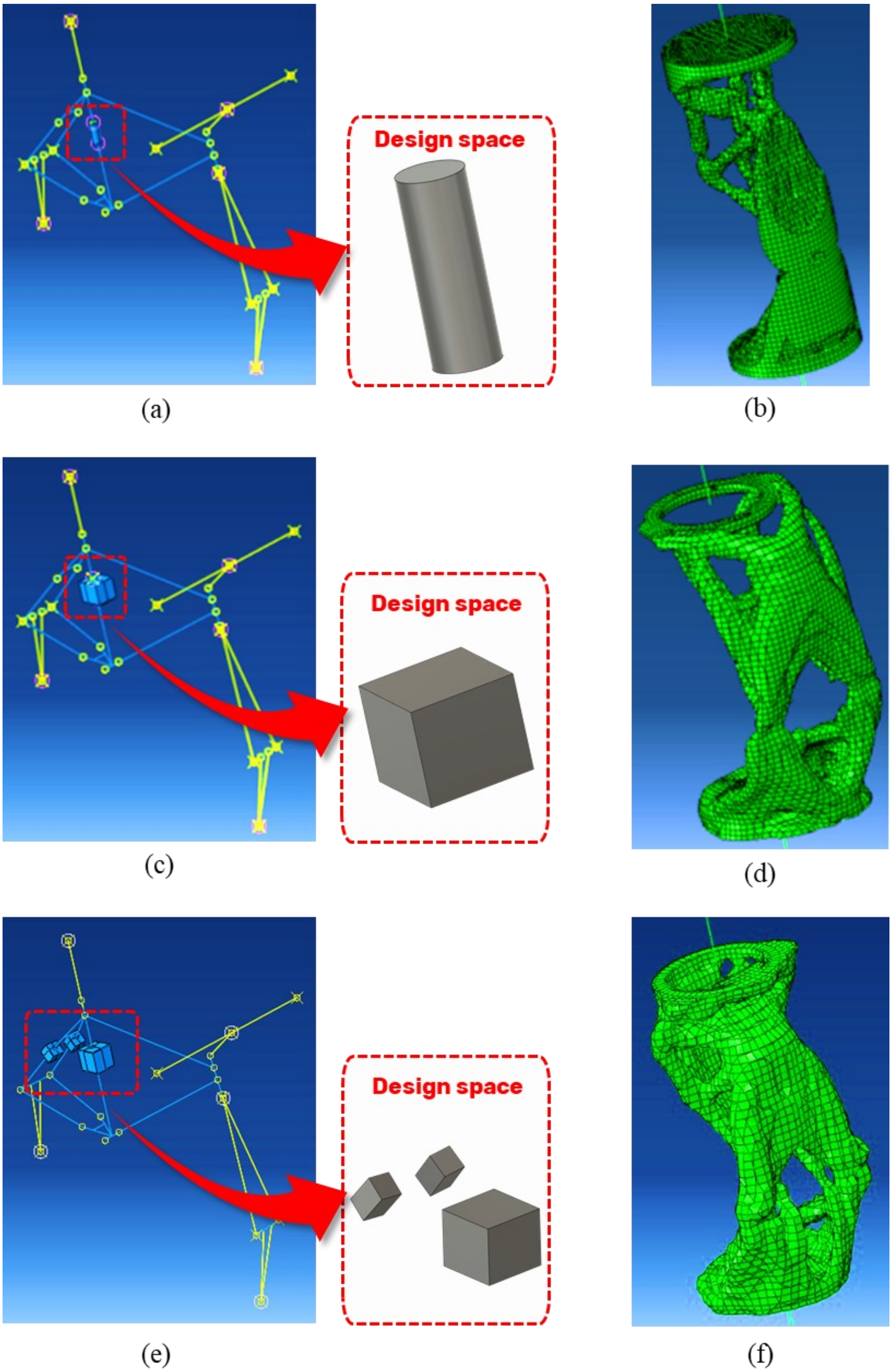



*Figure 74. TO outcomes for each design space considered.*

For the first iteration, as shown in Figure 74a, a design space equal to that of the original tube of approximately 28 mm was set and meshed with a hex-dominant algorithm. The rest of the frame was modelled with beam elements has been coupled with the 3D design space through Continuum Distributed Coupling. A symmetry constrain has been added along the axis of the entire MTB. The optimisation goal was set for the minimisation of VM stress. The result of the first iteration (Figure 74b) resulted in an increase in travel of 29% in the load conditions requiring greater damping and 2% for the conditions requiring greater stiffness.

In the second iteration, a larger initial design space was chosen, described with a 50x50 mm cube, visible in Figure 74c. In this solution, the increase in travel (Figure 74d) was 45% over the original frame in the conditions requiring greater compliance and 3% in the conditions requiring greater stiffness. The result, while satisfactory compared to the non-damped frame considered as the basis for development, is not remarkable when compared to the bi-damped systems on the market.

Continuing the iterative approach, the seat stays was chosen as the second optimisation area, in addition to the seat tube, as can be seen in Figure 74e. This component was also divided into segments to identify the most suitable part for optimisation. The combination of several optimised segments improves the performance of the entire frame. The final configuration therefore allows a rear stem displacement of 10 mm and at the same time a good stiffness, approximately 2 mm, in the conditions where non-deformability is required (Figure 74f).

*Table 12. Specs comparison between traditional frame and TO outcomes.*

| | **Load Case** | **Original Frame** | **Seat Tube Optimization** | | **Seat Tube + Seat Stays Optimization** |
|---|---|---|---|---|---|
| | | | **1st Opt.** | **2nd Opt.** | **3rd Opt.** |
| **Von Mises Stress [MPa]** | **LC2** | 42 | 196 | 227 | 265 |
| | **LC4** | 15 | 150 | 120 | 78 |
| **Rear Hub Displacement [Magnitude, mm]** | **LC2** | 0.5 | 2.4 | 4.0 | 10.4 |
| **Bottom Bracket Displacement [Magnitude, mm]** | **LC4** | 0.4 | 0.8 | 2.1 | 2.4 |

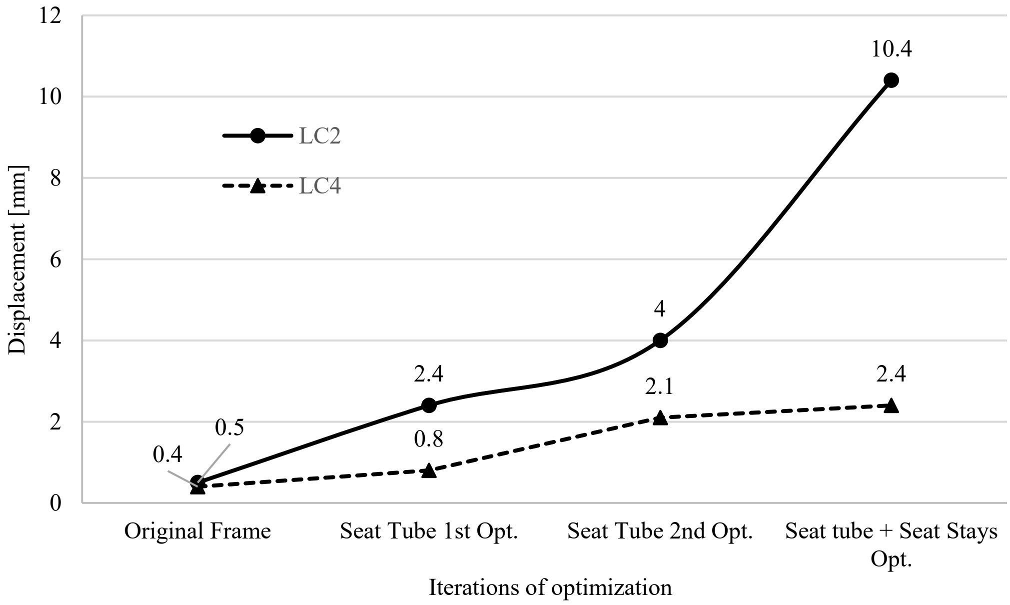



*Figure 75. Displacement comparison between Load Case 2 and Load Case 4.*

Table 12 shows the mechanical characteristics with respect to the two load cases LC2, where maximum displacement is required, and LC4, where maximum stiffness is searched for. After optimisation, the stress increases while remaining within the yield strength limits of the aluminium material. The displacement of the rear hub increases considerably for LC2 in the various iterations, while in LC4 the increase is relatively smaller. This methodology therefore makes it possible to separate the functions of a component by finding alternative solutions directly from the form of parts of the same component. As can be seen from the Figure 75, as the algorithm completes iterations, the more the frame performs specifically to the request given as input. Precisely because of this differentiation of functions, the core of the methodology has been defined as "functional optimisation". The definition captures the purpose of the approach, i.e. the ability to improve the behaviour of a component in diametrically opposite load situations by modifying its shape only. The proposed functional optimisation therefore departs from the methodologies exposed up to now, by considering different load cases but present at the same time and solved with the same optimised shape. The methodology is only applied in the field of static load cases. Therefore, important contributions such as fatigue, welded connections and corrosion have not been considered. Other limitations concern the production method of the optimised components: their complex shape only allows production by AM. The presented case study theoretically validated the proposed algorithm, shown in Figure 76.

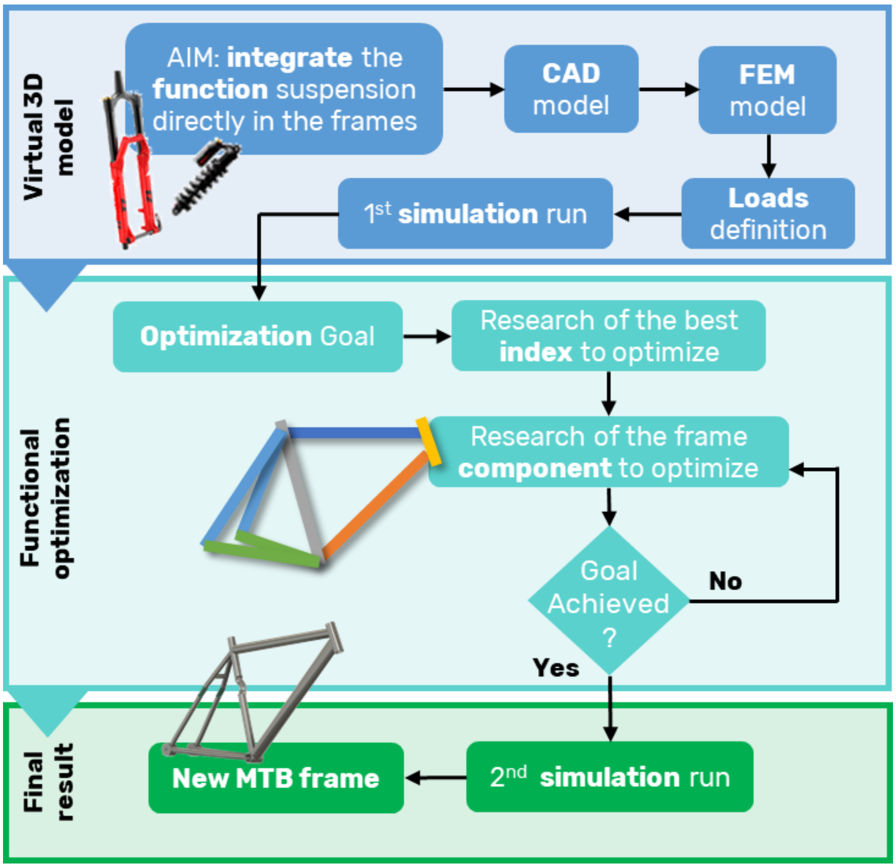



*Figure 76. Functional Optimization algorithm presented.*

# Chapter 3
# Application of optimisation methodologies in the development of innovative design approaches

## 3.1. Introduction and research of optimisation approaches in eco-design

In recent years, and especially nowadays, the importance of energy and environmental impact in the industrial sector is crucial. The energy crisis and, even before that, environmental sustainability has given great impetus to the search for alternative and innovative solutions to common energy-consuming production methods, such as those based on material removal. In this context, additive manufacturing technology is one of the most interesting: highly complex components are produced while consuming less and creating less material waste, especially in the production of metal components. At the same time, 3D printing can theoretically transform the supply chain in favour of local production and without the need for a spare parts warehouse. AM can also avoid the use and wear of tools and the handling of liquids due to lubrication. The interest in AM as a green technology is since it has been seen as a technology capable of reducing the impact of global manufacturing, which accounts for 22% of total energy consumption and 38% of $CO_2$ emissions [150], [151]. Compared to these advantages, this technology accounts for only 0.1% of total production [152]. It was therefore decided, in relation to methodologies acting in the field of AM such as OT and GD, to evaluate new research frontiers in the field of eco-design through an early Life Cycle Assessment (LCA) of the production of a gear using Laser Engineered Net Shaping (LENS) and Computer Numerical Control machining (CNC) technology. The research was presented at the 29th CIRP Life Cycle Engineering Conference under the title: "Comparative life cycle assessment of two different manufacturing technologies: laser additive manufacturing and traditional technique". The study carried out is of the “cradle to gate” method, i.e., it refers to a particular step in the gear life cycle, the characteristics of which are presented in Table 13. The processes from the extraction of the raw material to the manufacture of the product are therefore considered. On the other hand, the manufacturing processes of the CNC and LENS machines, the impact of gear use and the end of product life are not considered. This is possible because the object of study of both production methods is the same.

*Table 13. Gear specifications.*

| | Characteristics | Value |
|---|---|---|
| **Component** | Spur gear | |
| **Material** | AISI 4140 | |
| **Shape and mass** | Length | 25.79 mm |
| | Width | 25.78 mm |
| | Height | 4 mm |
| | Volume | 1.26 $cm^3$ |
| | Mass | 9.81 g |
| **Quality** | Average surface roughness | 1 µm |
| | Tolerance on tooth thickness | 0.05 mm |

The procedure followed is based on the ISO 14040 standard. The first step concerns the creation of the Life Cycle Inventory: a basic activity to quantify the flow in and out of the system. The flow, shown in Figure 77, includes the use of raw materials and energy and their interaction with the external environment, and the data is taken at the company's production plant.

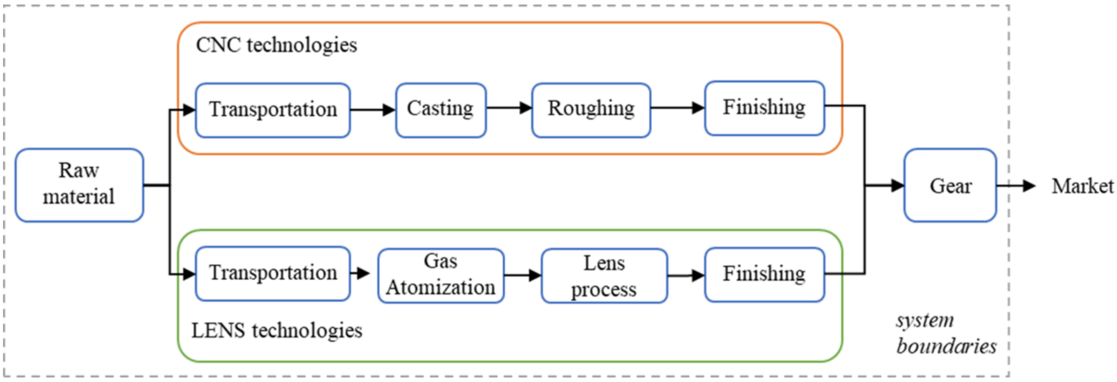



*Figure 77. Schematic representation of the production system considered*

Once the list of material and energy quantities involved in production has been created, the next step is taken. This consists of extrapolating the secondary data via a database in the GaBi 2021 software. The chosen functional unit is the production of a single gear. The most important quantities of material, energy consumption and resources for both production technologies are presented in the inventory in Table 14. Simplified LCA inventory..

*Table 14. Simplified LCA inventory.*

| Scenario | Phase | Flow | Quantity |
|---|---|---|---|
| **LENS technologies** | Transportation by aircraft and truck | Truck transport (Euro 5, 3.5-7.5 tons lorry) | 50 km |
| | | Aircraft transport | 2500 km |
| | Gas atomization by high-speed gas | Electricity | 0.1296 MJ |
| | | Steel ingot | 84.16 g |
| | LENS process | Powder | 77.85 g |
| | | Argon | 221 g |
| | | Electricity | 2.6532 MJ |
| | Finishing grinding | Electricity | 0.1404 MJ |
| | Recovery powered process | Powder to recovery | 58.23 g |
| | | Electricity | 0.097 MJ |
| | | Recovery powder | 46.4 g |
| **CNC technologies** | Transportation by aircraft and truck | Truck transport (Euro 5, 3.5-7.5 tons lorry) | 40 Km |
| | | Aircraft transport | 2000 Km |
| | Casting | Steel ingot | 94.01 g |
| | | Electricity | 0.2376 MJ |
| | Roughing by form milling | Lubricant | 15.9 g |
| | | Electricity | 0.0792 MJ |
| | Finishing grinding | Electricity | 0.1404 MJ |

The calculation of the environmental impact was carried out using GaBi's LCA software. The “ReCiPe 1.08 Hierarchist” was chosen as the impact assessment method. This method quantifies the impact of 18 different categories. Once the results presented by the software have been analysed, there is no one technology that prevails over the others. Considering CNC technology, 80% of the environmental impact is due to the use of lubricants and electricity consumption. As for LENS technology, 70% of the environmental impact is due to the production of waste material. The same scenario can be applied to water consumption.

To understand the most sustainable solution, Figure 78 helps by showing the trend of the end points for both production technologies. For all categories of end points, ecosystem, human health and resources, CNC technologies produce more ecological damage than the

LENS process. As already mentioned, the higher consumption of materials and the use of fossil-based lubricants produce a high impact on resource consumption.

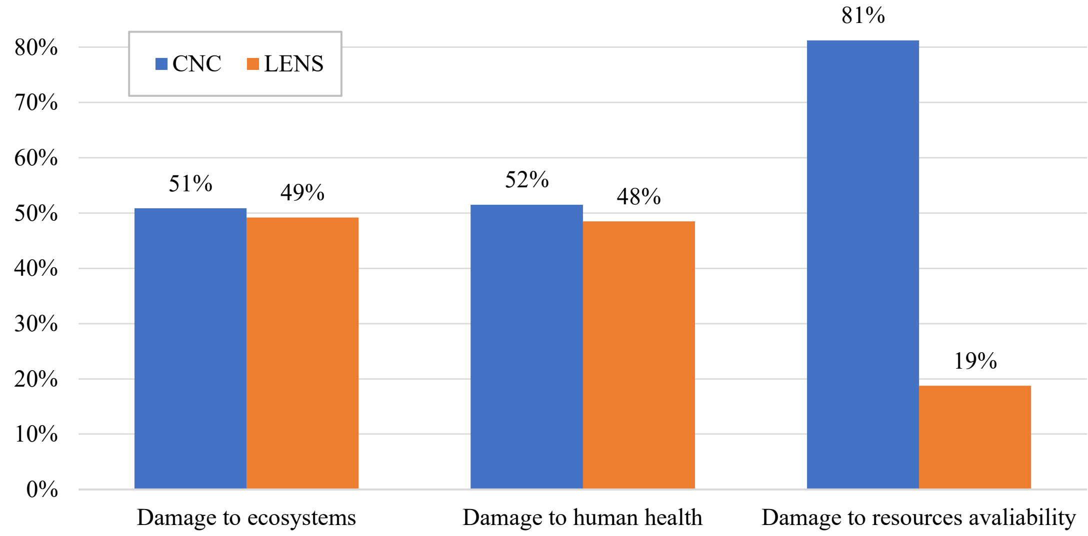



*Figure 78. Simplified LCA end points.*

This evaluation was carried out by keeping the gear geometry the same for both productions. But the inherent advantage of AM technology is that the product shape can be redesigned through GD and OT methodologies. This is due to the greater freedom to create complex geometries without the constraints of traditional production technologies. LENS technology is at an experimental stage, with ample room for improvement compared to an established manufacturing technology such as CNC. These considerations make it possible to hope for a major improvement in the sustainability performance of LENS in the future, compared to CNC. Hence the decision to continue research to interpolate optimisation methodologies and approaches for evaluating the sustainability of products and processes. The aim of the study is therefore to develop optimisation methodologies that consider the ecological impact aspects of the designed products.

## 3.2. Innovative optimisation approach at multiple levels of detail in Additive Manufacturing for sustainability

As outlined previously, through Design for Additive Manufacturing (DfAM), designers exploit several methodologies to expand the space of solutions compared to design constrained by traditional machining. Optimisation approaches find great freedom of expression and modification of the studied component. This is because AM technologies allow the designer to manage high design complexity related to external shape, internal filling, materials and hierarchy between different levels of detail [153]. It all starts with the fundamental unit, which is the smallest dimension of material that the printer can solidify based on 3D printer technology. This unit of material can then be reproduced to create the next level of design and so on following the guidelines of the GD or OT. Managing these complexities in production leads to several advantages, including reducing mass while maintaining constant mechanical properties and diversifying the volume of the final product. While maintaining the same external shape, it is also possible to vary the internal density or type of filling and thus change the behaviour of the component. The advantages are even more evident when the designer is able to understand and make the most of the hierarchy of complexities in relation to optimisation approaches. He or she then proposes solutions at different levels of detail according to the functional characteristics that the final product requires (shape, internal pattern, density, etc.).

The study was submitted to the "International joint conference on mechanics, design engineering and advanced manufacturing JCM 2022" in Ischia in June 2022.

The initial hypothesis is that multi-level Design for AM can also lead to environmental sustainability benefits by reducing the mass of the component or decreasing the energy required for its production. Several studies in the literature investigate the environmental sustainability of solutions derived from Design for AM, often relating the assessment to an established production technology, but do not consider the influence of the various levels of detail [151]. Moreover, limited considerations emerge from these studies because they do not consider comparisons between different levels of detail in the same component [34], [154].

The environmental impacts were considered through the mass of the components in the different Design for AM options and the energy consumed in their production. This was expressed through the amount of carbon dioxide released during production (kg $CO_2$ eq.). The evaluation was carried out through a simplified LCA analysis, where the functional unit considered consists of the production of a Polylactic Acid (PLA) sample, as shown in Figure 79, using a MakerBot 3D printer based on Fused Deposition Modelling (FDM) technology [155].

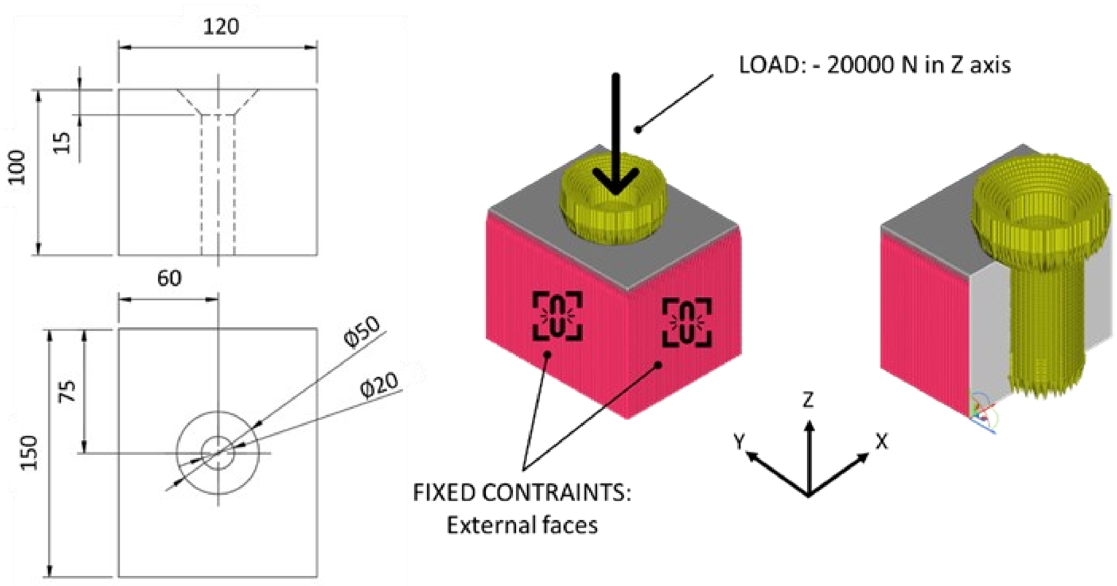



*Figure 79. Sample specification and constraint applied.*

Printer specifications are shown in Table 15.

*Table 15. MakerBot Replicator+ specifications.*

| MakerBot Replicator+ | Technical specs |
|---|---|
| Build Volume (LxWxH) | 295 mm x 19 mm x 165 mm |
| Layer Resolution | 100 µm |
| Layer Height | 0.2 mm |
| Max Power Requirements | 182.4 W |

15 specimens were used, each of them designed with a single feature from the Design for Additive Manufacturing. The design features were created through the methodologies present in different software, to cover the totality of the approaches available for DfAM. In particular, the Autodesk Fusion 360 software enabled the implementation of the Generative Design methodology and nTopology [156] was used to study outcomes for OT, lattice structures and internal component filling. Three different design levels consistent with the hardware and software system of the 3D printer were considered: macro level, relating to morphological optimisation, meso-level relating to the cellular internal structure and micro level relating to the choice of the infill. Figure 80 shows the parametric functions used to create the three levels of detail inherent to the nTopology software.

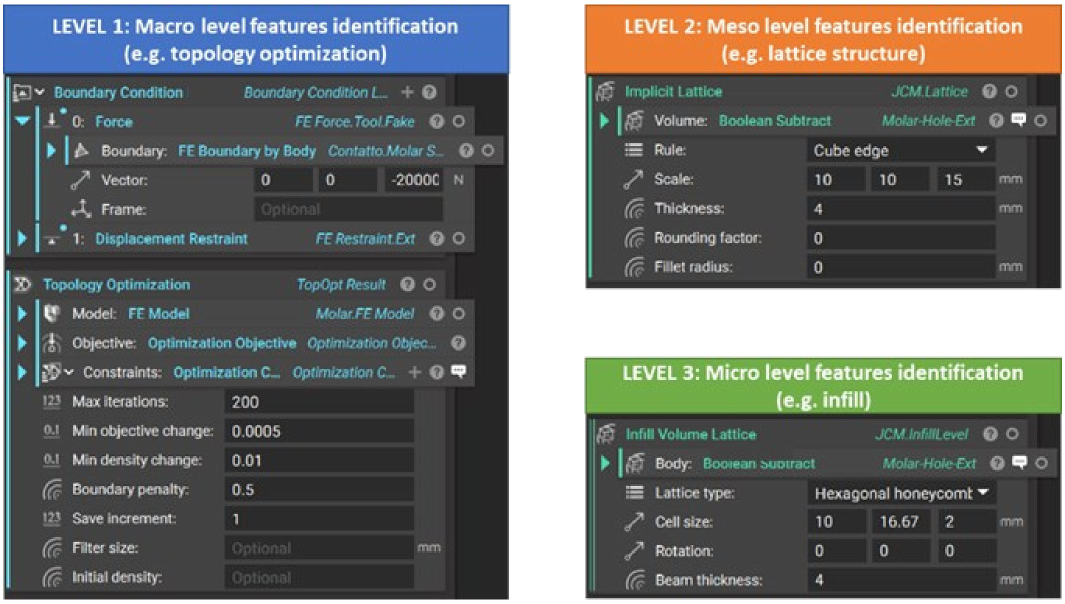



*Figure 80. nTopology functions applied for the case study.*

Figure 81 shows the final design performed for each different level of detail. In each level, the optimisation of the other levels has not been considered: for example, the third level has no topological optimisation and no changes inherent in the lattice structures.

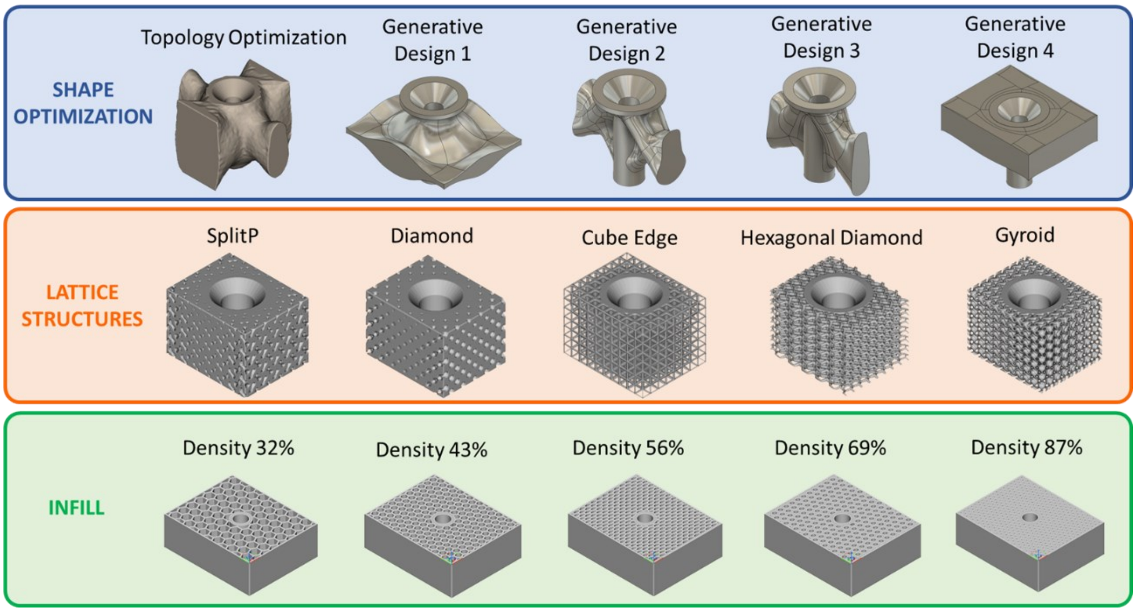



*Figure 81.Outcomes from each level of detail considered.*

For each sample, mass and manufacturing time data were imported from the 3D printer's dedicated software named MakerBot Print. Print energy was instead calculated by multiplying the component's print time by the maximum power of the MakerBot printer. The mass and energy data were then multiplied by the corresponding environmental impact coefficients (Table 16) to derive the impacts of each individual specimen, expressed in kg of $CO_2$ eq. These coefficients refer to the average specific environmental impact of PLA by means AM and to the average Italian electricity mix referred to 2021.

*Table 16. Coefficients of environmental impact considered.*

| Environmental coefficient | Unit | Amount | Reference |
|---|---|---|---|
| Average environmental impact of PLA filament for Additive Manufacturing | Kg $CO_2$ eq./Kg | 0.8 | [157] |
| Electric energy environmental impact in Italy: average national electricity mix | Kg $CO_2$ eq./KWh | 0.494 | GaBi software database 2021 |

Table 17 shows the estimated environmental impacts calculated for each individual sample grouped by level of detail. The total impact is therefore the sum of the impact of the PLA mass and the printing energy. A zero level was also tabulated, which refers to the non-optimised full specimen, also produced with an FDM 3D printer. This specimen is used to compare the values of the other solutions against a situation where no Design for Additive Manufacturing optimisation methodology is used.

*Table 17. Environmental impacts estimated for each sample studied.*

| Level | Sample type | Mass [g] | Energy [Wh] | Mass Impact [g $CO_2$ eq.] | Energy Impact [g $CO_2$ eq.] | Total Impact [g $CO_2$ eq.] |
|---|---|---|---|---|---|---|
| Standard | Full Volume | 2092 | 7682 | 1674 | 3795 | 5469 |
| Shape Optimization | TO Solution | 1058 | 4943 | 846 | 2442 | 3288 |
| | GD Outcome 1 | 488 | 8141 | 390 | 4022 | 4412 |
| | GD Outcome 2 | 235 | 3362 | 188 | 1661 | 1849 |
| | GD Outcome 3 | 229 | 3374 | 183 | 1667 | 1850 |
| | DG Outcome 4 | 647 | 6010 | 518 | 2969 | 3487 |
| Lattice Structure | SplitP | 1218 | 16696 | 974 | 8248 | 9222 |
| | Diamond | 1182 | 11892 | 946 | 5875 | 6821 |
| | Cube Edge | 614 | 19070 | 491 | 9421 | 9912 |
| | Hexagonal Diamond | 592 | 20228 | 474 | 9993 | 10467 |
| | Gyroid | 1276 | 26846 | 1021 | 13262 | 14283 |
| Infill | Density: 32% | 658 | 7022 | 526 | 3469 | 3995 |
| | Density: 43% | 1003 | 9293 | 802 | 4591 | 5393 |
| | Density: 56% | 1238 | 10987 | 990 | 5427 | 6417 |
| | Density: 69% | 1537 | 13127 | 1230 | 6485 | 7715 |
| | Density: 87% | 1911 | 15844 | 1529 | 7827 | 9356 |

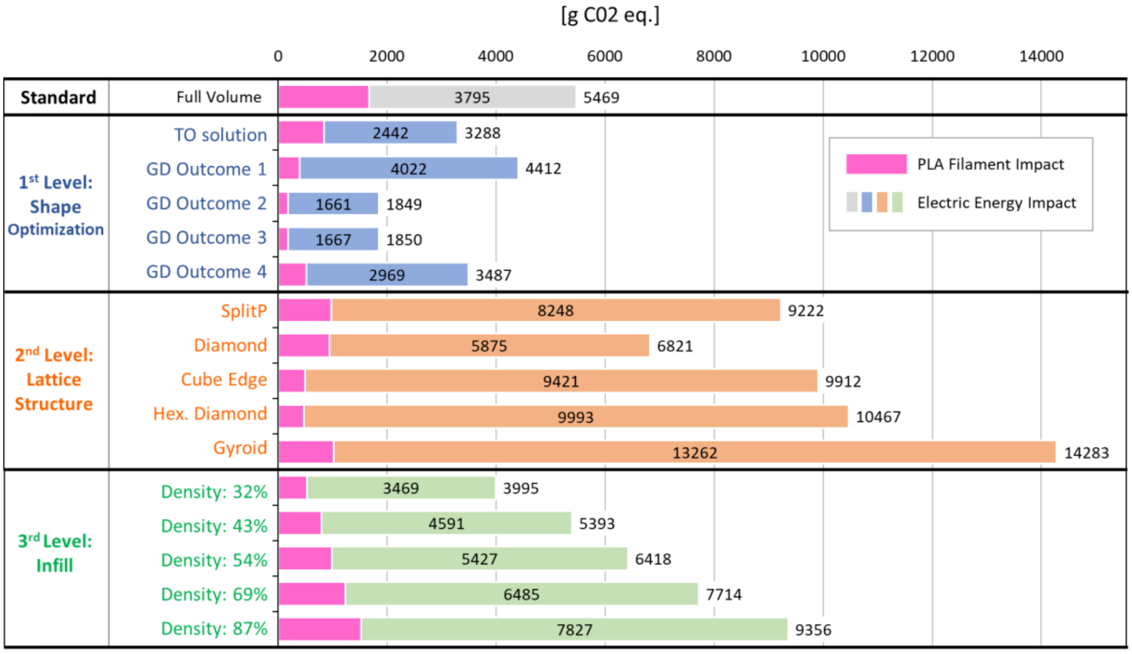



*Figure 82. Graphical comparison of each environmental impact calculated (PLA and energy impact).*

Figure 82 shows how 8 of the 15 design-optimised samples increase the environmental impact of $CO_2$ eq. compared to the standard sample. In the first level of detail, the shape optimisation methodologies decrease the environmental impact in all Topology Optimisation and Generative Design results. On the other hand, all specimens in the second level of detail, which concerns optimisation using lattice structures, significantly increase the environmental impact. In the third level of detail optimisation, specimens with 32% and 42% density achieve a better $CO_2$ impact than the standard specimen. On average, therefore, the first level of detail optimisation reduces the $CO_2$ impact by 54%, the second level increases it by 85% and the third level by around 20% compared to the non-optimised standard sample.

In all cases studied, the environmental impact of the PLA filament mass used is negligible compared to that of the electrical power used by the printer. In fact, on average, the PLA filament production process generates 12% of $CO_2$ compared to 88% generates by electricity consumption. Thus, machine time, an expression of the path taken by the print nozzle, is the ecological bottleneck of design optimisation through AM with FDM technology. The higher power consumption is due to the complexity and thickness of the latex structures, which are not handled properly by the printer's slicer software. In fact, it can be seen in Figure 83 how the path created for the movement of the nozzle is extremely articulated and requires many non-fluid movements to be carried out.

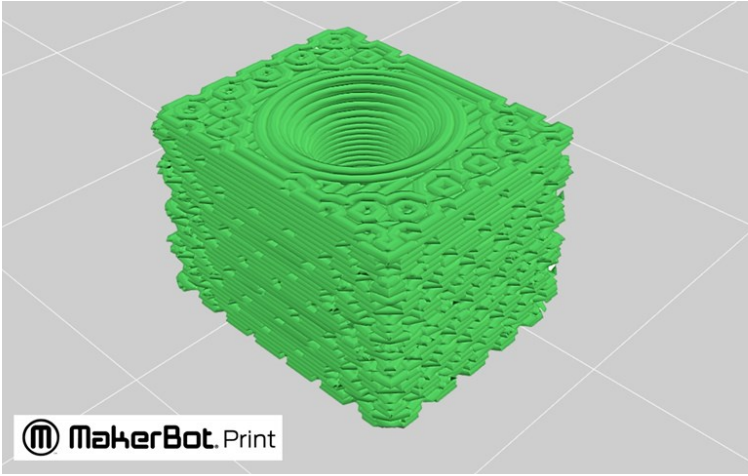



*Figure 83. Example of complex sample slicing in MakerBot Print software.*

The $CO_2$ environmental impact of PLA filament production is shown in Figure 84. In this case, the Design for Additive Manufacturing methodologies bring benefits in terms of ecological impact at all optimised levels of detail. The first level of detail shows how the solutions proposed by the GD algorithms require less PLA filament than the result proposed by the TO methodology. The material used in the second level, i.e. the lattice structure, appears to be correlated with each different nozzle layout created for each solution. Finally, the increase in printed material is directly proportional to the density of the filling volume, which confirms the consistency of the study carried out.

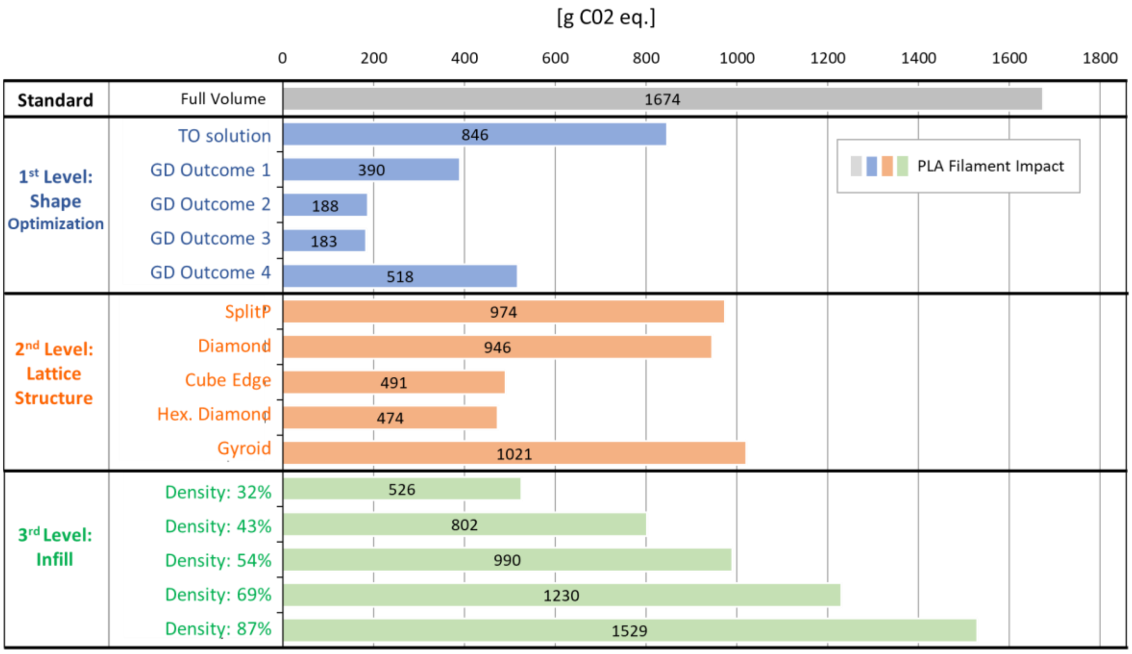



*Figure 84. Graphical comparison of PLA environmental impact calculated for each sample.*

After the study, it was concluded that optimising the multi-level design with a consumer FDM 3D printer generally does not reduce the environmental impact of CO2 eq. In fact, the machine time is much higher compared to the non-optimised sample and has a very high influence on the energy consumed compared to the savings due to the use of less PLA mass.

However, with a relative evaluation at each level of detail, the individual results can also lead to positive considerations.

In particular, for a consumer 3D printer, the first level of detail can be optimised with GD or OT methodologies and propose form results with excellent performance on an ecological as well as mechanical level. At the same time, a smaller level of detail requires suitable hardware, with very high melting point handling characteristics and different technological solutions, such as Selective Laser Sintering (SLS) for polymers and Selective Laser Melting (SLM) for metals. This is to have very good prospects on design optimisation linked to that of environmental sustainability. To summarise, it can be claimed that:

- Regarding the filament consumption, the multilevel design optimization always reduces the environmental impact

- Regarding the overall consumption (PLA + electricity), the environmental impact of the filament mass is negligible compared to that of the electricity consumption
- The shape optimization of multilevel design decreases the environmental impact
- The lattice structure design of multilevel design increases the environmental impact
- The infill density of multilevel design decreases the environmental impact if the density remains under the 43%

The appreciation of the research carried out at international conferences has confirmed the strong interest of the scientific community in the study of Design for Additive Manufacturing methodologies related to environmental sustainability. The current research aims to propose an automated system that optimises the parameters and type of lattice structure according to the mechanical and ecological constraints of the component designed with FDM additive technology. The first phase of this study concerns the definition of the main groups of lattice structures to be referred to. Given the large number proposed in the literature, the structures were grouped into the following classes:

- Body Centered Cubic
- Diamond
- Hexagonal Prismic Vertex Centroid
- Square Honeycomb Rotated
- Troncated Octahedron

Subsequently, the structures were subjected to static and steady loads in the embedded beam condition, which is often used in the literature. Data on the displacement, the machine time for creating the structure and the amount of mass used were then extracted. The latter two data were translated into kg of CO2 eq. emitted into the atmosphere. The data were then normalised to the condition of an embedded beam with a solid structure and weighted with 50% importance for displacement and 50% for ecological impact. The relationship to the standard full-volume test sample condition made it possible to find a relationship between the different structures, so that an objective and easy-to-understand comparison could be made. At this point, the algorithm finds, among the solutions, the one that minimises the mechanical stress and environmental impact and then propose graphs to support the human decision phase. Figure 85 schematically shows the methodological procedure applied.

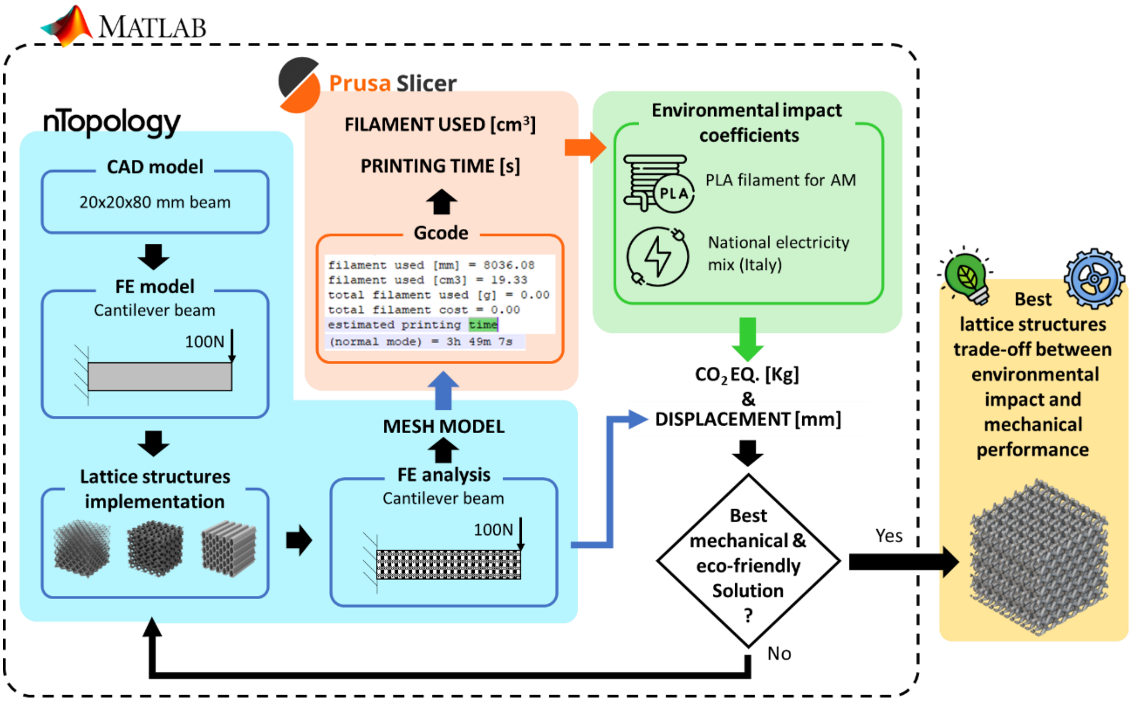



*Figure 85. Iterative approach to decrease environmental impact using DfAM methodologies.*

The software used for the creation and parameterisation of structures is nTopology. It allows both the management of structure parameters (e.g., layer thickness, variable density, etc.) and static analysis under certain load conditions. In addition, it is possible to export the structure as a mesh for editing or development by means of finite element software. An important feature of nTopology is the possibility of controlling the software via scripts and functions in the Matlab environment [158]. In this way, the process of studying and finding the optimum is automated. On the other hand, the software does not export files in .gcode format, so PrusaSlicer was used for slicing the component [159], this software can also be driven in the Matlab environment to automate the slicing and gcode creation process.

Figure 86 shows the first analysis step: the environmental impact and displacement graphs were normalised to the performance of the comparison specimen, as described in eq. 3 and 4.

$$CO_{Rel} = \frac{CO_{2_{Opt.\,Sample}}[Kg]}{CO_{2_{Comp.\,Sample}}[Kg]} \tag{3}$$

$$Disp_{Rel} = \frac{Displacement_{Opt.\ Sample}[mm]}{Dispacement_{Comp.\ Sample}\ [mm]} \tag{4}$$

The “Square honeycomb rotated” structure is clearly the best in terms of both environmental impact and mechanical behaviour.

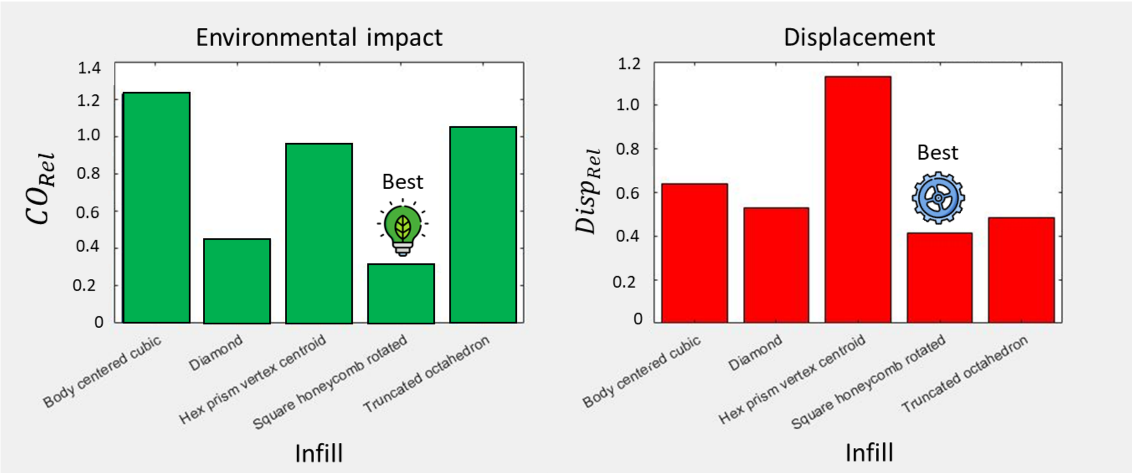



*Figure 86. Sample environmental and mechanical performance normalised.*

Afterwards, the relative data were processed using a weighted average, so that the importance of an ecological benefit versus an improvement in mechanical behaviour was defined according to the circumstances. Eq. 5 shows the weighted average implemented in the function in Matlab.

$$Weighted\ Average = \frac{CO_{2_{Rel}} * Ass.Weight_{co2} + Disp_{Rel} * Ass.Weight_{Disp}}{CO_{2_{Rel}} + Disp_{Rel}} \tag{5}$$

Figure 87 shows how the “Square honeycomb rotated” is the best according to the weight given to the environmental impact versus the mechanical performance of the beam under test.

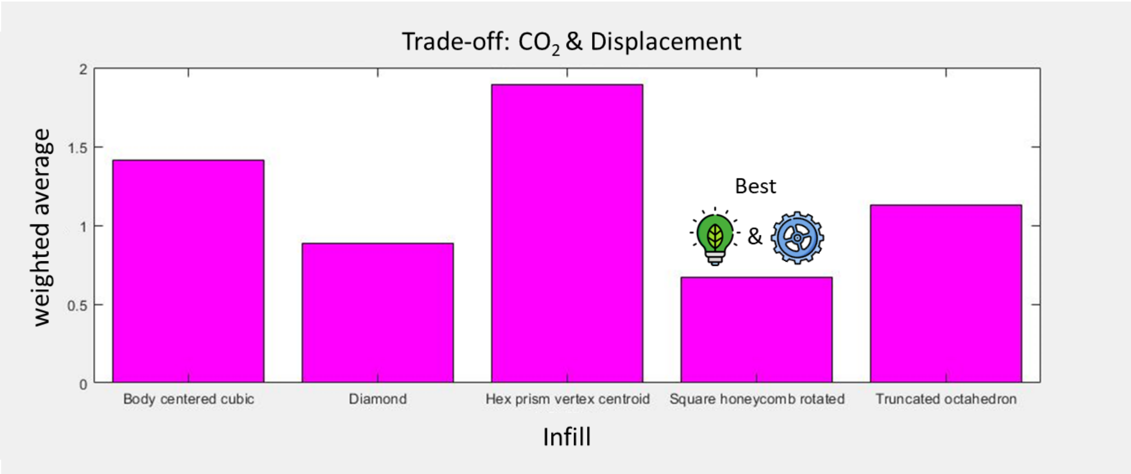



*Figure 87. Graphical trade-off between environmental impact and mechanical behaviour.*

The proposed approach can therefore be used for any single component subject to static loads. Future developments concern the study of more tests on various geometries and lattice structures to validate the system, and then move on to the creation of a simplified graphical interface and a stand-alone programme that can be proposed for future studies.

## 3.3. Multilevel optimisation to solve design contradiction problems

The multilevel approach developed in Design for Additive Manufacturing can be applied in contexts other than sustainability, which concern the possibility of giving the component mechanical and physical characteristics that are theoretically incompatible with each other.

In particular, the case study approached led to the creation of a methodology that supports the resolution of problems given by design contradictions thanks to the freedom of form provided by AM technologies. The method is based on the theoretical approach called “Theory of Inventive Problem Solving” or TRIZ [160]. This approach abstracts the specific problem, models it as a contradiction and resolves it through the solving principles inherent in the TRIZ method.

The novelty proposed with this study concerns the association of the TRIZ method, i.e., the identification of contradictions and their resolution, with the design freedoms inherent in Additive Manufacturing and in the management of the features of the various levels of detail (external shape, latex structures, filling, etc.). Figure 88 illustrates the main phases of the methodology.

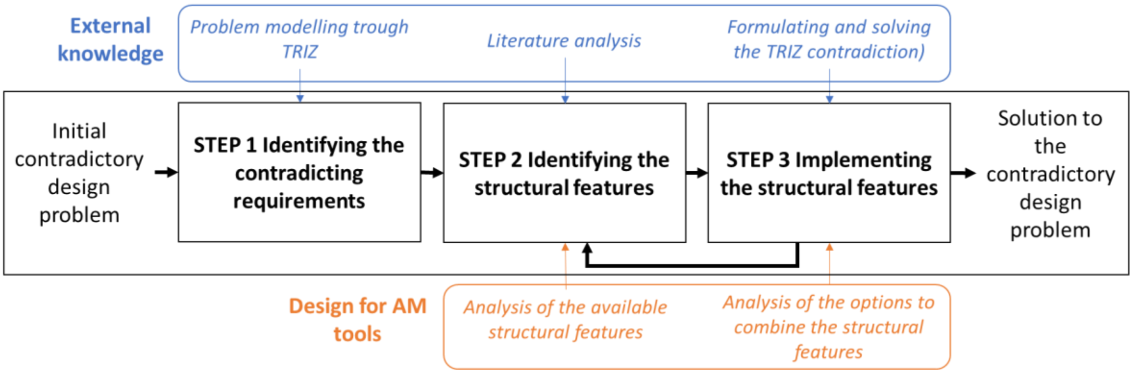
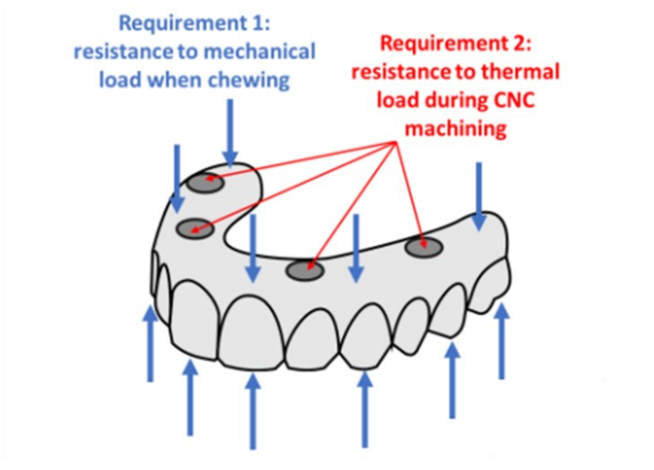



*Figure 88. Methodology workflow presented.*

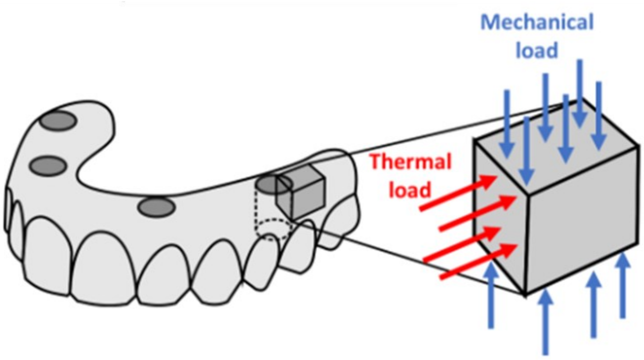
The case study was proposed by a company producing customised dental prostheses, which is now entering the field of Additive Manufacturing. The known advantages of AM in highly customised medical contexts are combined with the disadvantage of surface quality. In the case of dental prostheses, the low surface quality compared to manufacturing methods by machining, does not allow the creation of holes with such roughness as to be perfectly assembled with the supports placed in the patient's mandible. This would require post-machining for a better finish of the internal surface of the hole. This second machining would put the structure of the prosthesis under thermal stress, creating distortions that would compromise the correct installation of the prosthesis.

The contradiction concerns the fundamental features of the prosthesis (Figure 89a), namely:

- Requirement 1: the mechanical strength of the prosthesis to withstand chewing loads
- Requirement 2: the capacity to dissipate post-processing heat through structures that increase the heat exchange surface area




(a)




(b)

*Figure 89. a) Case study requirements and b) Mechanical and thermal loads identified.*

To apply the methodology, a cubic sample of dimensions 40mm x 40mm x 40mm was conceptually extracted from the prosthesis, as shown in Figure 89b. The optimisation of the multiple levels of detail was set through the functions available in the nTopology software, as well as the finite element analyses, both mechanical and thermal. In the first case, the specimen was subjected to a compressive load distributed on two opposite faces simulating chewing. In the second case, the specimen was exposed to thermal stress on one lateral side face.

Each of the two structural features was then defined in different levels of detail, as shown in Figure 90.

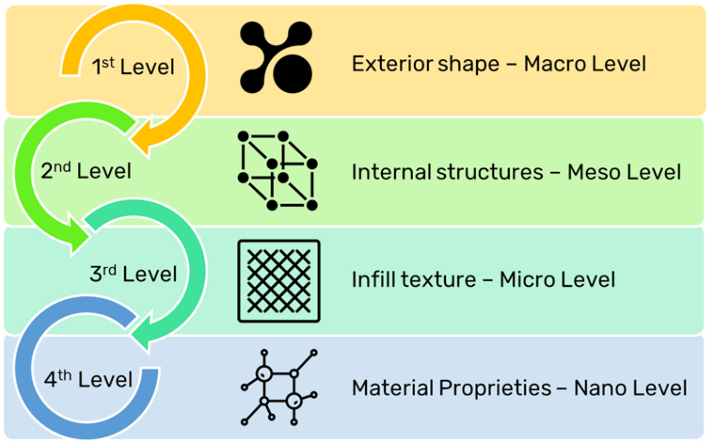



*Figure 90. Levels of detail considered for the case study.*

In particular, to meet the first requirement, the optimisation process identified a lattice structure of the "Triply Period Minimal Surfaces Diamond" type, characteristic of the meso level, as the best. In contrast, to meet the second requirement, a micro-level structure was identified as "Diamond Fill". Therefore, Structural Feature 1 (SF1) and Structural Feature 2 (SF2) were combined in a single sample. This merging was possible because the two optimisations were developed at different levels of detail and then incorporated into a sample with both desired features.

To validate the method, the sample with both structural characteristics (SF1 and SF2) and a sample with only one optimisation in the meso level were printed, as shown in Figure 91. The test specimens have the same external dimensions (40mm x 40mm x 40mm) and were printed by the same 3D printer with the same material. For simplicity, it was decided to produce the test specimens in PLA polymer. The mass of the two specimens is different, so the results were normalised to the mass.

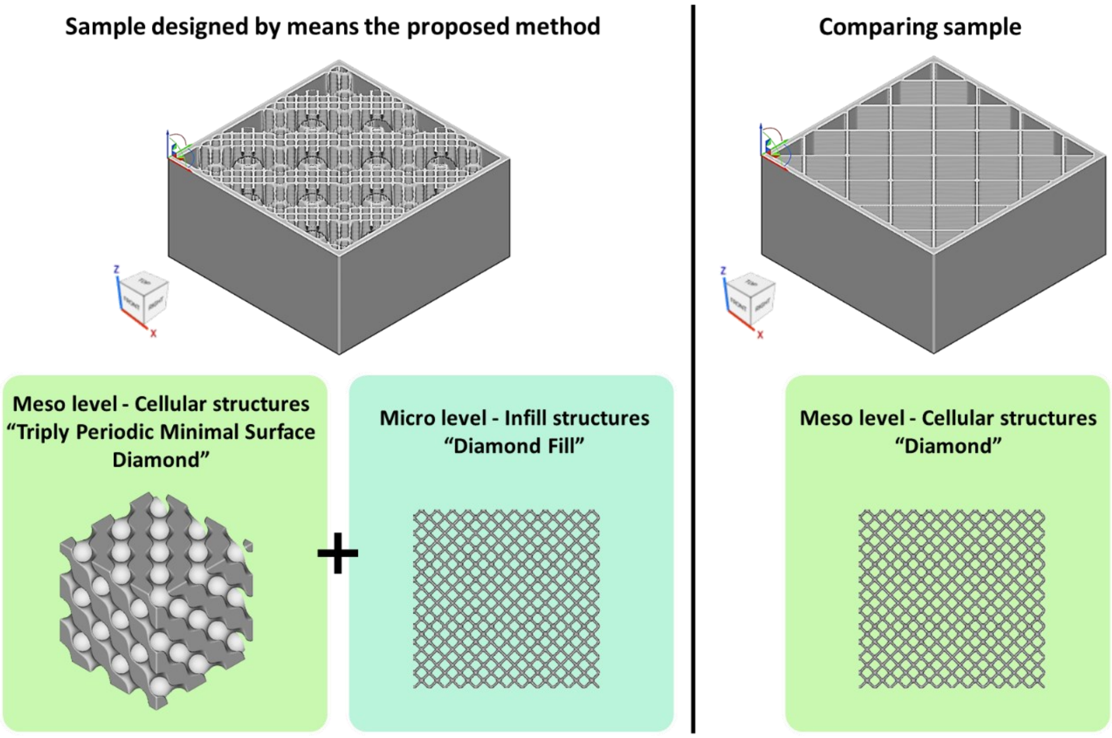



*Figure 91. Comparison of the structural feature of each sample.*

For the mechanical test, two samples of each type were compressed by a mechanical press with maximum thrust equal to 50 kN in order to evaluate the compression load and the behaviour of the proposed solutions. The result in Figure 92 shows how the two test samples break approximately at the same load. The biggest difference is in the deformation behaviour: in fact, the test sample developed with the method presented obtains a much greater deformation (+240%) than the original comparison sample.

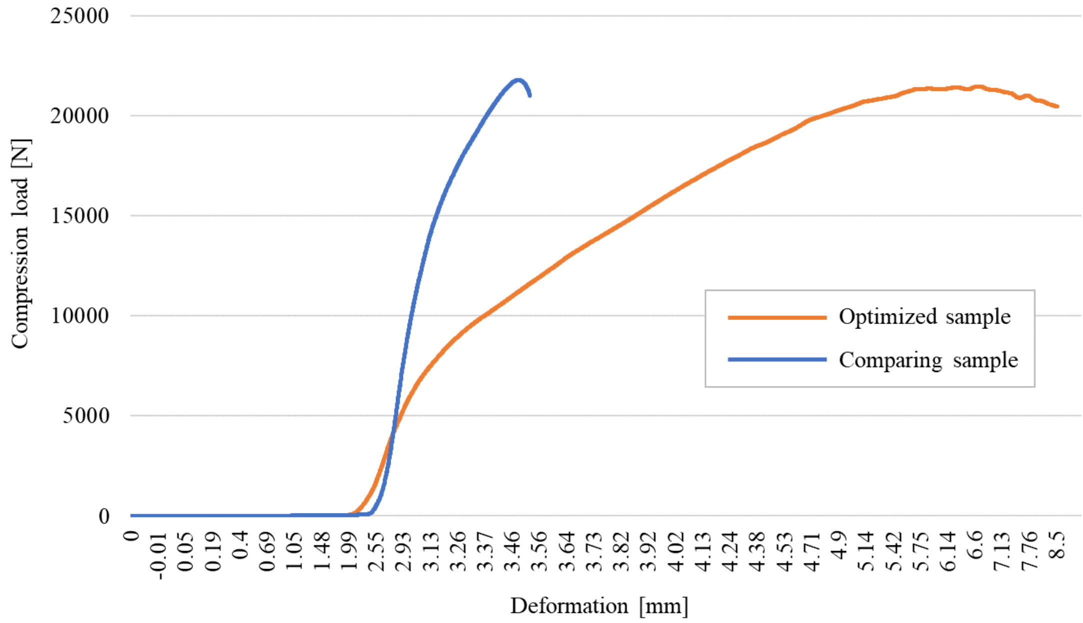



*Figure 92. Comparison stress-compression diagrams for both samples.*

Regarding the thermal test, both sample variants were heated up to 373 K and then the cooling trend was evaluated as the distance from the heat application point changed. As the simulations in Figure 93 and then the thermal test graph in Figure 94 show, the sample optimised with the proposed methodology (Figure 93a) has better thermal insulation than the comparing sample (Figure 93b).

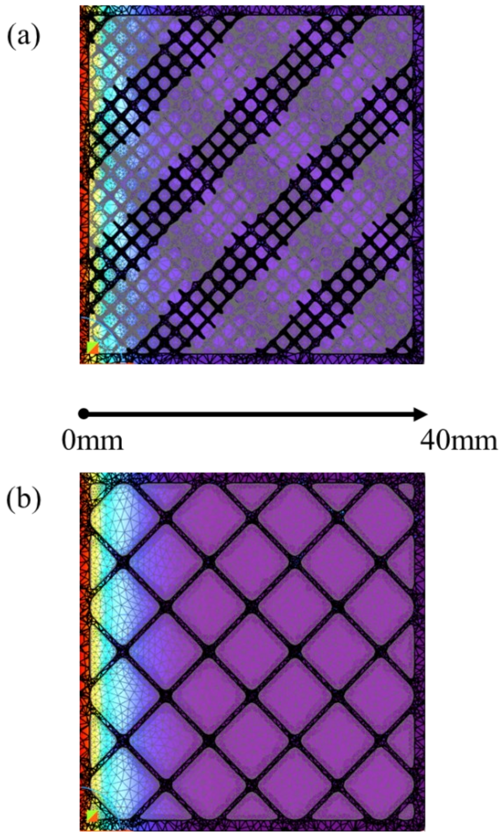



*Figure 93. Comparison of thermal simulation of both samples: a) Sample optimised by means innovative approach and b) Traditional sample optimization.*

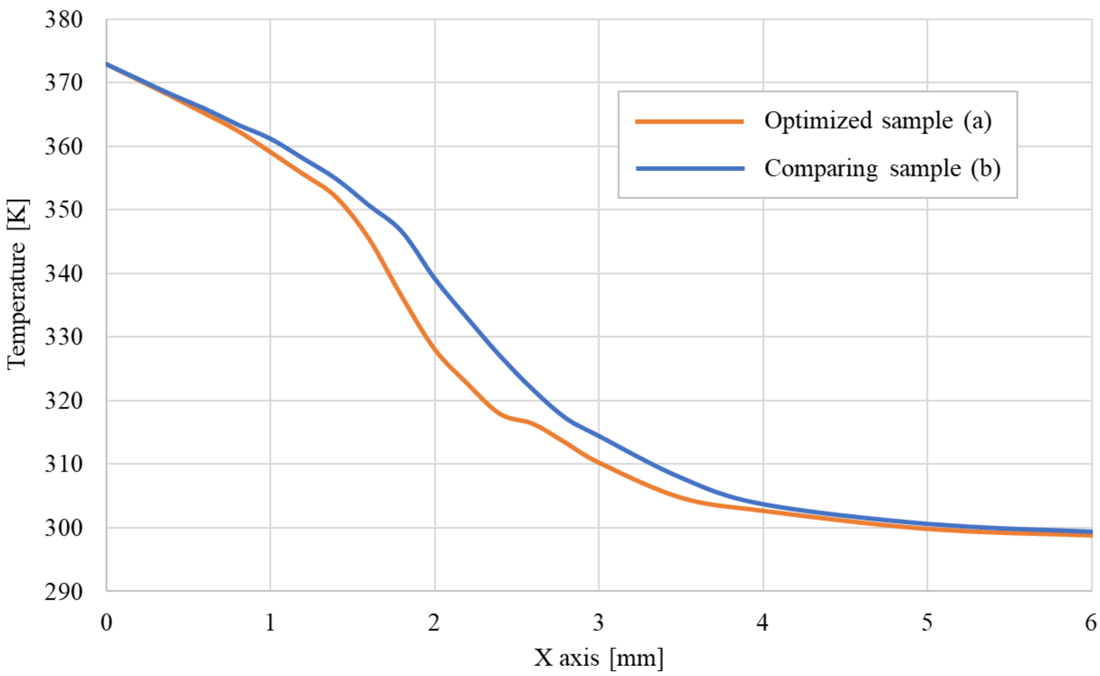



*Figure 94. Thermal analysis graph of both samples.*

The greater insulating property is given by the internal surface of the optimised sample with respect to the comparison sample. In fact, from Table 18, the internal surface of the multilevel optimised sample is 69% greater, while maintaining an identical volume and external surface to the comparison sample.

*Table 18. Comparison of thermal and volume features.*

| | **Volume [mm$^3$]** | **External surface [mm$^2$]** | **Internal surface [mm$^2$]** |
|---|---|---|---|
| **Optimized sample** | 64000 | 9600 | 60748 (+69%) |
| **Comparing sample** | 64000 | 9600 | 35950 |

As regards final considerations, the methodology presented has succeeded in implementing an approach within Design for Additive Manufacturing to solve the contradiction problem. This is due to the methodology's ability to expand the problem space using the multilevel design optimisation made possible by the inherent characteristics of 3D printing technology. In addition, the utilisation of the TRIZ methodology combines perfectly with the ability to modify and optimise multiple layouts of different details simultaneously, solving the contraction of space and time. Future developments involve the use of additive technologies other than FDM, for example using metallic powder materials and Selective Laser Melting (SLM) technology to increase the levels of detail available for component optimisation.

## 3.4. Generative Design and Motion Capture: combining approaches for ergonomic optimisation

As regards the study of new methodologies incorporating Generative Design, a research area has been developed that concerns the development of ergonomic products starting from the biomechanical analysis of the movements of the subject interacting with the component.

The objective of this innovative methodology is to propose a design flow of the shape of ergonomic products, by means of Motion Capture and Generative Design techniques, as shown in Figure 95.

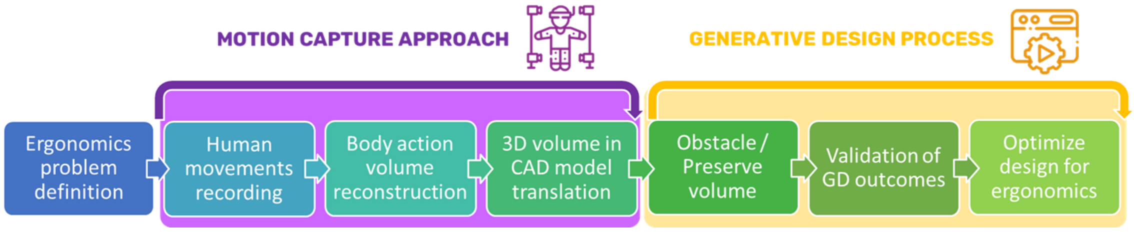



*Figure 95. Workflow of an innovative approach by means GD and Motion Capture methodologies.*

The methodology applies Motion Capture techniques to record the movement of the subject and in particular the volume occupied by the subject's body throughout the movement phase. This has made it possible to use the volume of movement of the subject as an obstacle geometry that has constrained the development, by means of Generative Design, of innovative geometries for components in the medical and industrial fields.

The study developed aims to introduce ergonomics into the design phase with a central focus on safety. The achievement of this objective is guaranteed by the possibility of virtualising the fundamental aspects of the development process and carrying out tests directly on the shapes proposed by Generative Design. In addition, the methodology mentioned is applicable to a wide range of problems without requiring an excessive cost for the study, adopting modular structures that can be adapted to various situations.

Two case studies were therefore used that differed in terms of requirements and type of constraining movement. Specifically, in the context of the ergonomics of wheelchair patients, an investigation was made into the design of a wheelchair frame adapted to the needs and pushing patterns of most users in terms of weight and height. Thus, a methodology was developed to optimise a chassis for the needs of various body types, so that it is generally more ergonomic than those now on the market. In the automotive field, on the other hand, a chassis has been designed to improve a particular aspect of driver safety: the egress phase. The test involves measuring the time in which the driver manages to exit the cockpit in the event of an accident. The chassis is type-approved if the minimum pilot egress time is also met, in addition to structural requirements.

The Optitrack passive marker system, produced by TrackLab, was used for body tracking [161]. This hardware enables the recording of human movements using marker-based technology. A set number of highly reflective passive markers are placed on the main joints of the human body such as the neck, shoulders, upper and lower limbs, back and feet. A combination of infrared and RGB cameras track the movement of the markers at high frequency and the connected software translates the information received from the sensors into x, y, z coordinates in space as a function of time. The result is the reproduction of human movements in a 3D environment, where one can interact with the recreated avatar to analyse the biomechanics of the subject (Figure 96). The output of this analysis phase is a virtual human model that reproduces with high accuracy the same body movements as the real recorded subject. The extrapolated skeleton is in .bvh format to be read by 3D volume editing software.

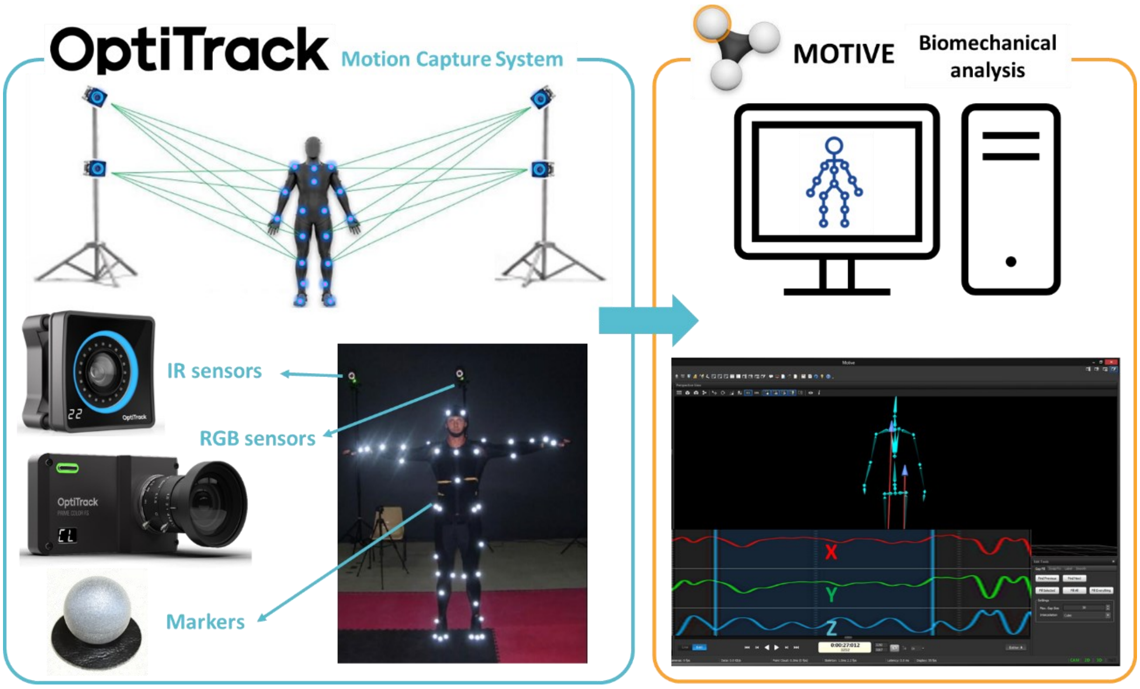



*Figure 96. Hardware and software used for the human motion analysis.*

The Blender suite was chosen to model and make changes to the volumetric model of the subject's body [162]. Blender is an open-source, cross-platform software that creates animations, modelling, rigging and texturing. The application of the software was fundamental for the manipulation of polygonal meshes using the "rigging" technique. The objective of using Blender is to obtain the entire capture volume occupied by the person tracked by the Optitrack system in the recording time, as shown in Figure 97.

*Figure 97. Virtual human volume occupied by body movements.*

In both case studies, the motion volume was found by merging the individual volumes extracted for each recorded frame, to combine them and propose a unitary mesh that could be used in the CAD environment.

The software made it possible to import files in .bvh format from Optitrack, which is a special format for handling information from Motion Capture. The .bvh format is one of the main standards for storing and exporting data extracted from the movement of human subjects.

Next, the rigging function is performed using a human skeleton model already available in Blender and adapting the skeleton to the shapes in the .bvh file. Once the skeleton has been created and adapted, the latter model is linked by creating a parent-child relationship between skeleton and mesh. This connection allows the movement of the reinforcement by moving the joints that make up the virtual skeleton that plays the role of father.

The rotations of the .bvh file are then assigned to the skeleton associated with the framework. The process then allows the polygons of the outer skin to be moved by following the movements tracked previously using the Optitrack MOCAP system. Rotation and/or translation movements of the joints are then assigned. The processes described above make it possible to obtain a complete three-dimensional animation of the reinforcement and then to save, for each frame, the .obj file of the volumetric mesh.

The next step involves the use of the "multiple import" function, in which all frames previously exported in .obj format are merged into a single .blend file. The import is performed with individual volumes and they remain separate even within the Blender project. The various frame positions are then overlaid and merged into a single volume via the "parenting" function. The generated composition corresponds to the whole volume occupied in the acquisition phase. The entire process is shown in Figure 98.

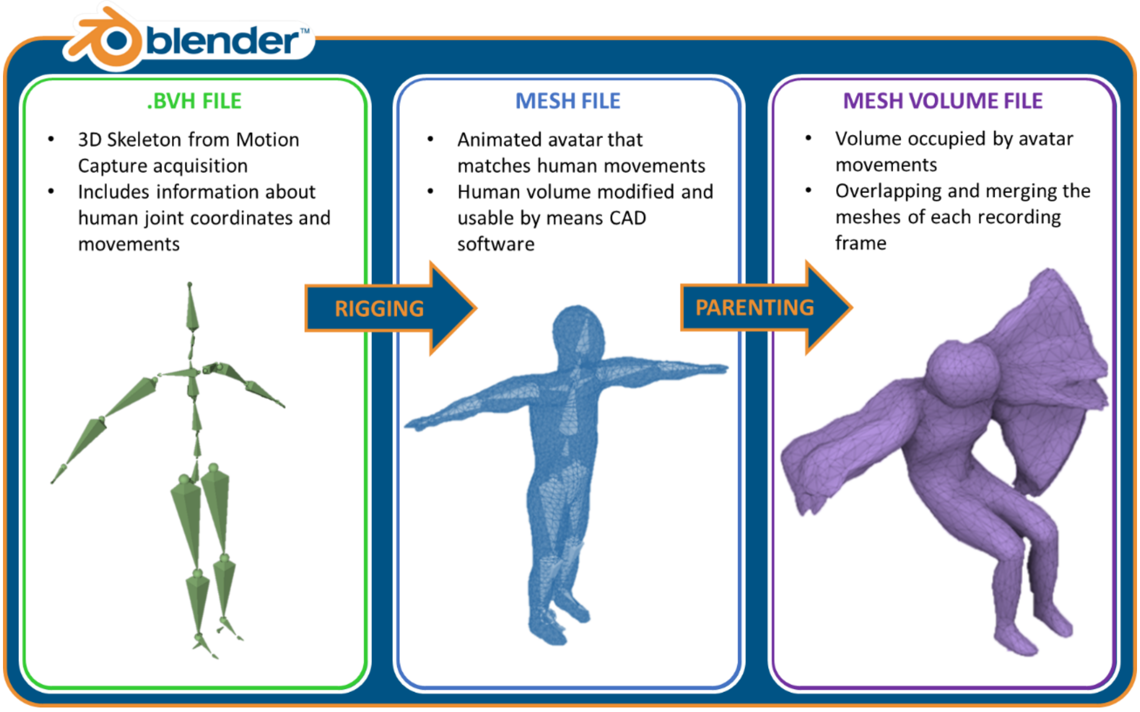



*Figure 98. Virtual human volume generation steps from subject acquisition.*

The generation of the mesh corresponding to the entire volume occupied by the recorded subject allows this information to be transferred to the CAD environment, so that the generation of ergonomic designs can be set up according to the action performed by the subject. As a platform for the use of Generative Design techniques, Autodesk Fusion 360 was used.

As seen in the previous paragraphs, the setting of the volumes to be preserved and obstructed is fundamental. In particular, in the two case studies, the volumes of the recorded subjects' movements were also selected as obstacle geometries.

The two case studies are now presented with details of the methodology just described.

### 3.4.1. Ergonomic optimization of a wheelchair frame by means innovative design approach

The wheelchair analysed, which can be seen in Figure 99 fits into the category of standard self-propelled wheelchairs, the most common type and not created to the specific dimensions and needs of patients. The wheelchair used to perform the takes is a "Mediland Kometa Standard" with a seat width of 400 mm, this model weighs 18.5 kg in its complete form, the frame is made of welded steel pipes, while the attached elements are made of aluminium.


*Figure 99. Standard self-propelled wheelchair analysed.*

The acquisition of the patient's pushing movement in the wheelchair was performed with Motive software using the Optitrack system. From the available skeletal structure protocols, the one marked "Conventional Upper Body" was chosen, which involves the use of 27 markers (Figure 100) and allows only the upper part of the body to be tracked, which is the only one affected by the movement. The distance (diagonal) covered in the tests is 7.50 m.

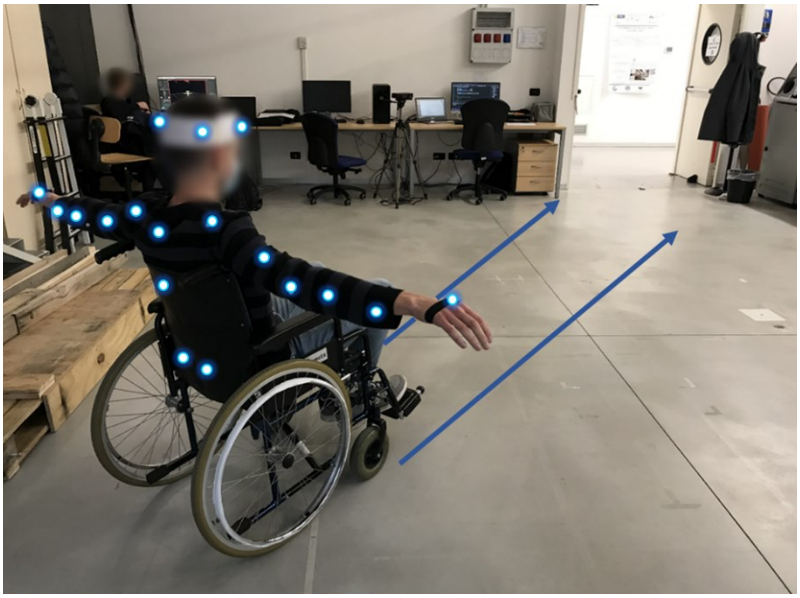


*Figure 100. Passive markers disposition on human body during the movements acquisition.*

The acquisition campaign involved 10 testers, for each of whom two recordings were made. The subjects were chosen to have as varied a sample as possible in terms of weight, height and gender. Table 19 describes the parameters measured for each subject acquired.

*Table 19. Subjects body parameters.*

| Subject | Height [cm] | Weight [Kg] | Gender |
|---|---|---|---|
| **1** | 182 | 86 | M |
| **2** | 170 | 62 | M |
| **3** | 185 | 80 | M |
| **4** | 174 | 64 | M |
| **5** | 179 | 75 | M |
| **6** | 190 | 85 | M |
| **7** | 171 | 95 | M |
| **8** | 179 | 55 | F |
| **9** | 181 | 85 | M |
| **10** | 170 | 60 | F |

After processing the videos and creating the motion volume of each subject, the solution generation was set up using Autodesk Fusion 360. Specifically, in the case of the wheelchair, the parts to be preserved during the generative study are:

- Handles
- Tubular backrest structure
- Tubular seat structure

- Tubular structure of armrests
- Connections of footboards
- Front wheels connection hubs
- Rear wheels connection hubs

As previously mentioned, to the obstacle geometries considered for previous studies, geometry extrapolated from the subject's movement is added.

Figure 101 shows how this significantly modifies the volume in which the generative algorithm creates geometries and thus solutions, compared to the case without human subject volume.

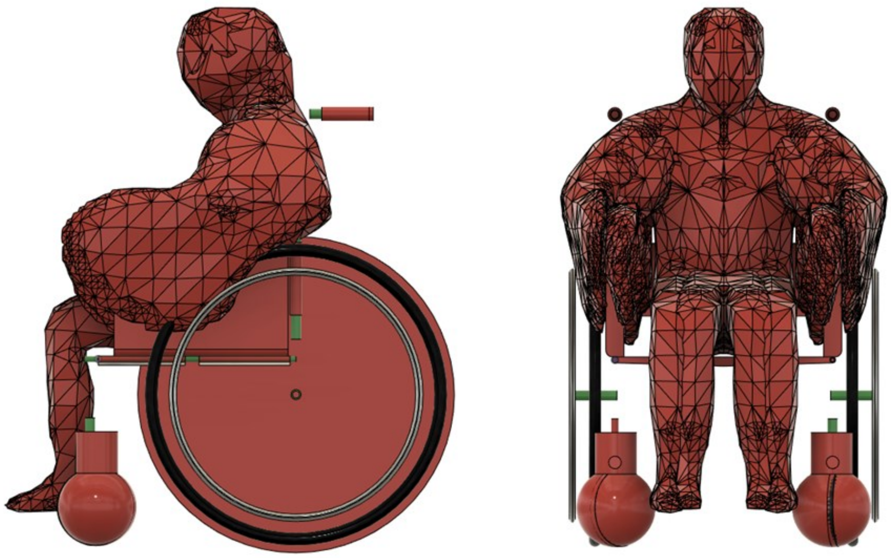


*Figure 101. Human movements as obstacle regions for the GD study.*

To summarise the volumetric constraints imposed, Figure 102 shows the preserves (Figure 102a) and obstacle regions (Figure 102b) identified for this study.

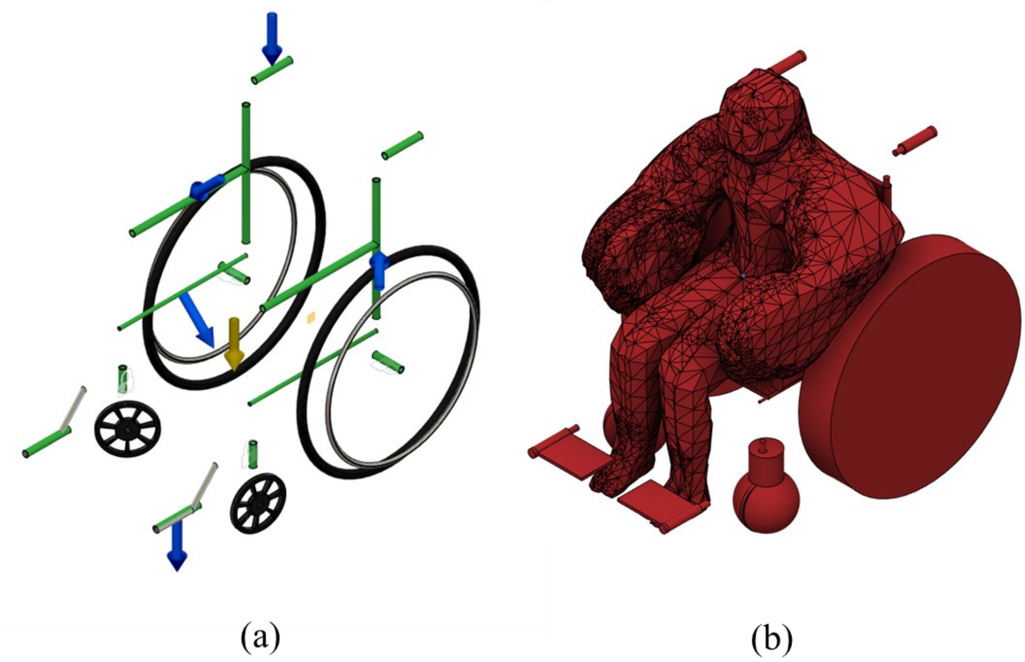


Figure 102. a) Preserved and b) Obstacle regions.

Concerning the loads and constraints, their positioning was chosen based on the present literature, considering the impossibility of simulating dynamic loads but only static ones. In order to obtain the specific loads to be attributed to the different structures, it is necessary to use a ratio between the mass of the subject used as a reference, the forces exerted by the latter and the weight of the subjects taking the measurements. The values of the loads obtained are listed in Table 20:

Table 20. Load constraints for each component and subject.

| Subject | Loads by component [N] | | | | |
|---|---|---|---|---|---|
| | Handles | Backrest | Seat | Footboards | Armrests |
| **1** | 593 | 283 | 573 | 675 | 101 |
| **2** | 428 | 204 | 428 | 486 | 73 |
| **3** | 552 | 264 | 552 | 628 | 94 |
| **4** | 442 | 211 | 442 | 502 | 75 |
| **5** | 518 | 247 | 518 | 588 | 88 |
| **6** | 587 | 280 | 587 | 667 | 100 |
| **7** | 656 | 313 | 656 | 745 | 112 |
| **8** | 380 | 181 | 380 | 431 | 65 |
| **9** | 587 | 280 | 587 | 667 | 100 |
| **10** | 414 | 198 | 414 | 471 | 71 |

The generative study requires the definition of the loads distributed along the geometries to be preserved. The parts to which loads have been attributed are (Figure 102a):

- Handles
- Tubular backrest structure
- Tubular seat structure
- Tubular structure of armrests
- Connections of footboards

The analysis performed on the sample of 10 subjects made it possible to obtain data on the correlations between the various parameters considered of the subject and the results of the generative study. The collection of information concerned the weight and height of the patient, the volume occupied by the patient's movement during the recording and finally the weight and minimum volume of the generated wheelchair frames. Table 21 shows the data collected in relation to the subject acquired.

*Table 21. human volume mesh and wheelchair outcomes for each subject.*

| Subject | Height [cm] | Weight [Kg] | Volume mesh of subject movements [$m^3$] | Wheelchair frame weight [Kg] | Wheelchair frame volume [$10^{-3}$*$m^3$] |
|---|---|---|---|---|---|
| 1 | 182 | 86 | 0.130 | 10.2 | 3.765 |
| 2 | 170 | 62 | 0.132 | 11.1 | 9.680 |
| 3 | 185 | 80 | 0.140 | 8.8 | 3.241 |
| 4 | 174 | 64 | 0.151 | 10.0 | 4.953 |
| 5 | 179 | 75 | 0.140 | 18.2 | 6.828 |
| 6 | 190 | 85 | 0.151 | 9.7 | 3.628 |
| 7 | 171 | 95 | 0.160 | 9.7 | 3.525 |
| 8 | 179 | 55 | 0.114 | 13.6 | 7.871 |
| 9 | 181 | 85 | 0.125 | 11.9 | 4.315 |
| 10 | 170 | 60 | 0.177 | 6.3 | 2.253 |

The main assumptions found in the study are then set out, the shape results of which can be seen in Figure 103.

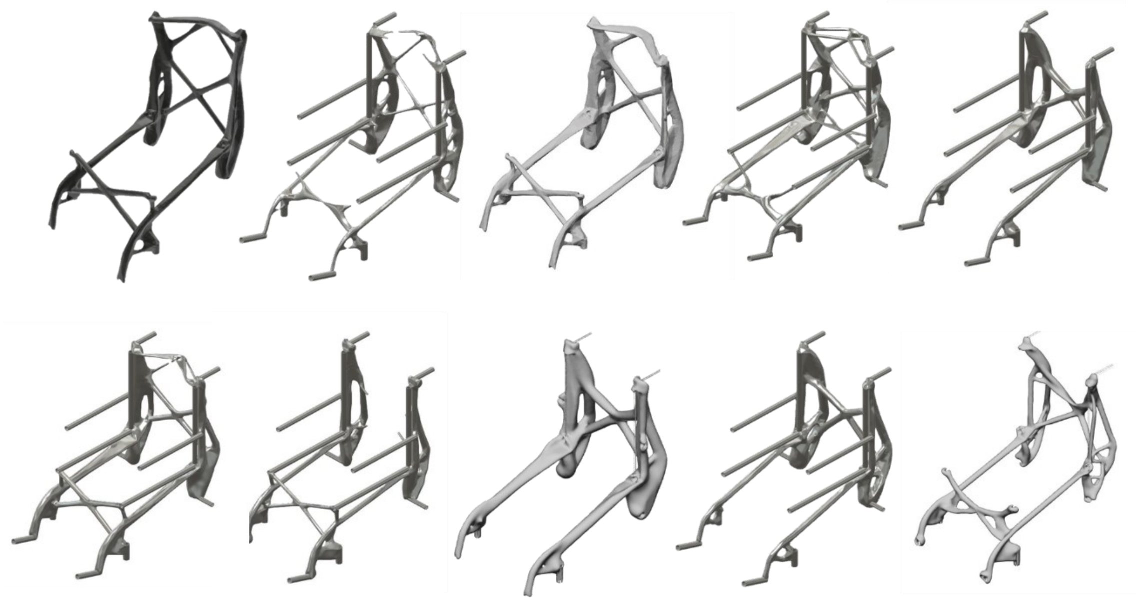


*Figure 103. GD outcomes from the presented methodology.*

In detail, the weight of the patient does not predominantly influence the weight of the wheelchair structure generated. In fact, as can be seen from Figure 104, the correlation index is $\rho = 0{,}057$. It can therefore be assumed that the patient's weight force, relative to the population analysed and in the case of static loading, does not affect the generation of lighter frame solutions.

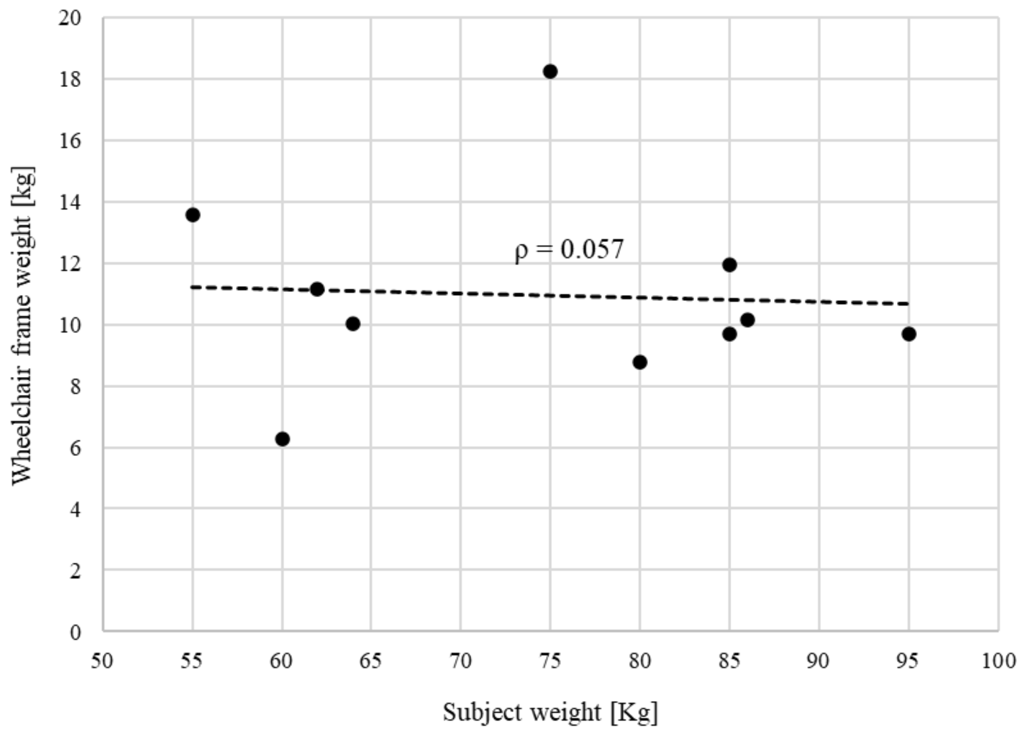



*Figure 104. Correlation graph between subject and wheelchair frame weight.*

On the other hand, with regard to the correlation between the volume of the patient's movement and the weight of the wheelchair frame, it can be seen that the solutions proposed by the Generative Design algorithm perform better in terms of lightness as the volume of movement increases. This information indicates how the algorithm reacts better to the change in geometric constraint than to the application of a greater static load in absolute value. Figure 105 summarises the Pearson correlation index $\rho = 0{,}56$ the graph of the data described.

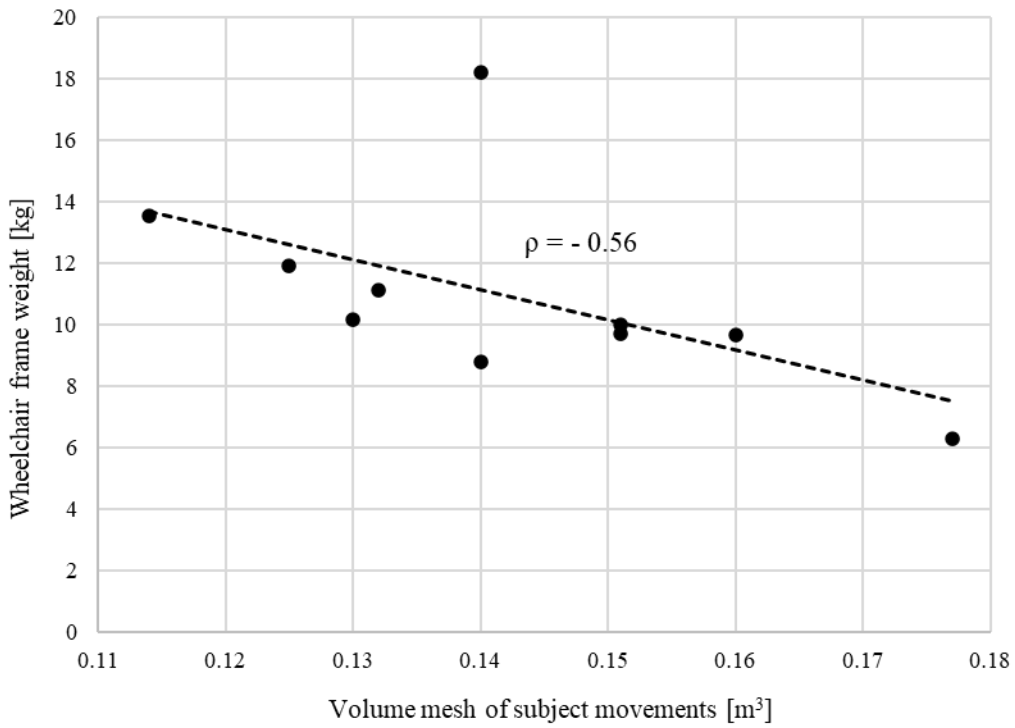



*Figure 105. Correlation graph between volume mesh of subject movements and wheelchair frame weight.*

### 3.4.2. Ergonomic and safety optimization of a Formula SAE chassis by means innovative design approach

The aim of the proposed study is to develop the chassis of a Formula SAE car that withstands a frontal impact and allows the driver to escape, using Generative Design and Motion Capture techniques in combination. The chassis must be able to withstand a frontal impact at a speed of 14 m/s. Following such an impact, the structure must also allow the driver to exit the cockpit in less than 5 seconds, as required by the Formula SAE regulation [163].

In this case study, the Motion Capture technique was adopted to track the volume of the driver's movement exiting the vehicle. Subsequently, Generative Design methodologies were used to optimise the chassis geometries based on the volumetric constraints derived from the previously recorded movements. The use of a real racing chassis was not possible due to the unavailability and because part of the track body was hidden from the infrared cameras for a large part of the test. Therefore, it proved necessary to create a chassis with reduced visual occlusion, equipped only with the necessary structure to simulate the correct position in the driving phase and an obstacle similar to the real one in the exit phase. Similar structures are available from various literature sources, and Figure 106shows the modular frame created for the driver Motion Capture tests.

*Figure 106. Modular frame developed.*

The inclination of the various seating panels follows precise specifications dictated by the regulations. The dimensions of the structure are summarised in Figure 107.

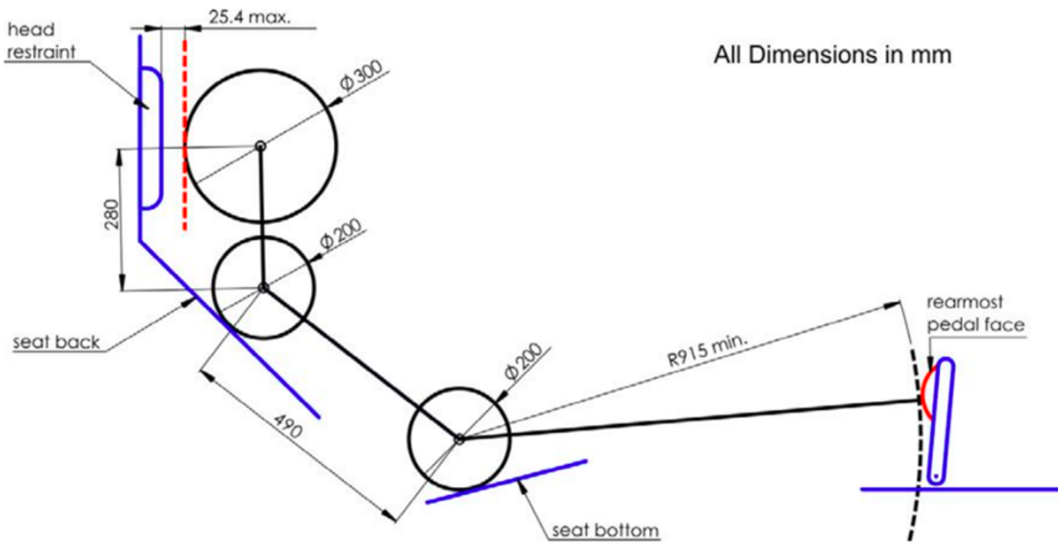



*Figure 107. Driver's seat geometries and dimensions.*

The acquisition of the sequence of movements to exit the vehicle was recorded using the Optitrack system. From the skeletal structure protocols available in Motive, the one called "Baseline" was chosen, which involves the application of 37 markers and the starting T-pose and allows the detection of the position of the whole body.

Similarly, to the recordings carried out for the wheelchair study, the acquisitions are carried out wearing tight-fitting clothes so as not to hide the markers from the cameras, which, as seen above, makes it impossible to reassign the trajectories to the correct device.

The chassis of the racing car is custom-made for each driver, the acquisitions were carried out by the same subject, it is therefore a repeatability test. The subject used is 170 cm tall and weighs 65 kg.

Seven recordings were made, during which the subject assumed an initial T-position inside the cockpit, then performed the egress manoeuvre, concluding again in T-pose. The T-position was used to simplify the rigging and parenting procedure, as seen for the wheelchair case study.

Table 22 describes the time taken by the pilot to exit the chassis and Figure 108 shows part of the exit movement.

*Table 22. Egress test results.*

| Test n. | Egress time [s] |
|---|---|
| 1 | 4 |
| 2 | 3.9 |
| 3 | 3.9 |
| 4 | 3.9 |
| 5 | 3.8 |
| 6 | 3.9 |
| 7 | 3.1 |

*Figure 108. Driver's movement during egress test acquisition by means Optitrack system.*

Compared to the processing of the subject volume acquired in the wheelchair case study, the following process has the following differences:

- Attribution of both movements (translation and rotation) is required, allowing relative movement between the permanent structure, i.e. the frame, and the moving shape attributed to the virtual avatar
- The study of the Formula SAE frame requires the acquisition of the entire human body and not just a part as required for the wheelchair

The overlapping of the subsequent movements provided the entire volume of movement of the driver. The acquisition, reconstruction and method used to track the displacement resulted in the creation of a volume composed of many mesh elements (~$10^6$ ). The large number of faces is therefore onerous in terms of processing by consumer computers. It is therefore necessary to carry out a lightening to obtain a file that is not excessively heavy for calculation but at the same time has a sufficient level of information to best approximate the data acquired. The simplification required the combined use of the software applications Blender and Meshmixer [164] through polygon reduction and remesh processes with voxels of 0.01 mm size. Figure 109 shows, at different point of view, the acquired motion volume compared to a standard truss chassis of formula SAE.

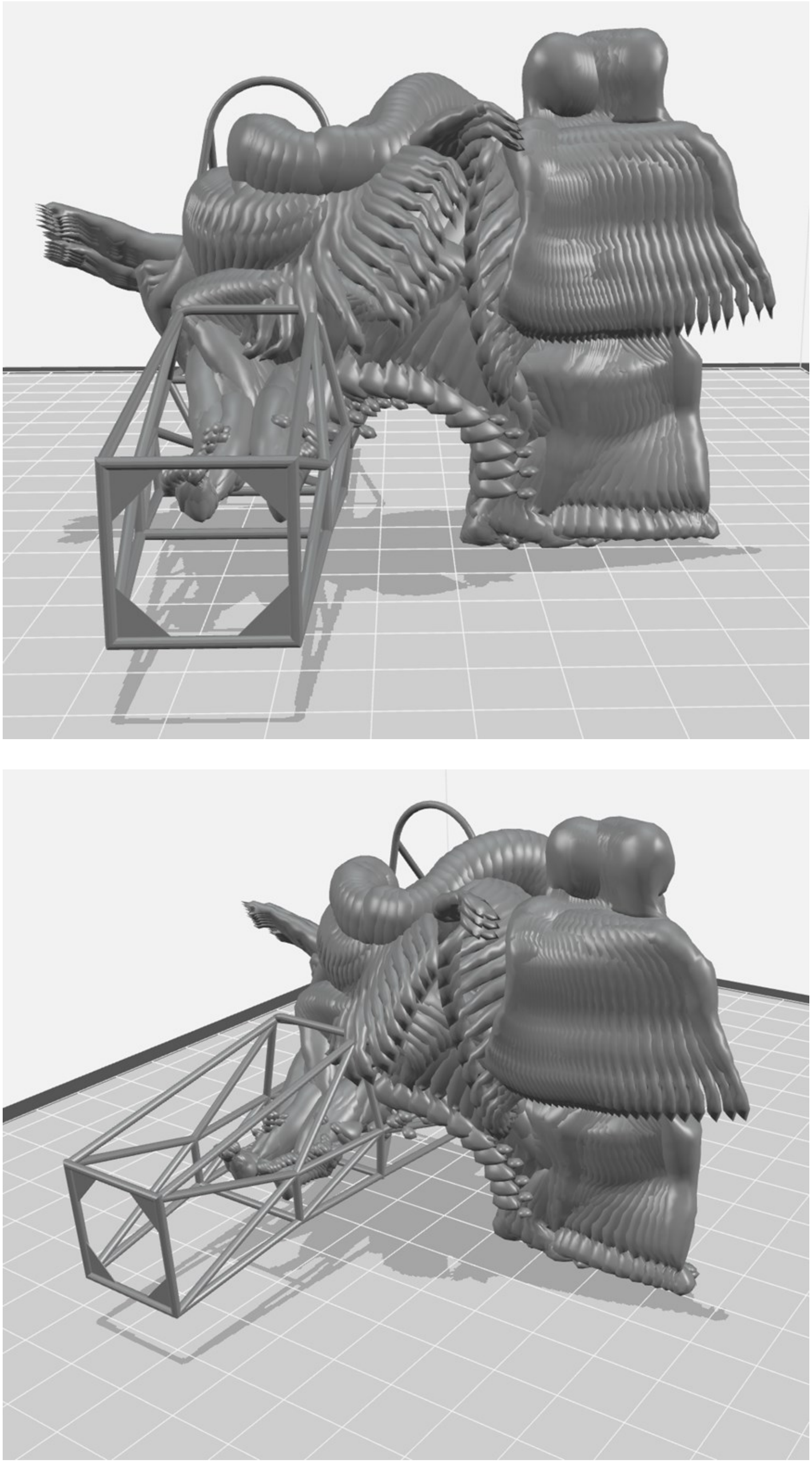


*Figure 109. Comparison between the driver's volume of movements and a traditional Formula SAE chassis.*

The development of a Generative Design study with the Fusion 360 software starts with the input of a CAD model of the prototype and continues with the definition of the geometries to be preserved, the obstacle geometries and the starting geometry. The reference CAD model was downloaded from Autodesk.

This action is possible because these are cars defined by strict regulations; therefore, the structure created in the laboratory for the take is an exact geometrical representation of the virtual model available online, which is used as the "starting-shape". This provides the programme with a good basis from which to start with the generative study.

This is followed by the identification of the geometries to be preserved, on which the loads are subsequently placed. In detail, the following parts of the vehicle are indicated:

- Engine supports
- Wheel hubs
- Backrest
- Driver's seat
- Steering column
- Pedals

The loads, obtained from bibliographical research, refer to a frontal impact at a speed of approximately 14 m/s and considering the total mass of the car (in all its components) and driver to be 300 kg. The Generative Design algorithms do not allow dynamic loads to be simulated. Instead, the applied constraints fix the wheel hubs, preventing displacement following the application of loads. Table 23 shows the strength of the applied loads according to the chosen chassis geometries.

*Table 23. Loads applied on Formula SAE components.*

| **Vehicle parts** | **Load applied [N]** |
|---|---|
| Engine supports | 230 |
| Wheel hubs | 230 |
| Backrest | 665 |
| Driver's seat | 510 |
| Steering column | 125 |
| Pedals | 355 |

Figure 110 shows the locations and directions of application of the loads.

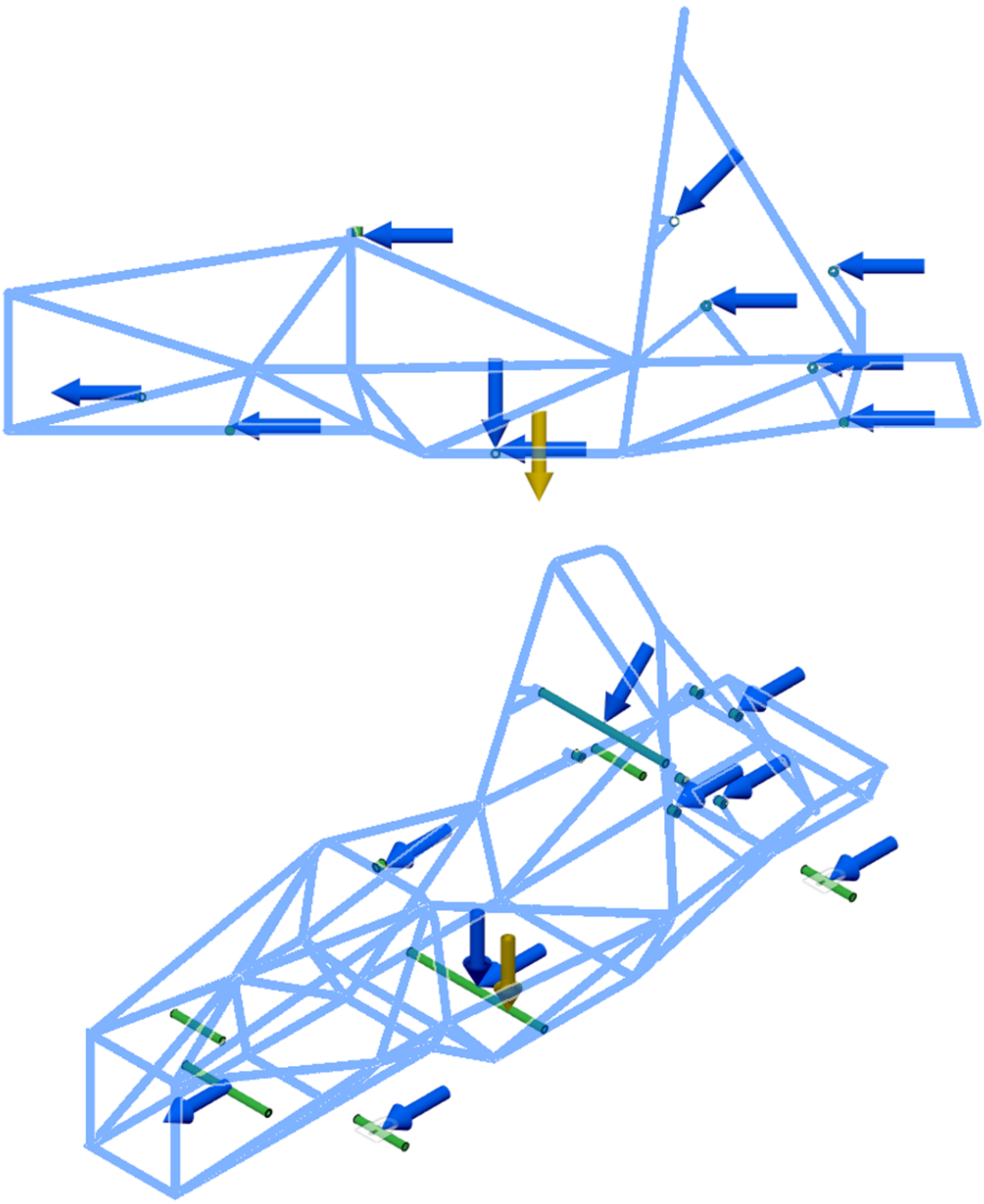


*Figure 110. Loads position related to starting frame geometries.*

Finally, obstacle geometries are implemented whose volume denies the generative study of adding material. Specifically, these volumes are:

- Volume of the driver’s movement occupied during egress test recording
- Steering wheel, seat, backrest and pedal pivot tubes.

Figure 111 describes the positioning of the obstacle regions in relation to the frame (in light blue). The volume of movement of the driver when exiting the frame is the predominant obstacle region to be considered as a constraint.

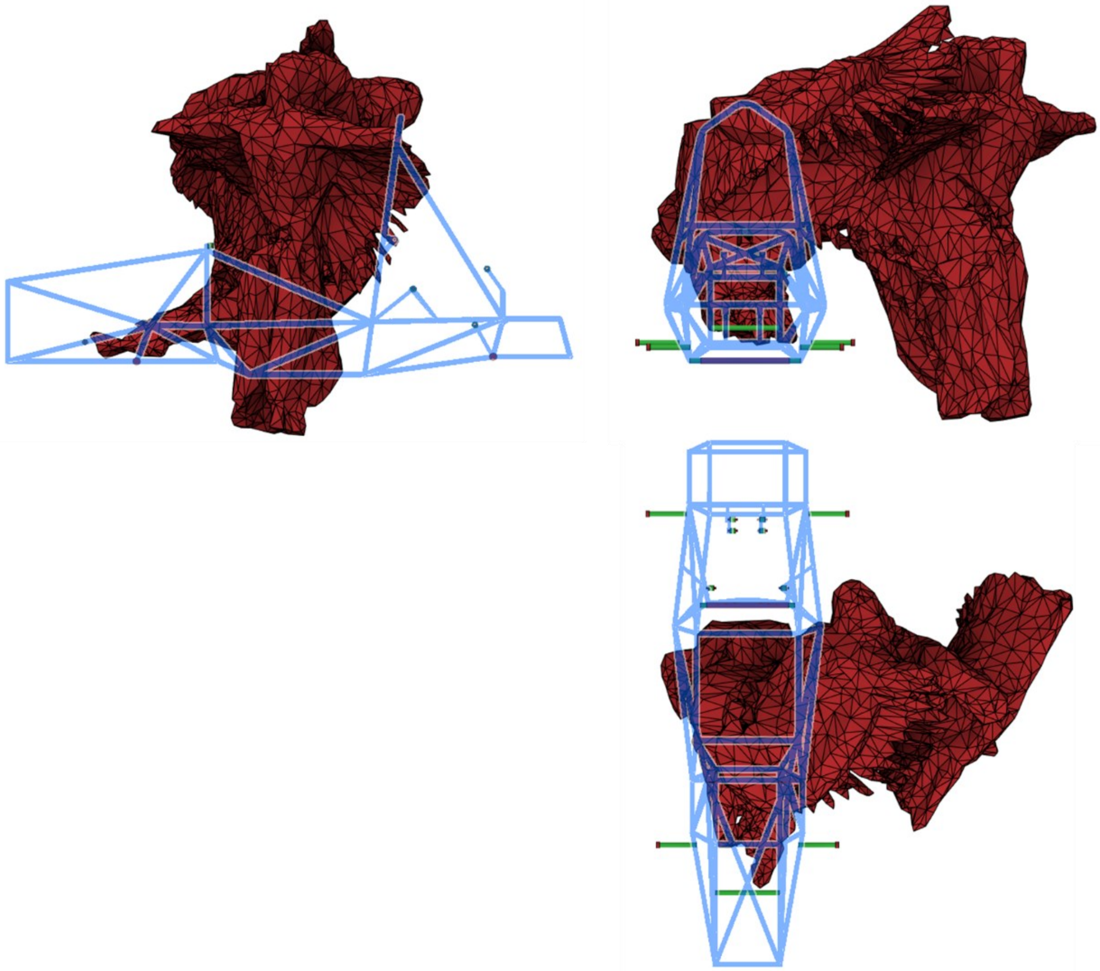


*Figure 111. Position and volume of obstacle regions.*

The last step consists in defining the materials that determine the characteristics of the results proposed by the generative algorithm. The literature review identified three types of materials for the Formula SAE chassis. Specifically, these are: Steel, Aluminium, and CFRP.

Figure 112 shows some results for the chassis of the Formula SAE, developed with generative algorithms.

*Figure 112. GD outcomes from the innovative method applied.*

All the Generative Design studies performed have in common the generation of solutions capable of withstanding the applied loads regardless of the material considered. From the analysis of the correlation between the volume of driver movement acquisition and the weight of the frame, steel is the material that has the possibility of finding solutions that are effectively influenced by the volume of driver movement acquisition (Table 25).

*Table 24. Correlation index between driver's volume acquired and chassis weight.*

| **Materials** | **Index of linear correlation: Volume acquired – Chassis weight** |
|---|---|
| Steel | 0.64 |
| Aluminium | 0.53 |
| CFRP | 0.23 |

This correlation indicates that some materials over others allow the algorithm to be more incisive according to the volumetric constraints of the obstacle regions. At the same time, as could be expected, the results of the Generative Design methodology propose frames with higher average weights starting with steel, then moving on to aluminium and finally CFRP being the lightest. As we can see from Figure 113.

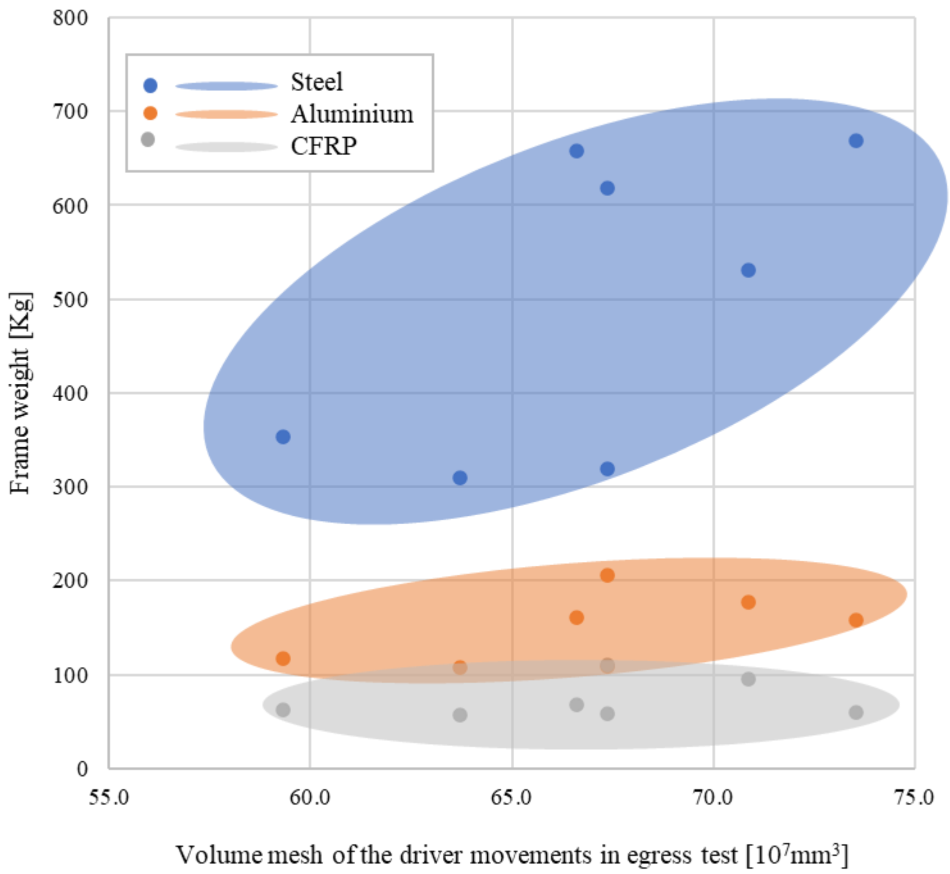



*Figure 113. Correlation graph between driver's movement volume mesh acquired and chassis weight.*

Furthermore, in all studies, the generative algorithm proposes a chassis structure with a wider cockpit than the original structure, even though the driver's movement volume is always within the standard starting frame. This aspect makes the exit manoeuvre easier and safer for the driver, at the expense of aerodynamic performance.

Table 25 shows how, for each material, the displacement and stress for the static load cases considered is low. This should allow the algorithm, which has an optimisation basis, to proceed with further steps in the development of the chassis geometry. The theoretical situation is not the one proposed by the Fusion 360 software, as the number of iterations is stopped due to "reaching convergence" of results.

*Table 25. Mechanical and physical features of Formula SAE chassis.*

| Test n. | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| **Volume mesh of driver movements in egress test [$10^7$ $mm^3$]** | | 59.3 | 66.6 | 70.9 | 63.7 | 67.4 | 67.4 | 73.5 |
| **Steel** | **Weight [Kg]** | 353 | 658 | 532 | 310 | 319 | 618 | 669 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Displacement [mm]** | 1.6 | 0.1 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 |
| | **Stress V.M. [MPa]** | 14.1 | 3.6 | 4.6 | 2.7 | 1.7 | 3.7 | 2.5 |
| **Aluminium** | **Weight [Kg]** | 117 | 161 | 177 | 108 | 109 | 206 | 159 |
| | **Displacement [mm]** | 1.9 | 0.1 | 0.6 | 0.2 | 0.1 | 0.2 | 0.2 |
| | **Stress V.M. [MPa]** | 6.1 | 1.2 | 2.9 | 1.8 | 1.3 | 2.0 | 1.6 |
| **CFRP** | **Weight [Kg]** | 63 | 68 | 95 | 57 | 59 | 111 | 59 |
| | **Displacement [mm]** | 0.7 | 0.1 | 0.3 | 0.1 | 0.0 | 0.1 | 0.1 |
| | **Stress V.M. [MPa]** | 4.7 | 1.3 | 2.6 | 2.1 | 1.5 | 1.7 | 1.4 |

One of the possible causes for this behaviour of the algorithm is the geometric complexity of the driver's motion volume. In fact, in these generative algorithms the obstacle volume plays a fundamental role as a constraint in the optimisation and could therefore penalise the achievement of a better condition of convergence of the results. A possible solution is to reset a new generative study identical to the one just completed, with the addition of a starting shape derived from a geometric solution generated by the first study. This forces the algorithm to resume iterations from the end point of the first study. This method could then present solutions closer to the convergence of the problem set, also considering the complex geometric constraints of the case study.

### 3.4.3. Innovative optimization methodology assessments

The case studies presented demonstrate how the methodology incorporating Motion Capture technologies in a product optimisation process through Generative Design methodologies is promising and of sure interest. Ergonomics is becoming increasingly important in the industrial and medical fields, and the proposed methodology finds wide scope within this research trend. In detail, the methodology applied to the two case studies has made it possible to find complex and innovative solutions, outside the comfort zone of classic design. The undisputed value of the approach collides with some technical problems. In particular, the management of a large amount of data requires powerful computers, higher than consumer level. The MOCAP technology used is the gold standard for accuracy and performance with regard to hardware for recording and collecting biomechanical data. This requires adequate computational support for the processing of the collected data, for the subsequent post-processing phases (rigging and parenting), and for the set-up and optimisation of products using Generative Design techniques. Future developments precisely concern the adaptation of software and hardware in order to obtain adequate results with less data, while maintaining an excellent approximation of the result with respect to the more onerous but detailed case.

# Chapter 4
# Conclusions

Nowadays, the variability of the business world, influenced by global socio-economic trends, necessitates dynamic and increasingly automated technological approaches. At the same time, the shift in the focus of design to humans and their physical well-being and environment opens the way for new product development methodologies that depend on new and more complex constraints. In this context, technologies derived from Design for Additive Manufacturing, find wide scope for use and evolution. The greater design freedom provided by additive manufacturing allows the development of innovative design approaches, such as Topological Optimisation and Generative Design. These are still confined to use in additive manufacturing, providing little support in the design of traditional manufacturing technologies.

The aim of the research is to equip designers with innovative methodologies with the interaction of DfAM tools and the traditional design approaches that optimise products by taking into account the variables that are crucial today in the entire production cycle. In particular, optimisation methodologies, derived from DfAM, were studied and made to perform better in conventional production contexts and closer to most manufacturing technologies in the industrial and medical fields.

In the first phase of the research, the most recent optimisation approaches in the literature were identified and studied. At the same time, the main optimisation software was catalogued and used to assess the pros and cons of each. In the next step, the most relevant and innovative optimisation methodologies were compared, such as topological optimisation and Generative Design. This step made it possible to clearly define both methods and to make up for the theoretical deficiency in the literature with regard to Generative Design. At the same time, experience was gained with the various optimisation software tools through collaboration with technicians from the leading specialised software houses. Once the theoretical background was built up, the methodologies were integrated and tested in various industrial processes and medical case studies. The use of the optimisation approaches led to considerable advantages in terms of product development and design at the prototype stage, with some shortcomings in terms of the economic feasibility of certain proposed solutions. In particular, it was noted that these optimisation methodologies renovate the classic compartmentalised design workflow, removing the designer from his psychological inertia that prevents him from innovative and sustainable design. After a careful evaluation of the case studies, we moved on to the next step of developing new optimisation methodologies to support eco-sustainable and human-centred design. In particular, optimisation methodologies were proposed that generate compliant structures for the consolidation of parts, methodologies that optimise structures depending on the movements of the subject interacting with the components, and design optimisation approaches depending on the ecological impact related to mechanical performance and the type of design required.

The main future developments concern the automation of these methodologies, making them independent of the designer's work background, in order to propose objectively optimised solutions depending on the constraints imposed. At the same time, the automation of design optimisation procedures can be readily connected to crucial market and ecological information to adapt the generation of new products to the cost or availability of raw materials, raw material supply issues, and social and ecological impact.

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