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Additive Manufacturing and Metal Replacement in the Automotive field: the case study of a headlight protection grid

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Abstract

Over the past years, the more and more stringent regulations on environmental impact of automotive industry have pushed manufacturers to strive for new solutions in terms of weight reduction. This phenomenon is translated in the well-known procedure of metal replacement, which has been present in the automotive world for a few decades but is lately gaining traction; this is thanks to the rising of a new series of polymer which can compete with the main metals used in the automotive world (steel and aluminium). To this day, metal replacement is adopted principally through the substitution of metal parts with plastic ones, in the majority of case injection moulded, while Additive Manufacturing, another process which is constantly spreading in the industry, is rarely taken into consideration.

The aim of this work is, after a brief excursus on both Metal Replacement and Additive Manufacturing and their use in the Automotive industry, to individuate an appropriate case study where these two approaches can be combined, selecting a component which is actually made of metal and could result equally or more competitive if produced in polymeric material through Additive Manufacturing.

After the selection of the component, the study continues with the analysis of its current manufacturing method, followed by the selection of the suitable Additive Manufacturing technique and corresponding material.

The next step is the evaluation of the current design and consequent redesign of the selected component, with the individuation of the variables that can be modified with respect to the original design and the objective of optimize it exploiting as much as possible the potentialities of Additive Manufacturing, taking into account also the mechanical requirements through the performing of Finite Element Model analyses. Finally, once one or more alternative designs have been individuated and developed, it will be possible to perform a comparison between the original component and the alternative one under different points of view and aspects.

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1. Introduction to Metal Replacement and Additive Manufacturing

1.1 Introduction to Metal Replacement

Metal replacement can be defined as the substitution of metals in a structure, part, object, with a different material with equivalent or higher characteristics from various points of view (mechanical, thermal, electrical, etc), typically polymers. This procedure has gained a lot of traction during the last decades and was made possible with the constant advancement during the course of the history of the characteristics of polymers and composites, in particular their high mechanical properties and excellent temperature resistance, which enabled new possible applications. A metal is in the majority of cases characterized by its crystalline bonds, which determines its features such high mechanical resistance, light reflection, electrical and heat conduction. From the chemical point of view, metal properties can be affected by both bases and acids, as well as water in some cases. Another important characteristic is their fusibility when subjected to heat, which makes most metals more ductile or malleable allowing for different manufacturing methods to be applied on them [1]. From this brief excursus, it is possible to understand why the metals have been the main protagonists of many of the manufacturing processes since man has begun discovering them: this is so true that the discovery and use of a new material has often marked a turning point in the mankind history. After the stone age in fact, the age of metals began, about eight thousand years ago (6000 BC), when humans learned to melt copper, even if the first big transition happened later, in 3200 BC, when the bronze age began. Bronze age can be recognized as one of the first cases of “industrial process”, since the manufacturing of bronze tools, ornaments and so on already required the following of precise steps. Since then, metals have experienced an increase in their use for production, with the iron age starting in 1200 BC and most importantly the Industrial Revolution starting in 1800 which introduced the intensive production and use of steel and aluminium [2]. Especially during the aforementioned period, metals have been considered the workhorse of almost all the existing industries mainly thanks to four characteristics [3]:

- First of all, their toughness, especially in fracture situations, with the steel which is one of the toughest known materials; this made the metals during the course of the industrial development very appetible especially for applications which involved high levels of durability and reliability.

- Second, the majority of metals possess a fundamental characteristic, which is isotropy, so the main properties of the metals do not change dependently on the considered direction; this is a great advantage since it makes metals in general more reliable and predictable with respect to other categories of materials.
- Third, the already mentioned conductivity properties of metals: this can be of course an advantage or a disadvantage depending on the application, but in general it can be said that metals like aluminium and copper are the main choice when it comes to transmit electricity; in addition to that, also the magnetic properties of the metals are difficult to find in other categories of materials.
- Finally, especially in the past metals had no comparable rivals in terms of mechanical and thermal properties in the main temperature ranges which interested the industrial applications, especially for which concerns the fatigue resistance.

The history of plastic is more recent as it was discovered a bit more than one century ago. The first polymer to be made by man was a nitrocellulose compound made by Alexander Parkes, while the first fully synthetic plastic was the Bakelite invented in 1907 by Leo Baekeland, also inventor of the term “plastic” [2,4]. In general, with respect to metals polymers are characterized by larger molecules called for this reason macromolecules, composed by lots of subunits which repeat themselves (hence the name “polymer”); for this reason, the properties of polymers vary accordingly to their different structures [1]. A first, big subdivision can be done between Thermosetting and Thermoplastic polymers, with the first characterized by stronger bonds with respect to the latter [4]. Almost immediately the plastics were considered an economic alternative to metal in lots of “not critical” applications, mainly consumer goods like toys, handworks, and so on. Especially during the first years, it was instead more difficult to realize a complete substitution of metallic parts with polymeric equivalent, due to the low mechanical properties of the standard polymers [1]. The situation has been improving constantly especially during the last 50 years, thanks to the advent of high-performance polymers and composites. The continuous improvement of the polymers coincided with an increasing and increasing need for reduction of the metal usage in different industries; this was driven by several reasons, nowadays mainly related to weight reduction and environment; in general, after analysing the main advantages that led the metals to overcome the competition and become the workhorse of the industrial revolution, in the same way some of the flaws which during the years pushed researchers to find and develop a valid alternative to them can be taken into account [3]:

- As already mentioned, one of the main flaws that characterize almost every metal is the strength to weight ratio: it is true that metals are (or, to better say, were) not rivalled by any other category of material, but this always came with a price, which is the notable weight of the most used metals, like steel, which has a density much higher than ceramics or polymers. If the objective is to reduce the weight of a metallic component, it will be necessary to look at lighter metals like aluminium or magnesium, but for sure something on the side of stiffness and toughness will be lost. One of the few metals which constitutes an exception is titanium, but the high price makes it not ideal for "everyday" applications.
- Another problem that was already mentioned earlier is the conductivity, be it thermal or electrical; first of all, if the aim is to strengthen the metals to increase their strength to weight ratio, this can lead to a loss of other properties like conductivity or corrosion resistance; other than this, as already said there are applications in which, instead of conductivity, insulation is wished.

1.1.1 Metal Replacement State of Art

Currently, thanks to the aforementioned high-performance polymers, characterized by high mechanical, thermal and chemical performance, it is largely believed that the fully potential of plastic in replacing metal has not yet been reached [1,4]. Like it will be seen later in this thesis, metal replacement in every case should be evaluated and analyzed, typically by performing a feasibility study. The component that will experience the metal replacement must retain its original characteristics despite the several changes that will be applied on production, manufacturing, implied technologies and so on. Often the metal replacement process will also require important changes in the structure, shape and aesthetic of the component, to improve its characteristics, always without affecting the performance and features. Finally, it is important to underline that the feasibility study does not always give a positive outcome, hence the importance of sustaining them in a rigorous and strict way. There are several advantages of the metal replacement: energetic costs reduction during the production phase, weight reduction (hence advantages both in performance and environment), possibility of stamping more complex geometries, shorter Lead Time and Time to Market, better chemical properties, some better physical properties, and so on. Historically, as seen before, it is possible to observe some examples of metal replacement starting from the 50s, when lots of metal toys and other common use objects started to be replaced with plastic equivalents, while from the industrial side lots of different fields of application can be taken into consideration [5]:

- Aeronautics and Aerospace: applications of metal replacement in the aeronautics field are dated up to the 60s-70s, when the properties of the polymers did not yet have the necessary characteristics to completely replace metals from structural and thermal point of view; nevertheless, the possibility of fast and economic (with respect to metal) shaping (also in complex way) and personalization, together with the higher resistance to corrosion, gave a huge incentive to the utilization of this kind of material [6]. In general, the need for weight reduction in these fields has always pushed researchers to try to replace metal components with lighter materials. Another interesting application of metal replacement in the aerospace (but also biomedical) field was explored by Nambiar et al. [7], which sought for an alternative to metal in the ambit of protection from radiation, being them generated from particle emissions, proton/electron/neutron, or high energy electromagnetic waves. All these are known to be dangerous for health, since may cause cell mutation, cancer, etc. The use of metal for the screening from this kind of radiations is not efficient, mainly because they may generate secondary radiations which will then require a further shielding system, increasing both the costs and the weight, making polymers a desirable alternative for developing materials to mitigate these radiations.
- Civil: despite the fact that steel and concrete have always been dominating the civil industry, over the past years the need for new and more efficient material has increased, especially for environmental reasons; another fundamental characteristic of polymers with respect to metals is their corrosion resistance, which may result to be crucial in these fields [5].
- Marine: like previously said in the civil field, also in the marine one the main drivers for the shift from metal to polymer are the environment and the corrosion properties, considering that ships, boats, submarines and similar work mostly in saltwater. In this case some outstanding properties of the polymeric materials with respect to the metallic ones (mainly weight reduction and corrosion resistance as already mentioned, as well as high durability and design flexibility) are counterbalanced by other disadvantages like the anisotropic behaviour, general lack of knowledge about the properties of polymers, which led to building structures with in mind the same concepts and rules to apply in case of a metal structure, losing almost completely the weight advantage, and the lack (in the past) of a high-quality low-cost production method [5,8]
- Automotive: can benefit basically of all the aforementioned advantages and has been one of the first industries to apply the concept of metal replacement especially with composite materials (just consider the carbon fiber parts in supercars/racing field). The automotive applications will be analyzed deeper in detail in a dedicated paragraph.

- Other fields can include also and not only electrical and electronic, home automation, medical, robotics, military, etc.

1.1.2 Metal Replacement in the Automotive field

One of the first cases of Automotive metal replacement is dated 1937 and was attempted by Ford to compensate the steel shortage given by the World War Two, but this model remained a prototype due to economic limitations and today it is not possible to state clearly which were the material used to produce it [9-12]. The first application of a polymer fibre composite was the fiberglass body of the 1953 Chevrolet Corvette [13], shown here in figure 1.

Figure 1 - Chevrolet Corvette fiberglass body, https://moldedfiberglass.com/about-us/history/corvette-story/

Another notable example comes from 1957 and is the VEB Trabant, which can be appreciated in figure 2, but even in this case the use of a plastic body with respect to the "classic" steel one was more a necessity driven by the shortage of steel in the German Democratic Republic during the start of the Cold War [9-12,14].

Figure 2 - VEB Trabant model [14]

Plastic door panels would have continued to be present in the automotive market throughout 70s, 80s and 90s, when thermoplastic materials still didn't have the characteristics to match the metal equivalents and suffered mainly from the thermal point of view, as well as the resistance to Ultraviolet rays one. During these years plastics also began to be used for other elements such as headlights, bumpers, fenders and so on, while also carbon fibre started to shift from the top-class racing fields (McLaren started using this material in 1981) to street low-volume supercars. As regards structural parts, the metal replacement wouldn't start before the 2000 and 2010 decades, when carmakers started the quest for the reduction of weight and replacement of conventional metals like aluminium and steel; today, it is a well-known, spread and consolidated process thanks to the aforementioned high-performance polymers and composites.

1.2 Additive Manufacturing State of Art

Additive Manufacturing is an innovative technology which makes possible the production and manufacturing of components and products, also with complex geometry, directly from the 3D CAD model. The peculiarity of Additive Manufacturing is, as the name suggests, that with this particular technique the material is added, rather than subtracted like in the traditional manufacturing methods which can be therefore defined as "subtractive". AM also allows the usage of less material with respect to traditional methods and a higher level of freedom in the component design phase; nowadays Additive Manufacturing has reached a level of performance which allow a production without the aid of an operator ensuring adequate characteristics of tolerances, rugosity and mechanical properties. Officially AM born is dated 1982, when Chuck Hull invented Stereolithography (SLA), an Additive Manufacturing technique for polymers which is still used today. In the last years, AM experienced a notable growth in the manufacturing industry, indicated by the high selling of AM machines and printers. The process can be subdivided in six main subprocesses:

- 3D CAD generation: it is the only prerequisite to adopt Additive Manufacturing techniques, and, considering the high diffusion of the CAD systems nowadays, this represents one of the advantages of the AM.
- STL file generation: STL is the standard mathematical model in Additive Manufacturing; it stands for Standard Triangulation Language and consists in the conversion of the 3D CAD model into an approximation done with triangles of different dimensions (depending on the wanted resolution) which will follow the model profile.
- Part orientation and supports generation: these two steps are typically performed automatically by the used software but can be also modified and customised by the user due to their crucial importance in the process. In fact, the supports will have to fix the object to the platform during the building phase, to protect the part during the manufacturing and to support the more fragile zones. The supports should also avoid that the component is stuck with the building platform and be easily removable when the part is finished. As regards orientation, it mainly defines the time of production of the part and its rugosity.
- Slicing: usually executed by the software, it is the realization of different section of a certain width which will compose the final part.
- Building: once the sliding is completed, the part is generated slice by slide as defined in the previous step.
- Post-treatment: not always necessary, the post-treatment activities may include support removal, surface finishing, thermal treatments and so on.

Additive manufacturing can be used for both metals and polymers. As regards metals, it is possible to subdivide the processes according to the initial state of the material (powder, wire or laminar) or to the energetic source (laser or beam). These characteristics will influence the mechanical and microstructural properties of the component, as well as the tolerances and rugosity. A similar subdivision can be done also for polymers, which can start the process as powder, liquids or solids. For this Metal Replacement activity, in Chapter 4 the main possibilities will be analysed to choose a process. In general, Considering the ISO normative ASTM2900-15 the Additive manufacturing processes can be divided into seven macro categories:

- Binder Jetting
- Direct Energy Deposition

- Material Extrusion
- Material Jetting
- Powder Bed Fusion
- Sheet Lamination
- VAT Photopolymerization

Most common application of Additive Manufacturing include:

- Aerospace sector, aiming at lightweight components with the same characteristics of the traditional ones.
- Medical sector, to print thinner, more ergonomic prothesis.
- Jewellery, to promote the concept of mass customization.
- Automotive.
- Etc.

1.2.1 Automotive Additive Manufacturing

Going more in detail about the automotive field, due to the initial high costs the first applications of this technology were in prototyping, thanks to the possibility of producing in a fast way even complex components to test and validate, and on racing cars, thanks to the possibility of reducing a lot the weight of some parts. Since when the first techniques of Additive Manufacturing were invented, some carmakers saw the potential of them and got interested in how exploiting them; some examples of rapid prototyping applied to automotive field are dated back to the first years of the 90s, when Ford, Mercedes Benz, Porsche, General Motors, Chrysler, Volkswagen, BMW and many other applied successfully the main techniques available at that time for the development of various prototypes [15-17, 22]. Ford in particular was one of the first to invest on the uprising technology in 1988 [22]. In 2010 already BMW is reported to actively make use of Additive Manufacturing technologies in their motorsport division, more specifically in their DTM race cars, with the 3D printing of a water pump wheel in aluminium, the result of which can be seen in figure 3, for the Z4 DTM model which proven to be as reliable as (if not more reliable than) the one produced with traditional manufacturing methods [22]; in 2012, the Nissan Motorsports V8 Supercar team have been able to perform some modification to the aerodynamics using 3D printing

[23]; the technology has been used by some Formula 1 teams like Sauber, Toyota and Benetton/Renault since the end of 90s – early 2000s for both rapid prototyping and direct production [18-20, 22] and is nowadays a well-consolidated technology in the majority of the Formula 1 teams.

Figure 3 - BMW Z4 3D printed Water Pump [22]

Other than the luxury brands and sport cars, 3D printing is used in the production of customized parts in production cars. For example, former Citroen sub-brand DS was one of the first to bet on mass customization in the mid-price sector with their DS3 (figure 4) model thanks to Additive Manufacturing processes, mainly linked to titan [21], while Peugeot used AM in the development of its Fractal concept car [22] (figure 5) and Alfa Romeo printed the Giulia's grille thanks to the technology (figure 6) [24].

Figure 4 - Detail of DS3 model 3D printed, https://www.3dprintingmedia.network/psas-ds3-dark-side-edition-surprises-titanium-3d-printed-interiors/

Figure 5 - Detail of Peugeot Fractal [22]

Figure 6 - 3D printed Alfa Romeo Giulia grille [24]

Another very interesting sector is the one of automotive spare parts of vehicle which are not produced anymore, especially historical ones: this is done both from dedicated start-ups and carmakers themselves and finds applications with both polymer and metal Additive Manufacturing processes: to mention some examples, Nissan has a dedicated heritage program and actively restored some components of the legendary R32 Nissan Skyline GTR, whether both Mercedes Benz and Porsche provided examples of metal Additive Manufacturing applied to the restauration of historical models (an example of a restored component of the Mercedes 300SL can be appreciated in figure 7) [25].

Figure 7 - Component of Mercedes 300SL restored through Additive Manufacturing [25]

1.3 Metal Replacement and Additive Manufacturing

As regards Additive Manufacturing applied to Metal Replacement, the combination of the two is quite a new technology with respect to the two separated fields: typically Additive Manufacturing, especially in the Automotive field, includes the use of metal Additive Manufacturing instead of parts built in metal with traditional processes or, vice versa, polymer Additive Manufacturing instead of parts built in plastic with traditional processes; on the other hand, while metal replacement is a well-known technology in the automotive field, the parts are typically produced using traditional processes like injection moulding or thermoforming. Some applications of Additive Manufacturing applied to Metal Replacement can be seen in the Oil and Gas sector, where the company Roboze used PEEK instead of metal to reach weight reduction and more complex shapes [26]. The hypothesis of Metal Replacement combined with Additive Manufacturing has been explored and studied also in the literature: Kumar et al. [27] examined the possibility of exploiting electrically conductive polymers instead of metals in aerospace applications, in particular for the lightning strike protection which is applied on aircrafts. Due to the fact that polymers are mostly known for their electrical insulation, rather than conductivity, it may come natural to ask why to replace metal in this particular application: the answer is to research in a leitmotif of the metal replacement activity, which is weight reduction, as already mentioned a crucial aspect in an industry like the aeronautical one. To overcome the typical insulant behaviour of polymers without losing their lightness, the addition of copper or graphene filler has been explored. Other than this, it is important to underline the production method of this experimental protection layers, which have been made exploiting Additive Manufacturing, in particular Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM). Despite the fact that during the experimentations the solution has proven to be more effective with respect to a situation in which the aircraft panels were not protected at all, it did not reach either the minimum protection requirements, arriving therefore to the conclusion that the adhesion properties of the material require further improvements. If it is preferred to consider an automotive application, Mohammadizadeh et al. [28] in 2019 thoroughly investigated the thermal behaviour of a 3D printed air intake manifold. This component was historically made in steel and aluminium, and lately it has been experiencing a partial shift to plastic, therefore, it may not be considered an example of metal replacement in a narrow sense; nevertheless, it is worth to mention this study as a case of "indirect" metal replacement. In the same study, also connecting rod were produced with the scope of performing the same thermal analyses, but samples have shown a significant degradation level not suitable for the substitution of traditional metal components.

2. Choice of the component on which to apply Metal Replacement

From what has been seen up to now, it becomes clear that performing a metal replacement operation in combination with additive manufacturing is a real challenge: a vehicle has tens of thousands of parts, if each single screw, nut and so on is considered, and it is therefore crucial to select the appropriate case study that can at the same time benefit from the advantages of both metal replacement and additive manufacturing, resulting competitive with respect to a production with the traditional process, not only from the economic point of view but also from the physical one. For these reasons, before starting with a first selection of possible components it is fundamental to fix some of the characteristics that the part itself must comply with in order to be considered viable for further studies. In the end, all the parts have undergone through a preliminary analysis considering six fundamental features that they should have:

- Volumes competitiveness: this aspect is more related to additive manufacturing than metal replacement; one well-known flaw of the process with respect to the traditional ones is in fact that the production times are not yet comparable with the traditional ones, unless small batches of complex parts (complexity will be also discussed later) are taken into account; if we imagine assigning a scale from 1 to 10 to this parameter, a 10 is a component which can compete with and even surpass the traditional process in terms of "convenience" for the production, therefore high values are typically assigned to parts characterized by a low-volume production and vice versa.

- Weight reduction: on the contrary, this aspect is more related to metal replacement than additive manufacturing; it has been already discussed in the previous chapter that one of the main advantages of metal replacement is that polymers are almost always lighter with respect to metals; hence, the choice of adding a parameter to measure preliminarily the advantage gained in terms of weight for the considered components; in this case a part which will reach a score of 10 is a part that would highly benefit of a shifting from metal to polymer. Of course, since in this phase a specific material is not selected yet, neither from the side of the traditional process nor from the additive manufacturing one, this score will only give a preliminary estimation.

- Mechanical feasibility: with this parameter it is indicated the level of mechanical stress to which the component is subjected, but giving a higher score not to a very stressed component, but to a part that is not solicitated at all or with very low levels of solicitations; this is done because despite the notable advances of the polymers in the last decades there are still some applications in which they cannot compete with metals (or at least, not with a significant increasing in the prices), or in which the anisotropic properties of the polymer has not been yet studied in deep.

- Thermal feasibility: a parameter very similar to the mechanical one, but for the thermal stresses; therefore, with a score of 10 is not indicated a very stressed component, but on the contrary a component which is not subjected at all to high temperatures; also in this case this is done in order to take into consideration the risks that the use of a not suitable polymer would have on the integrity of the component at high temperature.

- Geometrical feasibility: this parameter is mainly related to additive manufacturing, since it is known that the majority of the AM machineries have a limited chamber volume which will consequently limit the dimensions of the part to eventually print at the end of the study. It is possible to also include the complexity into this parameter, considering that it is typically a positive parameter for the additive manufacturing processes, so that a part which receives a score of 10 on this aspect will probably be a component at the same time small and quite complex, so that it can benefit of an additive manufacturing production.

- Cost feasibility: one of the fundamental parameters to understand whether to proceed or not with the study is for sure the cost of the operation; since this aspect is influenced from other ones already seen, like the volumes and the geometry, other than also from aspects which will be treated after the final choice of the component, like materials, machinery and so on, the score obtained in this preliminary phase will be just an estimation.

2.1 Preliminary subdivision

Now that the main characteristic to analyse have been specified, a preliminary subdivision can be done. A first subdivision was done according to the functionality that the part printed in Additive Manufacturing would have:

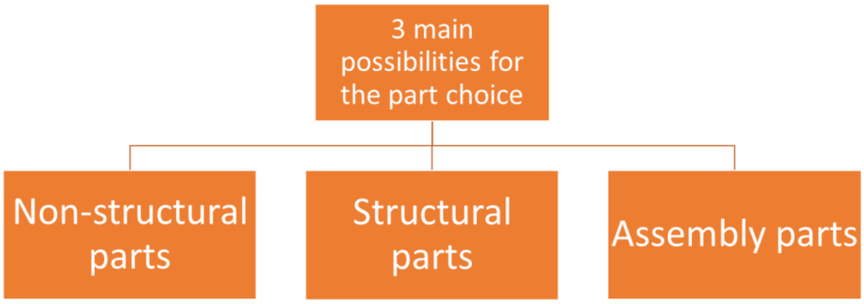

Figure 8 - Preliminary subdivision done by functionality.

For each of the categories, some proposals are presented, together with a brief description ad some comments on the characteristics that have been listed before.

2.1.1 Non-structural single parts

With "non-structural" single parts it is meant parts that are aesthetical or not subjected to high stresses, mainly from the mechanical and thermal point of view.

Motorcycle levers

In a motorcycle, levers are used for controlling the clutch and the brake of the vehicle. In the majority of cases, they are milled from steel or aluminium.

Figure 9 - Hybrid 3D printed motorcycle levers, https://www.3dprintingmedia.network/ktm-technologies-presents-case-for-hybrid-3d-printed-and-composite-motorcycle-parts/

An Additive Manufacturing process in polymer would have the advantage of weight reduction and high possibility of customization, other than the possibility of creating highly ergonomic components; therefore, in this case the highest score would be geometrical feasibility and thermal resistance, while a low score is obtained from the volume point of view.

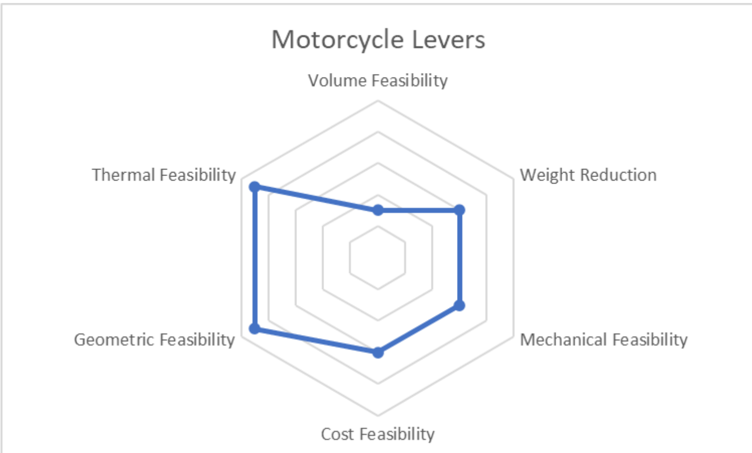

Figure 10 - Motorcycle lever radar graph

Hood Scoop

These components are typically used for aesthetical purposes only, therefore a printing in Additive Manufacturing would increase the customization level; nevertheless, they are already produced in plastic in the majority of cases, therefore the purpose of the metal replacement would be lost; for this reason, even if the component has been analysed with the six characteristics like all the other, it has been almost immediately rejected.

Hood Rod

Remaining in the hood zone, a component which would benefit a lot of the Additive Manufacturing and Metal Replacement from the weight point of view, is the hood rod.

Figure 11 - Hood Rod, https://www.alamy.com/stock-photo-car-with-open-hood-23596952.html

This component is used to hold the hood when it has to be opened for repairing or maintenance purposes. Nowadays it is typically a very standardised bar of steel, whether with an AM printing in polymer also a partial customization would be possible. As already said in this case the highest score will probably be on the weight reduction, but on the other hand very low scores of volumes competitiveness and geometrical feasibility will be reached: the fact that it is a very standardized component installed on all the vehicles will impact negatively on both aspects, while also the dimensions will partially influence (in a negative sense) the score of geometrical feasibility.

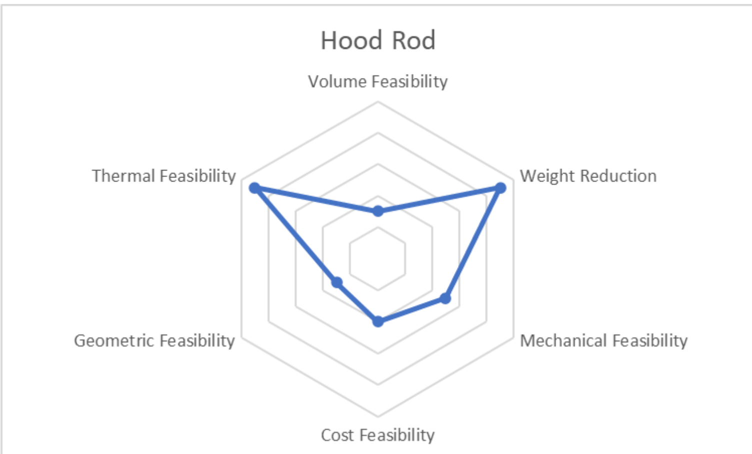

Figure 12 - Hood Rod radar graph

Car pedals

Pedals are used to control throttle, brake and clutch of the vehicle; they can be made in plastic or in aluminium with the traditional processes, and also in this case the part would benefit of both weight reduction and partial customization.

Figure 13 - Additive manufactured pedal [40]

It is a quite "balanced" component, with neither too positive nor too negative aspects, but the high volume of production of these components may be a negative one.

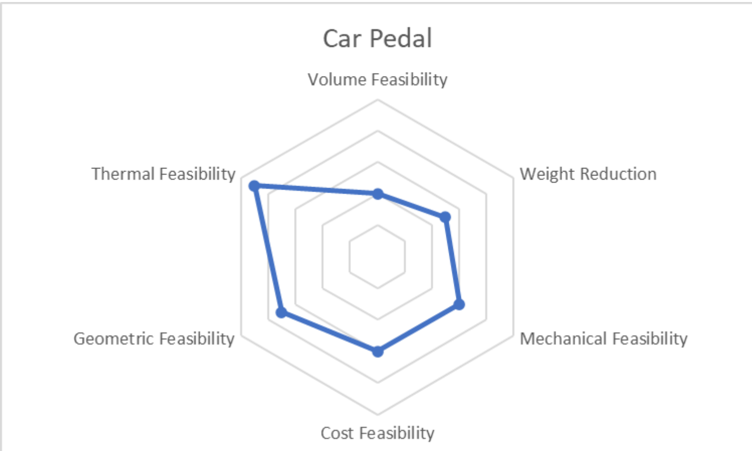

Figure 14 - Car Pedal radar graph

2.1.2 Structural single parts

With "structural" single parts it is intended components that are subjected to high solicitations, from the thermal, mechanical or from both the points of view.

Rods, pistons, flanges, etc.

All these components are subjected to both very high thermal and mechanical stresses, therefore the only way to obtain a feasible part would be to adopt a very strong polymer, which would rise too much the costs with respect to traditional production. For these reasons in all the previously mentioned aspects and characteristics the scores were very low, and these components were discarded almost immediately.

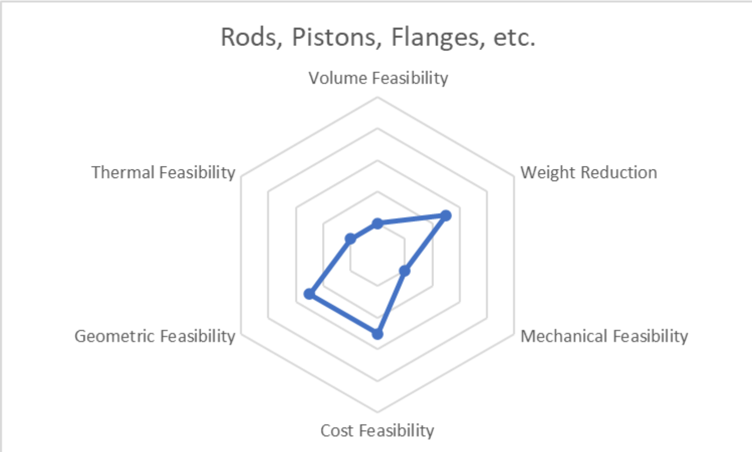

Figure 15 - Rods and other similar components radar graph

Door or trunk hinges

Hinges are fundamental to allow a correct opening and closing of doors and trunk.

Figure 16 - Car door hinge, https://www.shutterstock.com/it/search/car-door-hinges

They are small components which could be easily printed with the main AM techniques, but the difference in weight would probably be marginal, so the lowest scores would probably be volume competitiveness, weight reduction and mechanical feasibility, especially considering the fatigue.

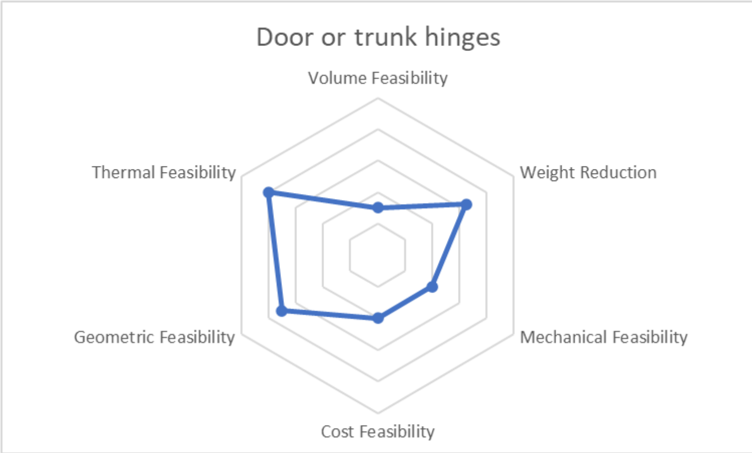

Figure 17 - Door or trunk hinges radar graph

Engine mounts

The main purpose of the engine mounts is to ensure that the engine doesn't move too much inside the car body, absorbing any vibration or shock that is transmitted to it when the vehicle is moving, especially in rough terrain. The most commonly used material when speaking about engine mounts is steel, due to its cost-to-strength ratio; however, sometimes aluminium is preferred due to its lighter weight, despite an increasing of the costs.

Figure 18 - Additive manufactured engine mount, https://forward-am.com/use-cases-and-whitepapers/engine-mount/

By knowing this trend, it is possible to understand that AM printed engine mount with polymeric materials would furtherly benefit from the weight reduction; on the other hand, the scores on volumes, mechanical and thermal feasibility may be a criticality.

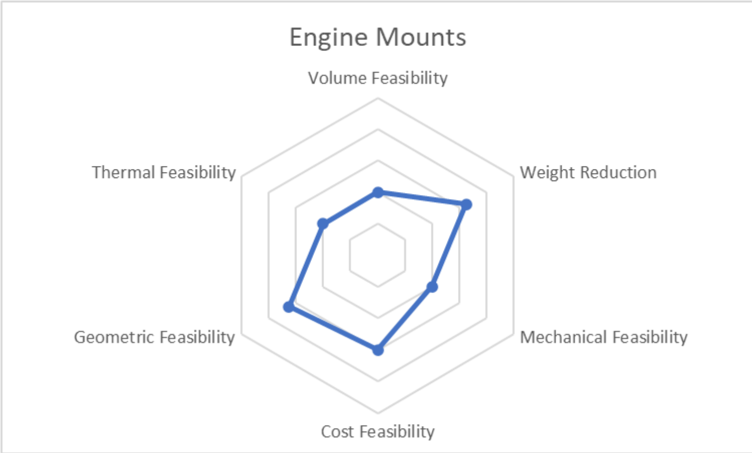

Figure 19 - Engine Mount radar graph

Muffler clamp

It is a simple clamp used to keep the muffler in the right position when subjected to solicitations of various genres.

Figure 20 - Muffler clamp, https://www.yourmechanic.com/article/symptoms-of-a-bad-or-failing-exhaust-clamp

Probably the temperature would be the main issue in this case, also keeping in mind that the benefits in terms of weight would be not so high, and therefore the lowest scores would be volumes, thermal feasibility and weight reduction.

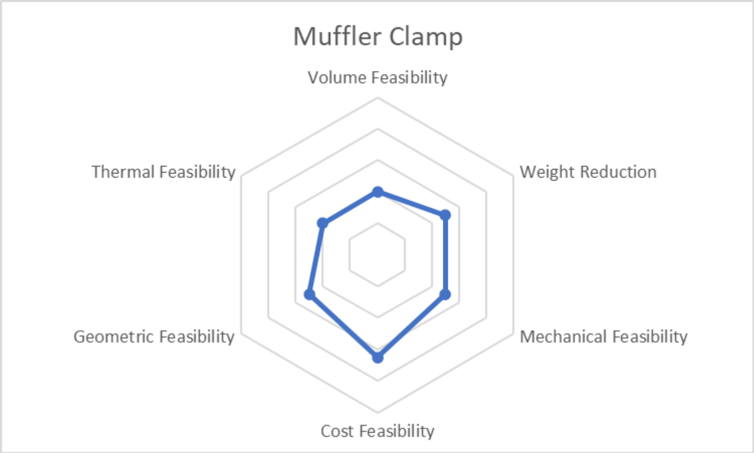

Figure 21 - Muffler Clamp radar graph

2.1.3 Assembly parts

This term is referred to components that are parts of an assembly, so that more than one component can be merged into a single component or just a single one is changed from metal to polymer.

Wheel hub

The wheel hub assembly is situated between the drive axle and the brake disk; its main components are uprights and hubs, so the fixed and rotating part, and other minor components like bearings, mounts, arms and so on [29].

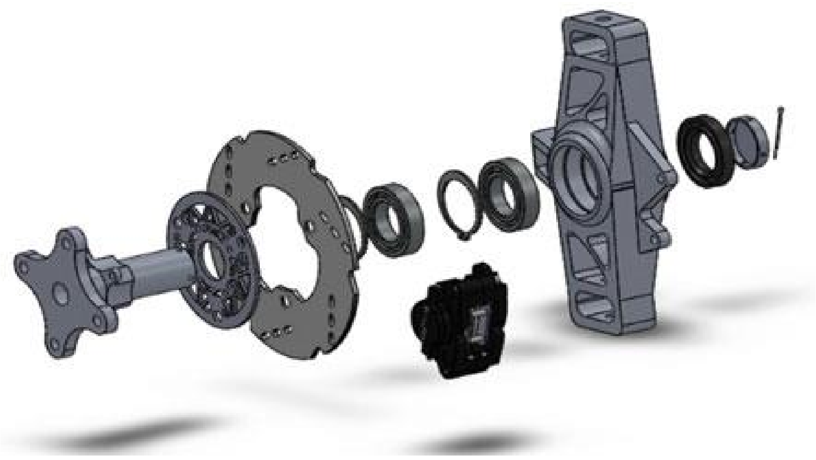

Figure 22 – Example of wheel hub assembly [29]

Therefore, a possibility could be to substitute a single component or to merge more parts into a single one.

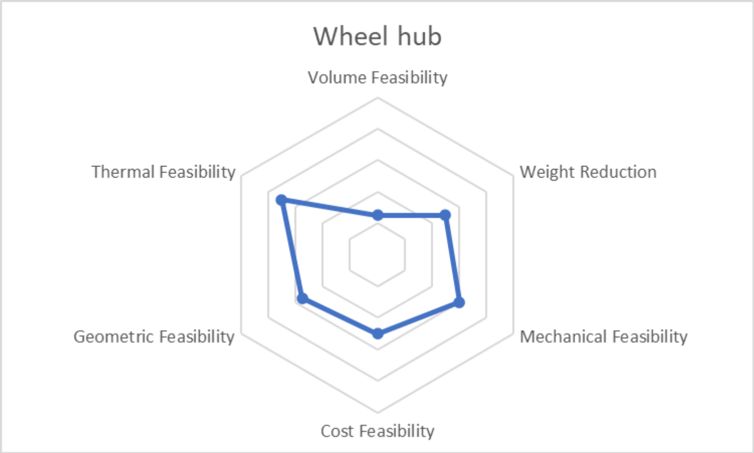

Figure 23 - Wheel Hub assembly radar graph

Control arm

The control arm assembly is referred to the suspension link between the chassis and the suspension hub, used for example in a MacPherson suspension; In the majority of the cases the control arm itself is obtained from steel through stamping and welding, and is connected to chassis and suspension through joints and bushings, that could be also in this case the main parts to be replaced with an equivalent component obtained from polymer 3D printing.

Figure 24 – Example of Control Arm [41]

The main issue is that also in this case the component is critical from the point of view of the mechanical resistance that it must endure, therefore careful studies should be made on this aspect.

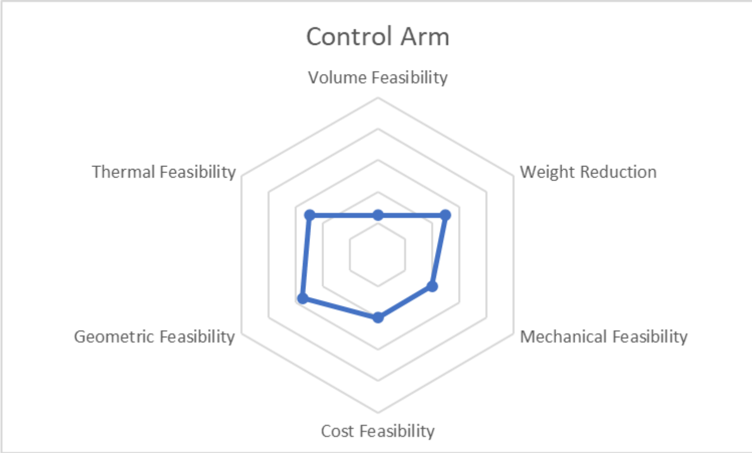

Figure 25 – Control Arm assembly radar graph

Seat assembly, seatbelt zone

This case is mainly referred to the bracket which links the fastening devices of the seatbelts with the body of vehicle, a relatively simple component but that in reality is made by about ten pieces welded together. This study was already brought on by General Motors in collaboration with Autodesk [30]: starting from their 8-pieces standard set bracket they developed through a software a wide plethora of different designs made by one single steel component, printable with the main technologies available today for the Metal Additive manufacturing. The final result can be appreciated in the figure:

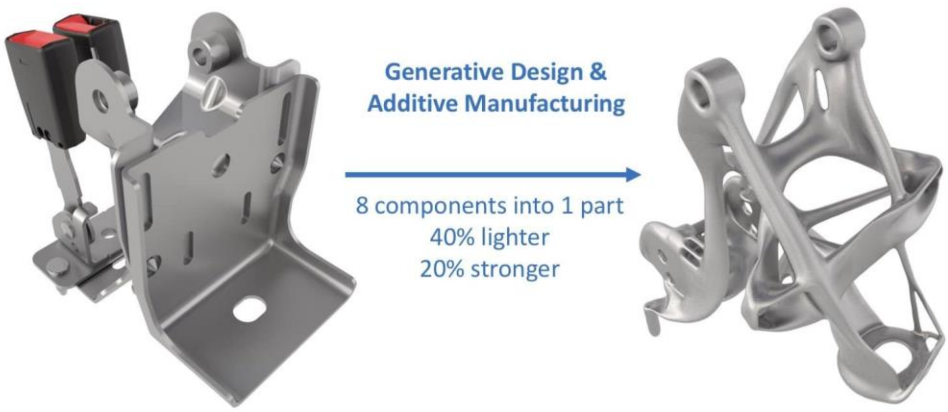

Figure 26 – Seatbelt bracket developed by General Motors in collaboration with Autodesk [30]

Starting from this example, a possible solution would be to take an existing (front or rear) seat bracket and perform a similar study but with polymers, perhaps not replacing the entirety of the components with a single object but replacing one or more metal components with a polymeric one.

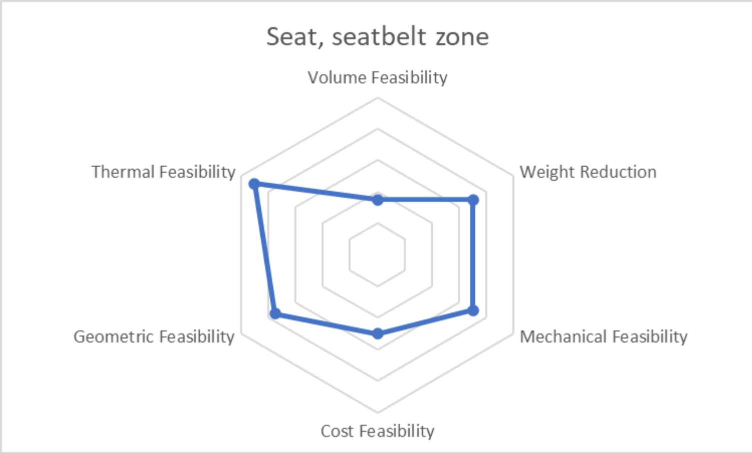

Figure 27 – Seatbelt zone assembly radar graph

Seat assembly, headrest zone

The headrest, considering also the two bars that link the cushion to the rest of the seat, can be considered an assembly: printing the two bars in polymer can give a slight advantage in terms of weight, but it would be necessary to consider the quickness of the production process with respect to the traditional one, so for sure the lowest score values would be volumes, cost feasibility and geometric feasibility (not for the dimensions, which is a positive aspect, but due to the fact that is a very standardized and simple component).

Figure 28 - Headrest, https://en.wikipedia.org/wiki/Head_restraint

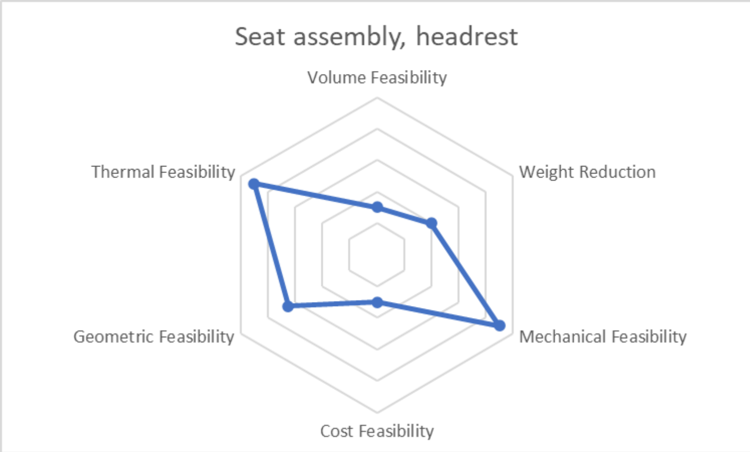

Figure 29 - Headrest zone radar graph

2.2 Niche subdivision

In general, all the proposals showed above share a common problem: nowadays, additive manufacturing technologies are very competitive in niche areas, while for the production of "common" vehicles, characterized by the so-called economy of scale and mass production, they struggle to compete with the traditional manufacturing process. For this reason, after this preliminary research it has been concluded that it is better to focus on low-volume applications in which Additive Manufacturing (and Metal Replacement) can be a viable option from the point of view of Time to Market, Lead Time, costs, and so on. Nevertheless, this preliminary subdivision it has been useful to better understand the "identity" of the component to further analyse: the completely aesthetical components should be discarded because, despite the benefits of additive manufacturing in the field of mass customization, would not underline the potential of polymers in replacing adequately metals, without sacrificing the peculiar properties of the metals but at the same time exploiting their lower weight; on the other hand, components that would influence the safety of the occupants with their sudden fatigue yielding should be, if not discarded, adequately deepened before giving the "go" for the feasibility study.

Therefore, despite the subdivision for category starting from the hypothesis that it is searched a component which is part of a passenger car has proven useful for a first, preliminary identification phase, it is in the niche areas that additive manufacturing gives its best in competition with traditional processes; as a consequence, a second classification should be considered in which the various proposals are grouped for different niche areas of application. Even in this second classification the six parameters already presented before (volume competitiveness, weight reduction, mechanical feasibility, thermal feasibility, geometric feasibility and cost feasibility) will be useful to assess whether is it worth to proceed with further evaluations of the component or not.

2.2.1 Aftermarket

With aftermarket is typically indicated all the spare parts and customization market that can be accessed by the owner of a vehicle after the purchase of the vehicle itself. The spare part market is more oriented towards self-maintenance and repairing, whether the customization market is more linked to the desire of making the owned vehicle unique and an expression of themselves, a desire that was born not that much after the diffusion of the automobile; in fact, the personalization of the car can be dated up to 1931 [31] and, despite the fact that it arguably reached its peak in the 2000s and is nowadays less diffused, it can be considered a still existing niche; for this reason, it is also a viable option for the research of this thesis. In addition to that, even if the aesthetic customization has been experiencing a decreasing trend over the last decades, as already said the aftermarket is not only that: nowadays, other than the already mentioned self-maintenance and repair, this niche is more interested in improving the performance and drivability of the car or in integrating some device that could simplify the general experience of driving. By taking all this into consideration, some possible components have been selected to understand their suitability for the application of metal replacement combined with additive manufacturing.

Strut bar

Strut bar is a component mounted between the two (usually front) suspension strut towers to increase torsional rigidity of the body, so that the driving feeling is improved, especially when tackling bumps or similar. While it is sometimes installed directly from the manufacturers, especially in sport models, in all the other cases is a component available as aftermarket. This element is mostly realized in steel or aluminium, proven that the used aluminium is strong enough from the flexural point of view.

Figure 30 – Example of strut bar [32]

Some literature is available on strut bars realized in composites [32,33], stating that it is potentially an optimal solution for reducing the weight of the component without sacrificing its structural properties; from the point of view of this thesis, considering the six parameters already mentioned before, main issues could be, other than thermal and mechanical feasibility, also costs, due to the fact that a complying material must be chosen in order to bear the stresses experienced by the bar, and geometric feasibility, mainly due to prohibitive dimensions, especially for an eventual printing.

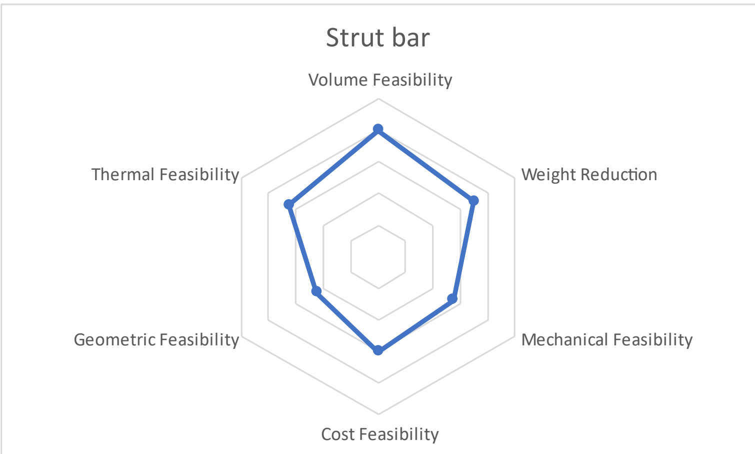

Figure 31 - Strut bar radar graph

Custom door handles

Despite the fact that in the previous paragraph merely aesthetic components have been discarded, actually door handles also have a functional role in the vehicle structure; this, combined with the fact that is still today one of the most requested aftermarket components, makes them worth to mention and to preliminarily analyse. The substitution of the original door handles can be done for repairing reasons, for aesthetic ones, or for weight reduction purposes by choosing a lighter component.

Figure 32 - Door handle, https://www.shutterstock.com/it/search/car-door-handles

Anyway, the main issue with this part would be the anisotropic properties of Additive Manufacturing polymers and their unknown fatigue properties; it is crucial to avoid a failure in the door handle after a certain number of usages, so deep studies would be needed to avoid this eventuality.

Figure 33 - Custom door handles radar graph

Blow off valve / Blow off adapter

These two components are more related to the performance side of aftermarket; while the blow off adapter converts a bypass valve into a blow off one, the blow off valve is the component itself, installable in case no other valves of this kind are present in the engine. In general, the aim of these parts is avoiding excessive pressure values in turbocharged engines, decreasing it when the throttle is closed [34]. This has mainly two advantages: reducing the so-called turbo lag, ensuring that the pressure values are more homogeneous, and avoiding damage to the turbo system due to the excess of pressure.

Figure 34 – Example of Blow Off valve and Blow Off adapter developed by Boomba

This is for sure a very solicitated component both thermally and mechanically, while probably the highest advantages would be on volume and geometric feasibility.

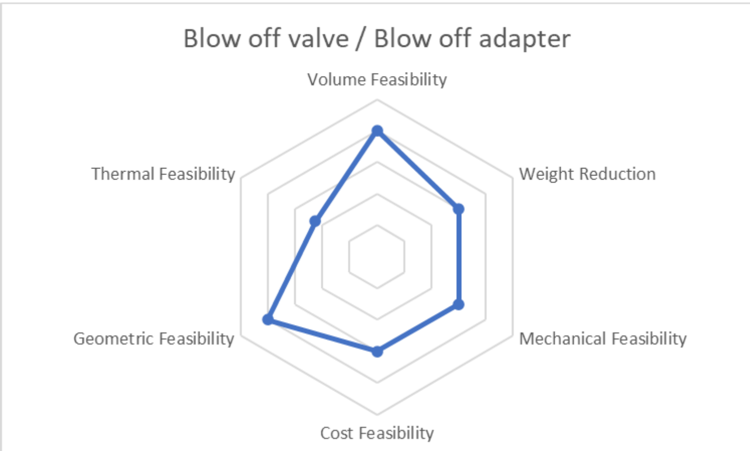

Figure 35 – Blow off valve / Blow off adapter radar graph

Wheel spacers

This component is in halfway between a customization and a performance one; wheel spacers are to be placed between the wheel hub and the wheel itself, increasing the wheelbase. This has mainly two consequences: changing the look of the car, which will be "sportier" and more aggressive due to the fact that the wheels are more spaced one with the other, and influencing the driving performances of the vehicle, mainly in handling. In general, it is possible to say that installing wheel spacers has both advantages and disadvantages: as already said, they will change the appearance of the car and its stability and handling, but the use of these devices can affect negatively the duration of the wheel hub assembly components [35]. Other than this, it is worth to mention that there is a severe legislation system in Italy about the modification of the wheel track of the vehicle so that for road applications only wheel spacer which do not overcome certain limits can be applied, while for offroad or racing application those limits may be overcome.

Figure 36 – Example of wheel spacers, https://cncwheels.com.au/are-wheel-spacers-safe/

As regards the "rating system" used up to now, this can be considered a very "balanced" component, with no particular flaws; anyway, particular attention should be dedicated to the thermal resistance, dependently on the type of brakes installed on the vehicle of interest, and to the fatigue resistance, because a sudden fatigue yielding of the component after a certain period of usage would be very dangerous for the driver.

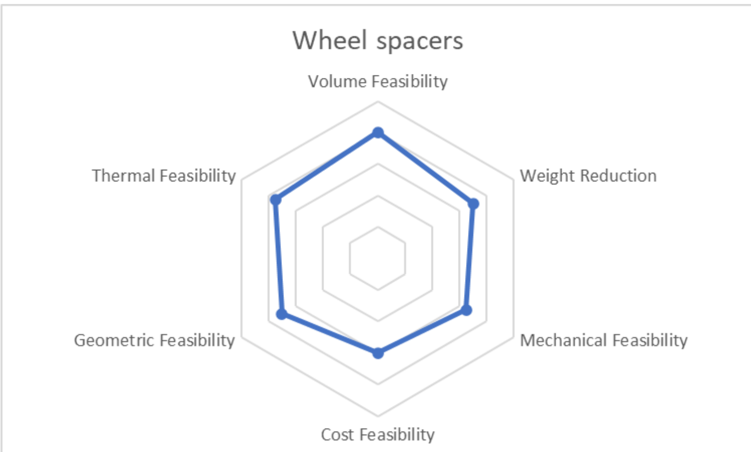

Figure 37 – Wheel spacers radar graph

Camber plates

As the name suggests, these components are installed on the suspension assembly to allow the camber regulation, mainly for track day or racing applications.

Figure 38 – Example of camber plate, https://www.shutterstock.com/it/image-photo/camber-plates-drift-aluminium-race-car-574903507

The most critical aspects would probably be the mechanical feasibility and the weight reduction, since these components are already not so heavy.

Figure 39 – Camber plates radar graph

Custom throttle body

Throttle body is an element already present in gasoline internal combustion engines, to allow having the stoichiometric ratio between air and fuel and to modulate the aspiration based on the pressure exerted on the throttle pedal. The component is nowadays made in aluminium, and should last as long as the vehicle, with eventually some maintenance needed; anyway, it is possible to replace it with a bigger customized part, mainly for performance reasons.

Figure 40 – Example of throttle body

Despite the feasibility in terms of volumes and geometry, the thermal issues that could arise should be monitored carefully.

Figure 41 – Custom Throttle Body radar graph

Custom muffler clamp

The muffler clamp was already mentioned in the previous paragraph as a possibility; being it also an aftermarket component, both for maintenance and customizations reasons, it is presented again here; anyway, despite losing its flaws in terms of volumes, thermal issues would still be present.

Figure 42 – Custom muffler clamp radar graph

2.2.2 Converted vehicles

Converted vehicles is a quite generic term which can incorporate different sub-definitions inside it: it is possible to say that a converted vehicle is in general a vehicle that has experienced some modifications in order to comply with some homologation rules, regulations, or simply to give to the vehicle itself a new purpose, different from the one for which it was initially designed. This macro-category is judged suitable for the considered application because in the majority of cases a converted vehicle has as direct consequence an increase in the weight with respect to the original one (apart from some exception like racing, which will be anyway discussed in a dedicated paragraph), with consequent increase in the fuel consumption and also potential loss in performance. Therefore, it is simple understanding why this kind of vehicles would benefit from the best characteristics of both the applied techniques: from the metal replacement point of view, for sure weight and consequent fuel consumption reduction would be got; from the additive manufacturing point of view, the limited volume of production makes this technology competitive with respect to traditional manufacturing processes. In the search for the appropriate case study two branches of converted vehicles have been deepened, that are converted vehicles for law enforcement purposes (like police, the Italian "Carabinieri", ambulance, firefighters, etc) and internal combustion engine vehicles converted into electric vehicles.

Converted vehicles for law enforcement purposes

Converted vehicles for law enforcement purposes usually have their starting point into common passenger cars or commercial vehicles, which are properly modified to adapt to the different law enforcement fields in which they will be applied. In order to find some appropriate components that could benefit from metal replacement combined with additive manufacturing at first preliminary research was performed to better understand how these vehicles are set up. In Italy, these vehicles are prepared by dedicated companies which receive then the national homologation necessary for classifying the vehicles as "law enforcement" vehicles. Considering that various modifications are applied depending on the vehicle taken into consideration, some viable components have been selected.

Writing desk and technical compartments

The writing desk can be found mainly on police, "Carabinieri" and "Guardia Di Finanza", installed over the car trunk and is useful when performing controls on the streets for checking documents, writing fines and so on.

Figure 43 – Example of writing desk, https://www.maritansrl.it/allestimento-fiat-punto-polizia-locale/

Despite constituting a significant weight adding to the original setup of the vehicle, it is already made in the majority of cases mostly in plastic, with some exceptions like the sliding guides which allow the opening and closure of the desk for when the vehicle is standing still or moving; even considering these metallic components for an eventual metal replacement and additive manufacturing operation, with reference to the parameters already used to classify the viability of the various components, probably low scores in weight reduction (the sliding guides are already not so heavy) and geometric feasibility (not for dimensions, but because are very simple and standardized components) would be obtained. Same considerations still hold for the technical compartments, which are found in the majority of the "law enforcement" vehicles with the scope of holding useful objects and items that are not present in the standard setup of the vehicles and are necessary for the execution of some particular tasks (some examples can include the technical compartments in ambulances for first aid kits, fire extinguishers holders for firefighter trucks, etc); even in this case in fact, they are mostly already made by plastic and therefore not suitable for the case study.

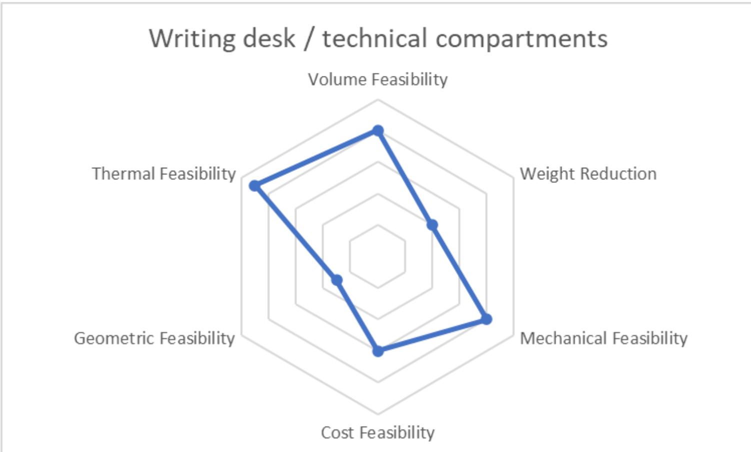

Figure 44 – Writing Desk / Technical Compartments radar graph

Pickup bed clamps

This possibility has been studied starting from the pickups used by "Carabinieri", Alpine Rescue Team ("Soccorso Alpino"), and Forest Ranger ("Guardia Forestale"), but can be applied to basically all pickups. The main difference is that in the "converted" pickups typically it is added a further coating to the pickup bed for protection and reinforcement purposes, and this further coating is typically clamped; this can be done also on common pickups, making this component a sort of hybrid between an aftermarket one and a "conversion" one.

Figure 45 – Example of pickup bed clamps, https://www.maritansrl.it/isuzu-d-max-allestimento-carabinieri-soccorso-alpino/

In both cases, it is possible to understand that the advantages in terms of weight reduction would be minimal, due to the low impact in weight that these components may have when installed on the vehicle; also, from the geometrical point of view, they are components simple enough to affirm that the use of additive manufacturing would not be exploited at the maximum potential.

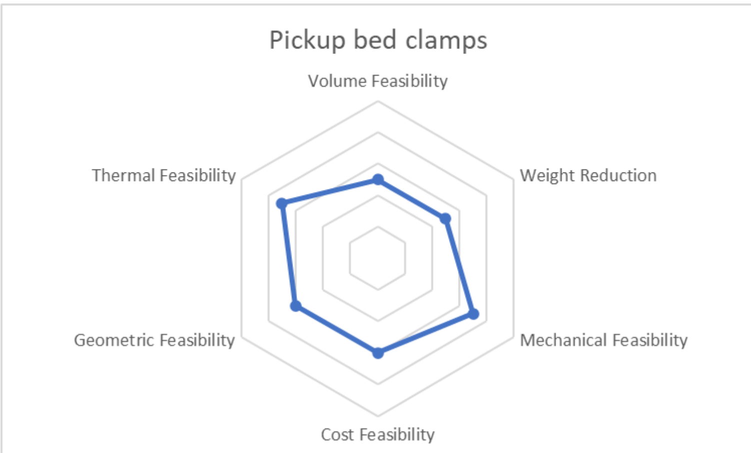

Figure 46 – Pickup bed clamps radar graph

Headlight protection grid

This possibility has been studied starting from a specific model belonging to the Italian police, which is the Land Rover Discovery in the setup "public order". This particular setup includes, among the other things, a set of protections for the most "fragile" elements like glass surfaces and headlights.

Figure 47 - Land Rover Discovery adopted by Italian police, https://www.autoingros.landrover.it/land-rover-discovery-polizia-di-stato/

In this specific model the protections are realized in steel and completely removable, while there are other cases in which they are fixed and non-removable (as regards the material, it is steel in the majority of the cases). In general, these protections are adopted when the vehicle is in situation in which is very likely to receive damage, being it from people (like in case of riots, protests, and so on) or from “nature” (like for example in offroad, high speed conditions). For this case study, unfortunately the protections for glasses have to be discarded due to their excessive dimensions, which would made difficult an eventual printing of the component at the end of the case study. Instead, for which concerns the protection for the headlights, they virtually don’t have any critical flaw, since they are for a low volume application, can benefit from a shifting from steel to polymer, and are not stressed thermally speaking. As regards the mechanical stress, of course they are solicitated, but the fatigue is not a critical issue like in other applications, since in case of fatigue yielding after a certain number of usages it is sufficient to change the component. The only remaining doubts are about the geometrical feasibility and consequent costs: it is very likely that nowadays this kind of components are produced with very fast and cheap methods, due to their usually simple shape (it depends on the vehicle on which they will be mounted and whether the final objective is to obtain an only-protecting device or also something that does not impact too much the original style and aerodynamics of the vehicle); nevertheless, it would be worth to deepen the analysis to understand with higher precision the convenience of the additive manufacturing process with respect to the traditional one. Finally, like in other previous cases it should be considered that this part can also be purchased by private citizens for their common vehicles, referring again to the concept of aftermarket: in this case of course the protections are usually mounted on the headlights only and are requested by people who travel a lot in rough terrain. All the other considerations done before for the converted vehicles applications still hold for this aftermarket case.

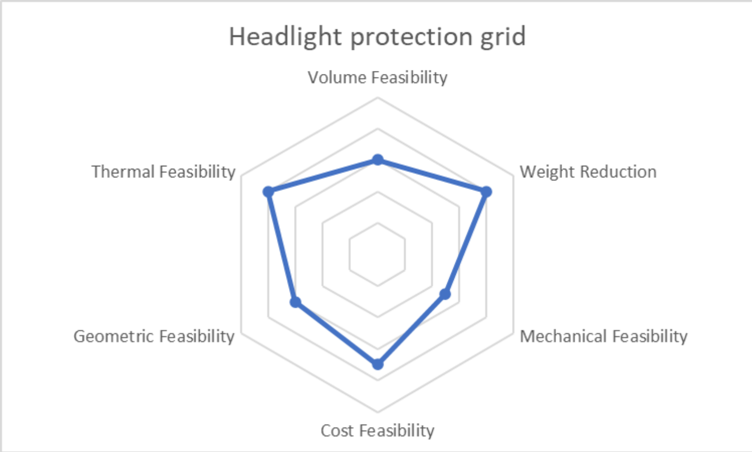

Figure 48 – Headlight protection grid radar graph

Snorkel

Another application which has been selected starting from a specific model is the snorkel, installed on some pickups belonging to Italian "Carabinieri" and Alpine Rescue ("Soccorso Alpino").

Figure 49 – Example of pickup snorkel, https://www.maritansrl.it/isuzu-d-max-allestimento-carabinieri-soccorso-alpino/

The snorkel is used in offroad conditions to bring fresh air to the engine even in extreme situation like crossing a river. Like for other previously seen applications, it can be added to a "common" offroad vehicle also from a private owner, being it for aesthetic or for effective usage. Anyway, after some research, this component had to be discarded almost immediately due to an important criticality: apart from some rare exceptions, it is already realized in plastic (even if with traditional processes), therefore in case of proceeding with this component part of the scope of the research which is metal replacement would be lost.

Converted vehicles for retrofitting

Now it is possible to consider another branch of converted vehicles, which is retrofitting. As well known, the diffusion of electric vehicles is increasing more and more in the last years, mainly due to the recent European regulations about the environment and the pollution limits; as an example, the Britannic government has the intention to stop the selling of diesel cars in 2030 and wants to reach the zero emissions objective by 2035 [36]. Nevertheless, majority of people are reluctant to executing this shift, mainly due to the high prices of electric vehicles today. For this reason, retrofitting is moving from a small niche brought on for almost the totality from hobbyist and mechanics enthusiasts to a practice still not so diffused, but that can be performed also by dedicated companies that are specialized in these operations. It is possible to consider some of the advantages and disadvantages of retrofitting with respect to the usage of an internal combustion engine vehicle or an electric one [36,37]:

- Retrofitting could reduce the environmental impact of the switching from internal combustion engines to electric motor vehicles: if anyone who owns an ICE vehicle would decide to scrap it and buy an EV, the impact on the environment would be catastrophic; in this sense, the retrofit could favour a more gradual shift.
- For people who don’t consider the car just like a tool to overcome long distances, but also have a sort of bond with them, the retrofit can be a solution to increase the life of a vehicle; this is particularly true for historic vehicles that cannot circulate anymore due to the more and more stringent regulations on the pollutant emissions.
- From the economic point of view, purchasing a brand-new vehicle is not always possible for everyone, so if retrofit would be cheap enough, it could be a partial solution to this problem. Unfortunately, it is not the current situation, probably due to the lack of diffusion of this solution: in UK, the price can range from 18000 to 500000 pounds, depending on the vehicle; similar prices in Germany, where they can go from 8000 euros for the smaller cars to 150000 euros for more complex cars. In general, considering for example a small vehicle, the retrofit is more convenient than purchasing a brand-new electric vehicle, but still less affordable than buying an ICE one.

- From the negative side, other than the cost, it should be thoroughly verified that the vehicle of interest is suitable for the retrofitting operation: despite the fact that performing this checks and the retrofitting itself is still faster with respect to building a new car from scratch, it is a quite complicated process, especially from the point of view of the engine replacement; the vehicle is not designed for hosting all the electrical components needed, and this can generate unbalance in the weight distribution of the vehicle, as well as affecting the brake capability and general handling of it and causing damages to the chassis. The same discussion can be done considering the battery pack.

A study from Germany developed by Hoeft [37] attempted to collect as much opinions as possible regarding the possibility of applying retrofitting; the results are resumed below:

- Despite the fact that some not completely "rational" factors may arise during the choice of a new vehicle to buy, in general the most researched qualities are reliability and safety, followed by price, prestige of the brand and style of the vehicle; finally, also optional features and propulsion type are taken into consideration. It is possible to see that people don't place the propulsion type on top of their priorities and therefore to deduce that the lack of electric vehicles in the streets is probably due to the excessive costs, linked to the price factor.
- The perception of retrofitting shifts from negative to positive with the adding of information about it, despite the fact that the costs are considered too high and the marketing action of this process too weak, since it is basically unknown to the majority of the car owners.
- Main doubts about the retrofitting regard the amortisement of the initial investment, the not proper knowing of electric motors and therefore the major reliability (or better, major knowledge) of the internal combustion engines; on the other hand, there are also expectations linked to it, which are partly shared with the ones of owning an electric vehicle, therefore the possibility of using the car also in city centres, where nowadays there are severe limitations, or the possibility of charging the car at home, while expectation strictly linked to retrofitting are more related to the possibility of not scrapping the owned vehicle.

From the technical point of view [37,38], the process of retrofitting consists in the removal of the internal combustion engine and all the parts linked to it, like for example the fuel reservoir and the muffler; instead, it is necessary to install brand-new components, which mainly consist of:

- Electric Motor: needed to get the mechanical energy, which is converted from the electrical one taken from the battery; both AC and DC motors can be used, of course the general structure will change depending on the motor that will be used.
- Motor controller.
- Battery: it is the main source of energy for the motor; in this case also different batteries can be chosen, so same considerations already done for the motor still hold.
- Charger.
- Converter.
- Vacuum Pump.
- Other Power electronics.
- In the majority of the cases, an adapter plate is used to keep the original gearbox.

From this list it is possible to understand that there are not many parts which could benefit from metal replacement; the adapter plate mentioned before could be a possibility, anyway the dimensions are quite prohibitive to allow the final printing of the component. A similar concept is present in some retrofitting situation, which is the coupler: the idea is like the adapter plate, but this time the component is placed between motor shaft and transmission shaft to couple them. The main issue is that this component should endure in time and a fatigue yielding would result in catastrophic consequences for the motor structure, therefore careful studies would be needed. Finally, it is possible to consider the motor mounts: as already stated before, the motor should be kept as still as possible to avoid damages, and this can be obtained with physical mounts. Considering this component, the main parameters to keep an eye on would be for sure the thermal and mechanical feasibility.

2.2.3 Limited editions

Another niche that can be considered is the limited editions one: most of the carmakers developed in the course of their history at least one limited or special edition model, intended as a particular version of an already existing model, to celebrate an anniversary, a collaboration with an external brand, a win obtained with the motorsport section of the brand, or simply to push the possibility of the specific model to the limit. Limited editions are usually great investments for the carmakers but can also turn into significant returns if well-advertised: the fact that these vehicles are produced in small numbers typically pushes customers (at least, the ones who can afford them) to purchase them in very short time, also considering that in the future the scarcity of them can lead to an increasing of their values. In addition to that, limited editions or special editions tend to increase the overall life of a model in a market that is more and more saturated over the years. In this case the objective can be considered to focus more on limited editions rather than on special ones since the limited editions can be defined as a higher level of "rarity" with respect to the specials, so even more a niche market. In general, limited editions can be "limited" in the sense of time or in the sense of quantity [39], even if in the automotive case the limited time "strategy" is quite unfeasible. In this case no specific parts will be proposed since it is just a "suggestion", and the topic of limited editions is so broad that almost any component of the vehicle can be included in it; also, the fact that the concept of limited editions is much related to aesthetics makes it not so compatible with this research and what has been stated about the purpose of the component that will be subjected to metal replacement combined with additive manufacturing.

2.2.4 Racing

Finally, the niche "par excellence" in the automotive industry is for sure the racing one. As already seen in the chapter about the state of art of the additive manufacturing, racing has always been in deep touch with it, thanks to the possibility of obtaining parts in a fast way and also to the concept of weight reduction which is always present in this ambit. Also in this case, like in the previous one, there is a wide plethora of viable solutions considering the racing field, some of which have been already discussed in other sections (think about the motorcycle levers, the pedals, the wheel spacers and so on); for this reason, only two very specific examples will be mentioned just to highlight the potentialities of the technology in the field.

Racing seatbelts

A first possibility has been explored which regarded almost the entirety of the automotive motorsport field, which is a possibility concerning the safety belts; while in the previous section only the "common" seatbelts have been considered, focusing mainly on the bracket zone, now the "racing" seatbelts are taken into account.

Figure 50 - Example of racing seatbelt, Sabelt catalogue 2022

Considering the structure of these seatbelts, a possibility of metal replacement and additive manufacturing can be seen looking at the seatbelt buckle and/or at the seatbelt regulator. In both cases a high level of concern should be put on the safety of the driver, mainly considering the fatigue behaviour of the material. As regards the weight reduction parameter, despite the fact that the first thought that may come in mind is that the gain in terms of it would be marginal, it must be remembered that in these racing applications even a single gram can make the difference. In the end, considering that the majority of the actions of a driver when putting himself on a racing car are by now sort of "automatic reflexes", apart from the necessary (and advantageous) topological optimization the component should stay as much as possible similar to the original one in order to not alter these "automatisms".

Motocross launch control

A second example considered is taken by the motorcycle racing world, in particular from the American Motocross Association (AMA) Supercross championship and MXGP. In these championships during the start of the race a particular device is applied on the motorcycles to help the riders improve their performances in the very first metres of the race: it is called launch control or hole-shot device. While the device exists also in MotoGP, arguably the pinnacle of motorcycle engineering, in this case it is much more linked to electronics and to the ECU installed in the motorcycle. Motocross bikes instead can have both the electronic launch control and the mechanical one, which is the one taken into examination here.

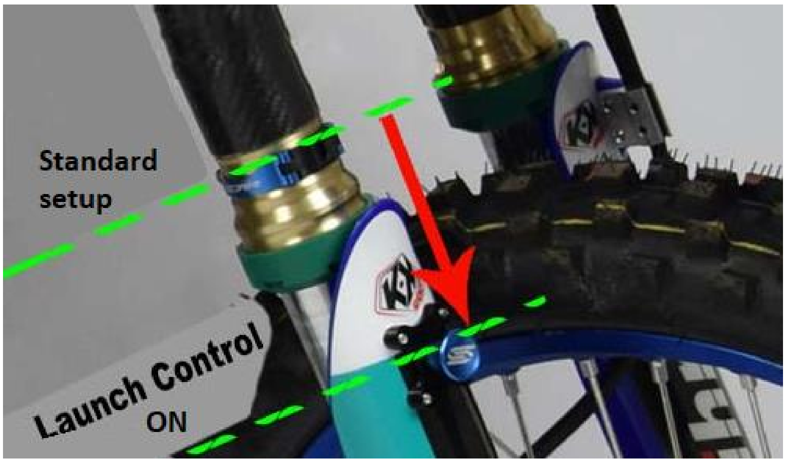

Figure 51 – Example of launch control, https://duomoto.it/launch-control-cose-e-come-funziona/

The concept behind is locking the front fork of the motorcycle during the start in order to avoid the wheeling phenomenon and gain advantage during the first meters. Usually these devices must have a "custom" design, in the sense that each motorcycle manufacturer has its own specifications for the forks and therefore the hole-shot device should have its dedicated measurements; like for many other proposals seen up to now, other than a component used in racing applications it is also an aftermarket one, meaning that also private owners of a motocross can buy the mechanical device and install it on their bikes. The part is nowadays realized in aluminium, and being it a rather small component, weight reduction would be minimal; another issue is that from the geometric point of view is quite simple, so the feasibility "score" would not be so high; finally, proper studies on the mechanical feasibility would be necessary in order to avoid improper working of the device, like wrong engaging or disengaging of it or sudden rupture.

Figure 52 – Launch Control radar graph

2.3 Final choice

Among all the components listed up to now, in the end the choice has fallen on the protection grid for the headlights; this component is probably the most "balanced" among the ones that have been presented, could result competitive enough with respect to the traditional production method and at the same time can prove that nowadays the properties of polymers can rival with the ones of metals in some applications; it will be the task of this research to assess the feasibility of this metal replacement activity from all the points of view, starting with a general overview of both the traditional and the additive manufacturing process, with a focus on this last one, since it is necessary also to study in deep all the properties of the selected material; in the end, after having tested it in a virtual environment with dedicated software the properties of the component, it will be also possible to print it.

Figure 53 - Land Rover Discovery 5 headlight protection grid detail [42]

3. Traditional material and production method

As it has been concluded in the previous chapter, a headlight guard system is considered; despite the fact that the design of the component is done starting from a specific model, which is the Land Rover Discovery V used by Italian Police, the concept of this study is applicable to every part of this kind, given that they share similar material and production method. In general, it is fundamental to start from the original production method to understand its lead time, costs, and also how the part is originally designed to facilitate the production; this is in fact one of the big differences with the Additive Manufacturing process: while in the traditional one the design is done also by keeping in mind how then the part will be manufactured, considering the availability of machineries, the difficulty of the process, its cost, and so on, in the case of the AM process there is much more freedom in the design, freedom that must be exploited in order to gain advantage with respect to the traditional process.

3.1 Traditional material

For the traditional material, several companies dedicated to the production of guards and/or grids have been contacted in order to get the most realistic possible information about the component. Unfortunately, the company which managed the production of the headlight guards for the Land Rover Discovery did not share the information; nevertheless, another company, the Sperotto S.p.A., allowed the sharing of some information like the used material and processes (which will be seen in the next paragraph). The company Sperotto S.p.A. produced headlight guards for vans, so a case comparable with the one subject of this work. The material used for the production of these grids is the S235JR steel. Information on this steel were taken from the website MatWeb; according to it, it is a "soft structural steel easy to weld and bend"; the composition may vary depending on the standard taken into account, but in all the possible cases iron, carbon, nitrogen and phosphorus are present, whether in some variants also percentages of manganese, sulphur, silicon and copper may be present. The website also provides the mechanical characteristics, which will be useful later for the analysis that will be carried on.

Density	7800 kg/m^3
Tensile Strength, Ultimate	415 MPa
Tensile Strength, Yield	235 Mpa
Elongation At break	24%
Modulus of Elasticity	210 Gpa
Poisson Ratio	0.3
Shear Modulus	80 Gpa

Table 1 – S235JR characteristics

The application of this kind of steel are very wide and can go from civil engineering applications to automotive industry ones. It is possible to find some applications in the literature from which it is possible to understand and better justify the choice of this steel from the company:

- Landi et al. [44] evaluated the application of S235JR steel, among other possibilities, in the field of safety inside an industrial plant; the sharing of common spaces between man and machine is a well-known problem in the industrial world, especially nowadays since the interaction between the two is constantly growing; despite the fact that with the passing of the years the machines become more and more "human-friendly", the risk of accident is always present. In the document a study regarding a protection grid between machine and man is presented, therefore a situation which can be partially associated to the one taken into examination in this work. In particular an examined case is the one of an "expulsion" of a mass, which can be a component of the machine or a component in production/processing/manufacturing, that can put in danger the health of a worker by hitting him/her with a certain speed. In this case the presence of the grid can help in minimizing or even cancelling completely the effects of this situation. This scenario, which at first sight may seem unlikely, is also regulated by international standards; for example, in the paper taken into account a testing according to ISO 14120 was brought on, where a mass of 0.1 kg with a speed of about 20 km/h is considered to hit a grid with a thickness of 2 mm to check the level of endurance of the aforementioned grid.
- Kortag et al. [45] performed simulations through Finite Element Model (FEM) in the study of an underrun protection guard to be installed on trucks; the chosen material for the running of the simulations was S235JR steel. In this case the problem is again a safety one, this time more focused on the automotive world: the underrun phenomenon is linked to the fact that, in case of crash between a car and a truck in front of it, depending on the relative height of the two vehicles there is the possibility that the car is able to pass under the truck itself, which is a very dangerous situation for the passengers of the vehicle. The protection guard in this sense has the objective to mitigate the effect of the crash, since a crash with a sort of "guardrail" mounted on the rear of the truck would still be critical, but less dangerous with respect to an underrun scenario. Also, in this case the applied forces are very standardized and taken from an international normative, the ECE R. 58, while the thickness of the guard was regulated in a certain range in order to check whether the results were satisfying or not. This paper also shows how the Finite Element Model can be helpful to save time in conditions where a lot of testing have to be performed.

- Neuenhaus et al. [46] performed simulation trough multibody system model (CAE) in the study of a guardrail protection mainly thought to protect car occupants in case of presence of trees or other obstacles outside the road. Guardrails are another element concerning safety and are therefore very standardized: as it is possible to see in this study, parameters like thickness, profile of the guardrail, kind of connections (bolt, screws, etc.) to use, and other characteristics, are clearly defined. Among these, there is the material, which can be S235 or S355 steel.

From these examples it is possible to understand why this kind of steel is chosen; also, two other important considerations can be made:

- If possible, it would be beneficial for the research to be based on real homologation data, in order to have a sort of "feedback" from the reality.
- The Finite Element Model (FEM) is a valid tool to perform simulations on the component, at least for a preliminary phase.

3.2 Traditional production method

For the traditional production method, several companies specialized in the production of protection grids were reached in order to have the most possible realistic information about their production. In the end, the company "Sperotto S.p.A." provided the information for the production of a protection grid for a van; it is not exactly the application considered in this study, but it is possible to hypothesize that the production method is very similar. According to the company, the production method can be schematized in six main steps:

- Laser cutting and/or punching.
- Cold forming with mould.
- Cataphoresis.
- Primer application.
- Painting.

Here a brief excursus regarding these six steps, with a particular focus on the state of art of the processes.

3.2.1 Laser cutting process

Laser cutting is a well-consolidated process in the manufacturing industries and is one of the possible methods for obtaining a cut element from a starting base, which is usually in form of sheet. It can involve a vast variety of material which can go from metal to polymers to wood and so on. The process can be divided and summarised in the following steps [47,48]:

- A laser creates a ray of light which is pointed on a surface, which, as already said, is usually in form of sheet, generating a sort of "route" through the melting of the material.
- The material melted by the laser needs to be removed from the rest of the component; this is typically done by means of a jet of gas, which usually is incorporated in the cutting machine next to the laser.
- Finally, the laser, the metal sheet or both can move following a CNC "logic" thus favouring the cutting of the material.

The majority of the cutting machine lasers adopt CO2 lasers; as regards the gas for the removal, a distinction needs to be made [48]:

- In the mechanism called Melt Shearing or Fusion Cutting, the one described up to now, the melt is removed by a gas characterized by a high level of pressure (usually the preferred one is nitrogen). The nitrogen gas removal is adopted for both metals and polymers.
- There is an alternative, which is called Oxidation Cutting, mainly used when dealing with steels, in which there are two big differences: the kind of gas adopted, which is oxygen instead of nitrogen, and the level of pressure, which is much lower with respect to the previous case. The lower pressure has two main consequences, improving the general quality of the process and allowing the production of cuts in less time and, if necessary, with bigger thicknesses with respect to the nitrogen case.

As it is possible to understand from this distinction, two of the parameters to tune when dealing with the laser cutting process will be for sure the kind of gas and the level of pressure. Historically, the first laser cutting machines made their debut in the industries in the 70s; during the course of the years, the process experienced a lot of evolutions, mainly linked to the available power, to the speed of cutting and to the maximum thickness, all parameters that will have an impact on the final quality of the cut [47]. One of the last technologies applied to the laser cutting process is the so-called Disk Laser or High Brightness Fibre Laser, which sacrifices partly the quality of the final cut in favour of a higher speed and power [48]. In general, the main advantages of this manufacturing process can be summarised as follows [47]:

- It is a quite high-speed process.
- CNC technologies can be applied to the process.

- The quality is not at precision-engineering level, but still fairly high.
- Despite the laser heats part of the component, the impact of this heating on the final quality of the part is negligible.
- Unlike other cutting technologies, the starting component, for example the sheet, does not need to be held too much firmly, like through clamps; this is again good for the quality of the final part, since the residual stresses will be reduced.
- Other positive characteristics are its quietness and safety, in comparison with other well-known cutting processes.

3.2.2 Punching process

Punching is one of the possible manufacturing process for removing a quantity of material enclosed by a certain geometry or to create separate component of the said geometry; it is usually associated to another similar process, called blanking: the main difference is that when performing the punching process the final part is the one which has experienced the removal of material, while when speaking about blanking the final component (or components) will be the removed one (or ones). In general, the main concepts of the processes are quite similar. Unlike laser cutting, punching is mainly adopted on metals and is more based on the shearing concept. The process can be again divided into a series of steps [61,62]:

- In the first phase of the process, the movement of a cutting element called punch against the metal sheet provokes its deformation; the deformation during this first phase is still an elastic one.
- At this point the continuing of the movement of the punch against the metal causes the reaching if the yield strength of the material and the shifting from the domain of the elastic deformations to the one of the plastic ones, which will also give birth to a rounding phenomenon on the edge of the part that is being removed (this is very important in case the considered process is blanking, since it is the part that is going to be kept, while in case of punching process it is usually a scrap therefore its final aspect and characteristics are not important). As soon as the plastic deformation starts, also cracks will start to appear.
- At a certain point of the punching process, the crack will propagate so much that consequent rupture and fracture will happen, therefore the removal of the desired part is completed.
- In the end the gradual friction work dissipation happens with the pushing of the fractured part outside of the rest of the metal sheet.

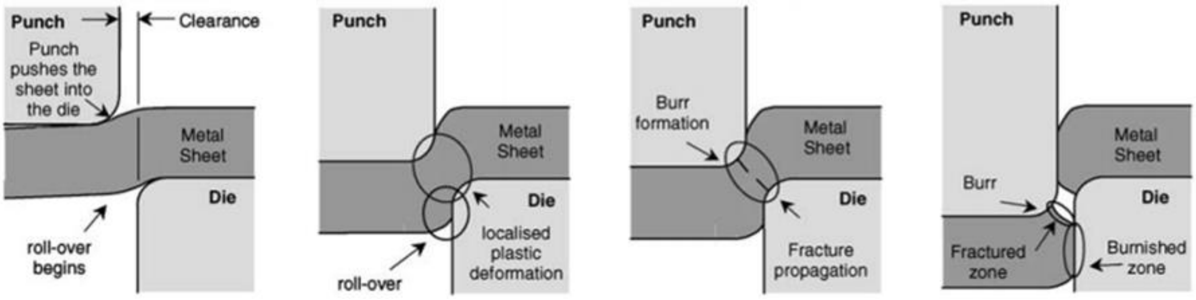

Figure 54 – Main steps of the punching process [61]

Despite it being a relatively simple process, there are some possible variants and a wide number of variables to take into account: as regards the process itself, in the majority of cases it is performed by means of a mechanical or hydraulic press, but additional tools can be adopted such as a counterpunch and/or a holder when manufacturing operations more oriented towards precision engineering are requested. For sure it is the simplest method to apply but it has its flaws, such as the adoption of the press itself which imposes some constraints on the levels of production and requires a high level of initial investments (to buy the machinery and relative tools). In addition to that, a press for its definition is a machine which is not able to work continuatively, and even the fastest press has a certain "frequency" of work in which it is necessary to interrupt the process. For this reason, there is an alternative to the "classic" punching process which exploits a rotary machine: the cutting operation is performed with the aid of rotational devices in order to make the intermittent process a continuous one. The advantages are evident, and go from the savings in terms of investments, floor space, production lead time and energy usage, to a reduction in terms of vibrations and noise and a consequent increase in safety [61]. As regards the variables which can affect the process, they are mainly related to the phenomena that are caused by the contact between the press and the part, therefore deformation, cracks formation and rupture: the main ones are thought to be the thickness of the starting metal sheet, the geometry of the adopted tools, the age of the used machine, the corner radiuses, but the most important is usually considered the clearance between the punch and the die, since it will influence the final characteristics of the component more of all the other variables [61,63]. From the historical point of view, punching is one of the oldest manufacturing processes, which have been studied since the start of the 20th century; its usage is very wide but is adopted especially in case of need of high volume production, mainly in the automotive and aerospace field [61,64]. As it has been possible to be understood from this brief excursus, the main advantage of this process is its simplicity, whether the flaws are to be researched mainly in the fact that there are lots of variables which can affect the quality of the final component.

Finally, it is worth to mention that sometimes the two processes of laser cutting and punching can be performed at the same time on the same component. The technique is called combined or compound manufacturing and tries to take only the positive aspects of both the processes, so the flexibility of the laser cutting and the simplicity of the punching. For this reason, the combination of these two processes is particularly suitable when it is necessary to get a complex contour with simple holes. The main issue with this technique is that, despite the fact that both the processes are CNC-oriented and therefore it will be possible to setup a unique program for performing both cutting and punching, the programming phase will be for sure harder [65,66]. The company Sperotto did not specify if that was the case for the production of their headlight protection grids, but considering the contour of the guard and the simple shape of the holes it is a possibility.

3.2.3 Cold forming with mould process

Metal forming is a quite generic term which embodies a series of manufacturing processes where the plastic deformation phenomenon is applied to modify the shape of a component. The shape is usually determined by a tool called mould or die. One of the possibilities to classify these operations is the working temperature, in this way the forming processes will be divided into three macro-categories: cold forming, warm forming and hot forming. The main advantages of cold forming with respect to warm and hot ones are:

- Possibility to obtain closer tolerances on the finished part, so in general a better accuracy of the manufacturing process.
- For similar reasons, also aesthetically the part will look better and with a smoother surface finish with respect to a warm/hot formed one.
- In general, from the mechanical point of view the finished component will be harder with a cold forming due to the strain hardening phenomenon.
- Finally, since the process is executed in a relatively low temperature environment (maximum 30% of the melting temperature of the selected metal), there will be some savings in terms of energy and consequent costs, allowing also a higher production rate with respect to the warm/hot forming.

There are also disadvantages characterizing this process:

- Due to the fact that the metal is not “softened” by the higher temperatures, the force required to manufacture the component will be higher.

- The starting surface should be as clean and regular as possible, again due to the fact that the process is going to be performed at room temperature.
- Finally, linked to the fact that the metal is not "softened" there is also the limitation in the forming activity that can be done on the material.

Instead for which concerns the subdivision for different deformation processes, it is resumed in the following scheme:

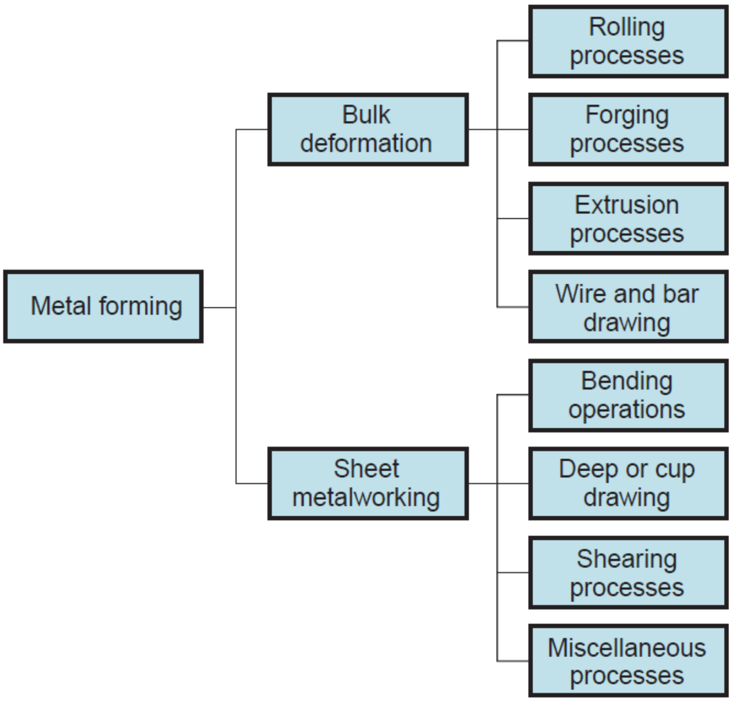

Figure 55 – Classification of the forming processes

3.2.4 Cataphoresis, primer application and painting processes

Once the final shape of the component has been reached, it is possible to move to the final steps, which in a certain way are post-processing phases: in the case of the production of a headlight protection grid, these processes will be the cataphoresis treatment, the primer application and the final painting. The scope of these processes is partly aesthetical, partly functional: for sure it is desirable to have a final part which is appealing to eyes, but it must also endure in time and resist to weathering and other phenomena. Usually, cataphoresis is done for endurance reasons (corrosion and water infiltration protection), painting for look reasons, primer application for both. Going in chronological order, cataphoresis is the first performed process among the three. The term derives from the combination of electrophoresis and cations, meaning that it is an electrophoresis process performed with positively charged particles. The cataphoresis process is physically executed by drowning the component in an electrocoating bath; this electrocoating is usually very similar in structure to a common water-based paint, with the difference that a chemical deposition process happens during the bathing. The process was introduced in the sixties by the Ford company, but in the first period the electrophoresis process was not with positively charged particles, but with negatively charged one (therefore an anaphoretic process). The shifting towards cataphoresis started in the seventies and from eighties on basically all the manufacturers started applying only it, because in general it allowed better performance as regards corrosion resistance. Cataphoresis is another process whose correct application depends on a lot of factors, such as the "electrochemical" ones like current and voltage, electrolyte concentration, paint conductivity or pH of paint, and the more "physical" ones like the temperature. Despite the main goal of the cataphoresis process is to ensure a higher corrosion resistance, another positive effect which is obtained is the chip resistance, because in case of a component which is hit by gravel or other small objects, a low resistance can increase the contact with water and other corrosive agents accelerating the process. After the cataphoresis chronologically there is the primer application (even if in between there are usually other processes, at least a drying one but often also a sealing one); the main aim of the primer is to act as proper "link" between the different layers. Nowadays there are three alternatives when speaking about primer: solvent-based primers, water-based primers and powder primers. Historically, solvent-based primers have always dominated the market, at first since they were the only one available and then because they still remained the most economical solution among the three; nevertheless, the more and more stringent laws about environment pushed for the reduction of solvent emissions, reducing the use of this solution, at least in Europe and in the United States: from a global point of view, solvent-based primers are still the most used ones. It is thought that the trend is a shifting towards more "green" solution, but it is hard to estimate how much time it will be necessary to perform it. Independently on the kind of primer that is taken in consideration, it is possible to state that they are a very regulated element in the (automotive) manufacturing industry. From the legislation point of view, as already said, especially from the environmental point of view, the composition of a primer is very stringent. From the technology one, since the primer must interact with different layer, mainly the cathodic below and the base coat over, adhesion is one of the most important aspects considered when speaking about the primer (adhesion problems can lead to both aesthetical and resistance problems). In a similar way to the cathodic layer, but in an even more important way, the resistance to stones and other elements must also be ensured, again because any perforation would lead to an acceleration of the corrosion phenomenon. These tests are so important that usually are conducted following an ISO normative (like the ISO 20567). Smoothness plays another fundamental role, mainly for aesthetical reasons. In this case it is more difficult to objectively measure the aesthetical quality, therefore some surface finishing testing based on scanning are commonly used. As it is possible to understand, since the primer has to satisfy both endurance and aesthetical requirements, its quality must be very remarkable and its composition is usually strictly defined: the main components are typically resins, binders, extenders, pigments, solvents (in case of solvent-based), additives. Finally, there is the superficial layer, which is the painting. As already said before, the painting process is mainly for aesthetic reasons: it is very important that the quality of the painting is maintained over the years, which is the other fundamental characteristic that must be ensured by this layer. In this specific case a powder painting process has been adopted. The use of this manufacturing process started in the seventies with General Motors and Ford, and nowadays is very appreciated and applied mainly for the following advantages:

- It is a very "green" technology, since it is solvent-free in the application phase (therefore the toxicity is noticeably reduced) and allows the direct recycling of the powder in excess after the painting of a component for another one.
- The wastes, as regards both the water and the paint, are minimised.
- The total energy necessary for the application of the paint layer is reduced with respect to a liquid/spray painting.
- It ensures a uniform thickness and consequently appearance in all the directions.

Powders are produced starting from the base ingredients such as resins, additives and so on, which, according to the specific composition of the paint, are inserted in a mixer with a rotating blade. The objective is to get an extruded material which will be later cut in chips that can be easily transformed into particles of an appropriate dimension. It is fundamental to ensure that the Particle Size Distribution (PSD) is very uniform, since too big particles would lead to aesthetic problems and too small ones wouldn't adhere correctly.

4. Selected Additive Manufacturing process and material

4.1 Additive Manufacturing process

The selection of the Additive Manufacturing process is done starting from the subdivision of the ISO normative ASTM2900-15 already presented in Chapter 1. Of course, for each of the macro categories there are several possible alternatives. It is fundamental to understand the bases of each process to choose correctly the one that will be applied for the production of the final component.

4.1.1 Binder Jetting

Binder jetting is a term which includes a series of patented process which can be applied to metals, polymers or ceramics; the most consolidated technology considering the polymer, which is the case of interest for this research, is the Three-Dimensional Printing, or 3DP. The process has been prototyped, tested and patented in the Boston M.I.T., and consists in two main phases:

- In the first phase, a polymeric powder is deposited on the working bed.
- In the second phase, a nozzle spreads a binder in the necessary zones to create particles agglomerate and to prepare the bonding with the next layer.

The solidification process is therefore led by the binder. The binder itself is usually a polymer, for example an epoxydic resin. Like in the majority of the Additive Manufacturing processes, after a layer is finished the printing bed is shifted down to allow the deposition of a new powder layer and subsequently of binder. Printing speeds are very high (around 500 m/s), so the time of production are very low. This is one of these processes in which some post-processing is needed, like removing of the powder in excess and other to increase the mechanical properties of the part.

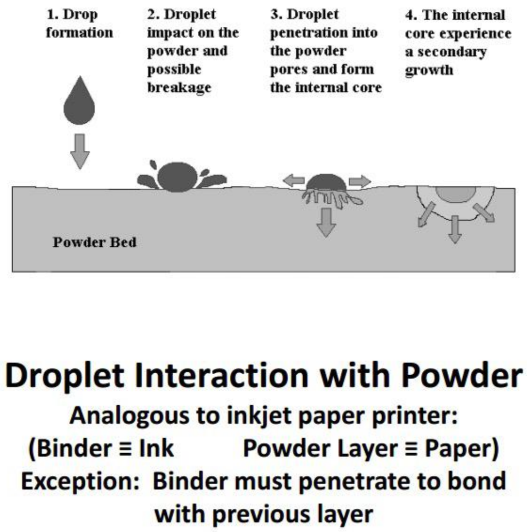

Figure 56 – Three-Dimensional Printing working principle

In general, it is possible to understand that the main advantages of technology are:

- High printing speed.
- Possibility of increasing the mechanical properties of the component through post processing.
- No supports needed.

While the main disadvantage is to research in the kind of material available for this technology, which are very suitable of aesthetic application due to their variety, but not for manufacturing applications which go outside of the prototyping processes. For this reason, this process is not suitable for the case study.

4.1.2 Direct Energy Deposition (DED)

Direct Energy Deposition (DED) allows the manufacturing of components through the melting of material and its deposition. The starting matter is in form of powder of wire. DED processes are based on the focus of energy in small region of the material; this is done usually through a beam which energy melts the deposited material. Despite it is virtually possible to apply this process to all kind of material, in reality it is used with metals in the majority of cases; for this reason, it has been almost immediately discarded.

4.1.3 Material Jetting

The term Material Jetting includes a series of commercial technologies which have been developed during the years, the most applied of which is Drop On Demand (DOD). This technique exploits the Jetting technology to obtain final components characterised by a high grade of details. The process finds its origins in the American company Sanders in 1992, which is nowadays acquired by Stratasys. The phases of DOD consist in the deposition of the material through a printing head and its manufacturing. The adopted material is a thermoplastic, characterised by a low melting temperature, which is deposited with a certain layer thickness. The process exploits a milling machine to obtain very precise details. It is one of those technologies in which supports are necessary, and in this case their main functions are to hold the most critical part of the component and protect the component from the action of the milling machine. When the manufacturing is over the part is detached and dipped in a reusable and recyclable solution to remove the supports. A schematization of the process can be appreciated in the following picture:

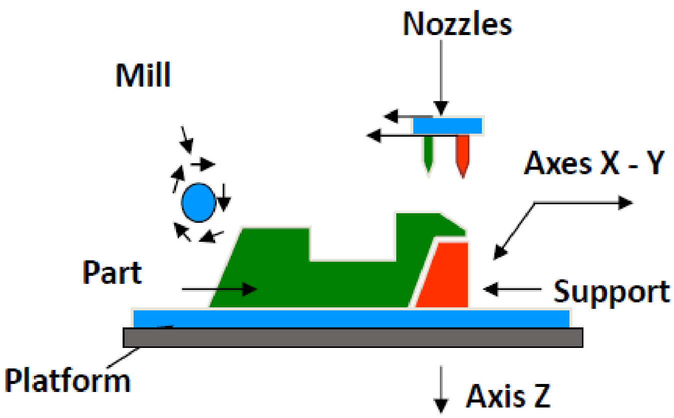

Figure 57 – Drop On Demand working principle

As it is possible to see, the printing is performed on a platform which is reworked before every new manufacturing process. Thanks to the milling process it is possible to apply the so-called adaptive slicing, which allows the possibility of very precise layers and the best following of the geometries of the component. One of the fundamental parameters to tune when performing a DOD process is the methodology of deposition; the discriminating factor is the requested accuracy and attention to the particular details. The basic rules are the same that hold for all the Additive manufacturing processes: fast printing will lead to weak surface finishing and details and vice versa. In the case of DOD, there are two possibilities:

- Vectorial deposition, in which there are two separate heads which can move in different X and Y directions one with the other; this allows the tracing of more precise geometries and higher quality surface finishing, at the cost of a higher printing time.
- Raster deposition: the multiple heads can move in only one single direction, generating therefore coarser surface finishing, but in less time.

Again, in this case it is possible to resume the main pros of this technique:

- Excellent performances in terms of tolerances and surface finishing.
- Non-toxic materials.
- No post-treatment needed.

But there are also some significant flaws: the optimal results in terms of surface finishing and tolerances can be reached only in case the printing happens with very reduced speeds, making this process not exactly competitive with the traditional ones; also, the materials don't show the necessary mechanical properties; in real applications, this technique is often applied when aesthetic is prominent or when it is necessary to produce stamps for the lost wax casting process, which will be very precise thanks to the characteristics of the DOD. In conclusion, also the Drop On Demand has been discarded for the case study taken into consideration.

4.1.4 Powder Bed Fusion (PBF)

Powder Bed Fusion (PBF) is a family of processes characterised by the selective fusion of a powder bed by a thermal energy. While for the metals this term includes a lot of well-consolidated technologies in the industry, such as Electron Beam Melting (EBM), Selective Laser Melting (SLM) and Laser Powder Bed Fusion (LPBF), for the polymers the point of reference is the Selective Laser Sintering (SLS). This Additive Manufacturing technique is one of the most diffused in the market and is based on the selective fusion of a polymeric powder through a laser source. The category of polymer adopted is usually thermoplastic, allowing the realization of definitive components unlike the techniques seen before. Another advantage with respect to the other Additive Manufacturing technologies is the possibility of printing more than one component at a time. The working principle is relatively simple: a powder layer is deposited and rolled uniformly; then, a laser emits the necessary heat to allow the fusion process in the designated point. The standard configuration of an SLS process is showed in the following figure:

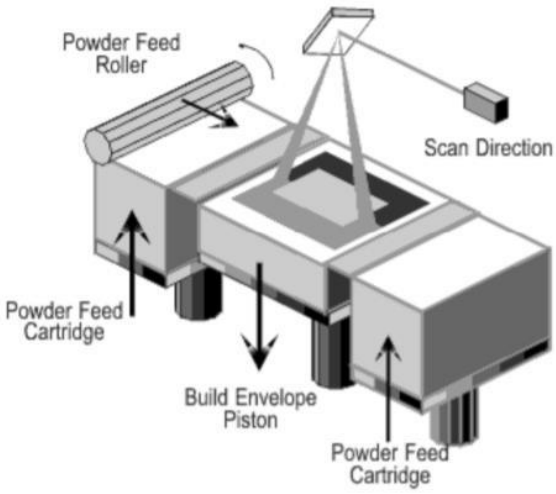

Figure 58 – SLS working principle.

As it is possible to see, the creation of the component is brought in a low-to-high configuration, like in the Majority of the Additive Manufacturing processes: the working bed is lowered while the powder dispensers are lifted, with the counterrotating roller which spreads uniformly and compactly the layer along all the working area. In the example in the figure, but also in the majority of cases, there are two powder tanks, so that the powder distribution process is more efficient: in the first machines of this process the powder tank was single, so the roller had to change direction for every layer, increasing the production times. As it is possible to see, the roller plays a fundamental role in the process, since the distribution and compacting of the powder directly influences the mechanical properties and the surface finishing properties. Another factor to take into account to get a high-quality component is the temperature of the working chamber, which should be pre-heated and kept at a temperature as close as possible to the one of fusion of the powder; also, the presence of nitrogen in the chamber to avoid the oxidation of the powder itself is necessary. The pre-heating of the chamber has two main advantages: reducing the thermal shock of the powder when it will enter in contact with the laser and reducing the necessary power for the laser to melt the powder. One of the consequences of the pre-heating is that, at the end of the process, it will be necessary to wait that the component decreases its temperature before it is possible to proceed with the remotion of the powder in excess (performing this operation when the part is still hot would lead to possible deformations of the part itself). The main flaw which makes this technique unsuitable for the competition with traditional manufacturing is the powder removal: this operation needs to be done manually, often by means of compressed air; the powder in excess can be recycled and reused but needs to be mixed with brand new powder; this allows to have minimal waste in this process. Another characteristic, regarding the SLS machines, is that the only needed maintenance operation is the changing of the laser source. It is possible to resume the benefits of the SLS:

- Good tolerance and surface finishing performances
- Possibility of realizing definitive components
- High productivity (during the manufacturing, not in the post-processing)
- No need of support material
- High flexibility (possibility of printing more than one component at a time and to add new component to print while others are being manufactured)

While the drawbacks are:

- Low productivity in the post processing phase, due to the manual removal of the powder in excess
- Availability of material not so wide

- Despite the possibility of printing definitive component, the technology was born and thought for rapid prototyping.

4.1.5 Sheet Lamination

Sheet Lamination is a term used to include a series of processes based on the elaboration and application of the information of a CAD drawing to build, layer by layer, the component, through lamination of a sheet of the selected material and successive laser cutting. The main processes which belong to this family are Laminated Object Manufacturing (LOM) and Ultrasonic Additive Manufacturing (UAM), but, since both are applied mainly with metals, have been almost immediately trashed for the selected case study.

4.1.6 VAT Photopolymerization

Vat Photopolymerization is another macro category of processes, principally referred to polymer: as a matter of fact, in these Additive Manufacturing processes a liquid photopolymer in a vat is subjected to the so-called light-activated polymerization. Among the possible processes it is possible to include:

- Polyjet/Projet
- Direct Light Projection (DLP)
- Stereolithography (SLA)

Polyjet/Projet

Polyjet process has been developed by the Israelian company Objet Geometries, acquired later by Stratasys. Polyjet allows the production of thin walls and complex geometries with a wide range of available materials. The process is based on the deposition of material through a multiple head nozzle (capable of printing component material and support material) in form of liquid photopolymer layers; these will be sensible to Ultraviolet (UV) rays, therefore the presence of two UV lamps will provide to the thermosetting phenomenon. The possibility of printing supports and component with two different materials allows to choose a soluble material for the supports. The liquid resins are transported by a series of pumps from the tanks to the head, which will provide to the deposition. Like for all the other technologies, once one layer is hit by the UV lamps the working bed is lowered of the needed quantity and the procedure is repeated. A very similar Additive Manufacturing technique has been developed by the American company 3D systems and is called Projet. Considering the characteristic described up to now, it is possible to understand why the main applications are for prototyping, especially in case of needing of high precision, or in general when small parts with a lot of details or style components are needed. This is mainly due to the main pros of these two Additive Manufacturing technologies, which are:

- Good performances in terms of surface finishing and dimensional tolerances
- Soluble supports
- Possibility of creating precise and detailed prototypes from the aesthetic point of view
- Possibility of creating complex and/or intricated shapes.
- Possibility of including in a single component more than one material, so different colours including also transparent/translucid details.

The limits, considering the characteristics of machine, process and technology, are the use of thermosetting materials and the dependency on the characteristics of the nozzle in order to get “high-resolution” components.

Direct Light Projection (DLP)

DLP Additive Manufacturing technology was introduced by the American company EnvisionTEC, and the used material is again a thermosetting resin, on epoxy basis. Unlike Polyjet and Projet, the supports are of this same resin, so a mechanical removal is necessary. The UV beam used for the photopolymerization is emitted by a projector placed under the working bed, so in this process the working bed is progressively raised and not lowered like in the majority of cases during the layer-by-layer building.

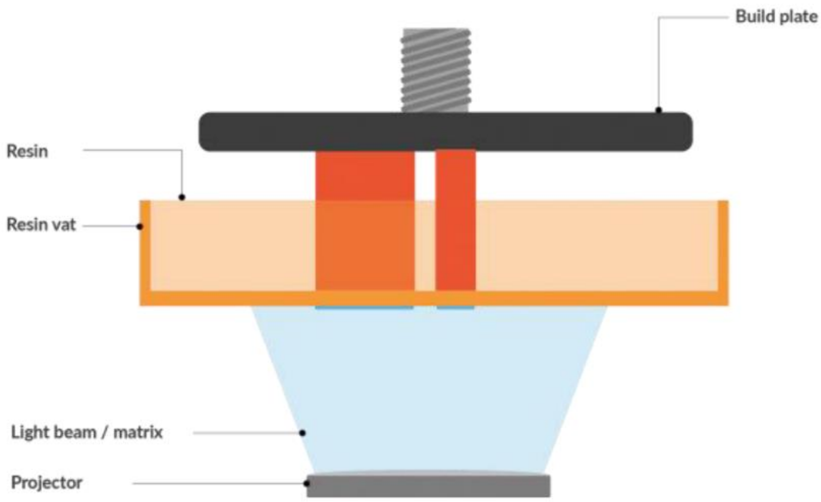

Figure 59 – Direct Light Projection working principle.

The advantages are similar to the ones already seen with Projet and Polyjet:

- Good performances in terms of surface finishing and dimensional tolerances
- No post-treatment
- Possibility of using transparent/translucid materials, in general choosing among a wide quantity of photopolymers.

While for the cons it has to be added that in this case support removal is necessary.

Stereolithography (SLA)

Stereolithography (SLA), as already said in Chapter 1, is the technology which inaugurated the use of Additive Manufacturing techniques in 1982, when it was still used only for rapid prototyping purposes. In this technique, each layer is realized through a laser source able to start the thermosetting reaction of a liquid photopolymer, in particular a thermosetting resin on epoxy, acrylic and vinylic basis. After the first layer is done, the platform lowers of a certain quantity set during the slicing phase, allowing the manufacturing of a new layer. Stereolithography process is divided into two main phases: the first one, also called green part, is the aforementioned laser treatment; the second one, also called red part, is a UV treatment performed in an oven. The green part is for the creation of the internal and external perimeters of the component, while the red part is the photopolymerization phase, in which the part that have remained liquid during the first phase are solidified.

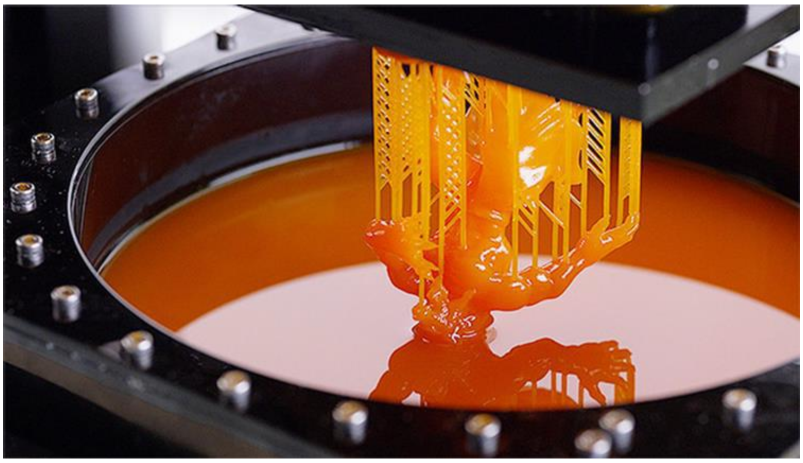

Figure 60 – Example of Stereolithography process.

Even today, SLA is mainly used for Rapid Prototyping, Rapid Tooling and Rapid Casting applications, especially in the Automotive field; this is thanks to its main positive aspects, like the fastness of the process and the possibility of realizing transparent/translucent components, while, from the point of view of the final component, the main issue is always the use of thermosetting materials instead of thermoplastic ones. Also, from a process point of view, it is fundamental to avoid any contact with sunlight during the manufacturing, which can affect the red part phase. Finally, flexible components are difficult to create, and in general the part will not present remarkable mechanical properties. For these reasons, also the Stereolithography has not been considered as a valid possibility for the case study taken into examination.

4.1.7 Material Extrusion

When considering material extrusion and polymers, the most important process is for sure Fused Deposition Modelling (FDM). It is one of the most known Additive Manufacturing techniques, mainly due to the fact that is historically one of the first techniques which was able to realize a component with the use of a thermoplastic, opening new opportunities for the AM processes other than for the prototyping. Another interesting characteristic of this process is the possibility of realizing the supports with a different material with respect to the one of the parts (at least in the industrial machines, as it will be seen later), so that it becomes easy to remove them without damaging the component. The printing process, as the name suggests, happens through the deposition of one or more filaments on the building platform until the part is completed.

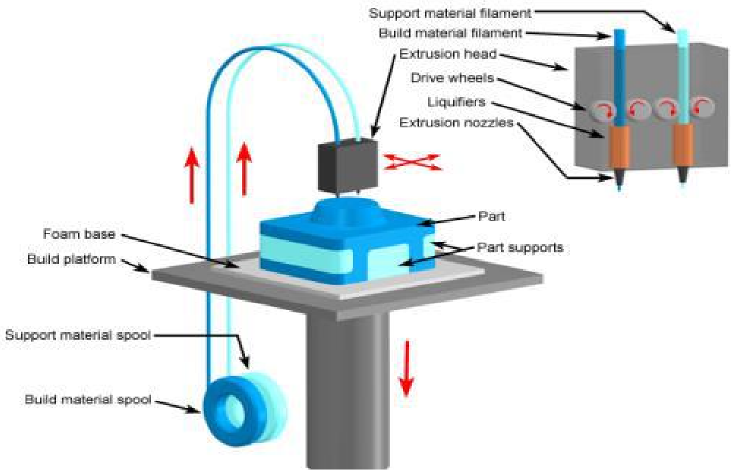

Figure 61 – Fused Deposition Modelling working principle.

Of course, some parameters must be monitored, like the extrusion temperature of the material, since an excessive value would cause unproper flowing phenomena, while a low value would obstacle the correct adhesion of the new layer with the previous one. Historically, Fused Deposition Modelling (FDM) was patented in 1987-1988 by Scott Crump and commercialized by the American company Stratasys in 1991 [43]; after the expiring of the patent, lots of different companies developed their own version of the process, to the extent that nowadays it is also known with the more "general" term Fused Filament Fabrication (FFF). The starting material, which is a thermoplastic filament, is put into an extrusion head where it is heated and consequently softened. After the part is complete, the removal of the supports happens through two main steps:

- At first, a preliminary removal is performed in a mechanical way, which can be manual, with the help of some tools or automatised; this first phase is favoured by the fact that usually the supports are built with a different material with respect to the part, so they will probably have a different colour.
- The difference in the material between component and supports is again helpful in the second phase of the removal, which is not anymore mechanical but chemical; due to the characteristics of the supports, a chemical bath can help dissolving the ones that are still present after the mechanical removal.

Considering what said up to now, it is possible to resume the peculiar advantages of the Fused Filament Fabrication process:

- It ensures good performances in terms of dimensional tolerances and superficial finishing.
- It is possible to realize both prototypes and definitive components.

- Easiness in removal of supports.
- No post-treatment.
- Very safe process, since the majority of the work happens inside the machine, without any contact from the operator.

On the other hand, the process also comes with some flaws:

- Impossibility of exploiting the entirety of the working volume (it is not possible to realize two components one over the other due to the presence of supports
- Depending on the adopted machine, possibility of limited speed.

Considering this, in the end Fused Deposition Modelling has been chosen as the most suitable process for the case study taken into examination, mainly for the possibility of printing not only a prototype but also the final component.

4.2 Fused Deposition Modelling machines

Fused Deposition Model machines can be categorised accordingly to their application into low-cost FDM and Industrial FDM: in the first case the machine is equipped with a single extruder, the chamber is kept at room temperature or cannot reach too high temperatures during pre-heating phase and calibration needs to be performed manually; these machines are the “domestic” ones, which can be purchased by privates and are sometimes called erroneously “3D Printers” from the commercial point of view. Instead, Industrial FDM has usually multiple nozzles, allows the pre-heating of the chamber at significative temperatures and has an automatised system of setting and calibration (usually the software is a proprietary one, unlike the open-source ones of the domestic FDM machines). The industrial machines are furtherly divided into two categories, Design Series and Production Series: as the name suggests, the first category is adopted mainly in the prototyping phase, when modifications need to be tested rapidly; the production series are typically bigger and allow the production of the definitive components. Of course, the higher dimensions of the machines affect the working speed, which will be slower (this is also influenced by the thickness of the layer). For this particular case study, the adopted machine will be the Roboze Argo 500.

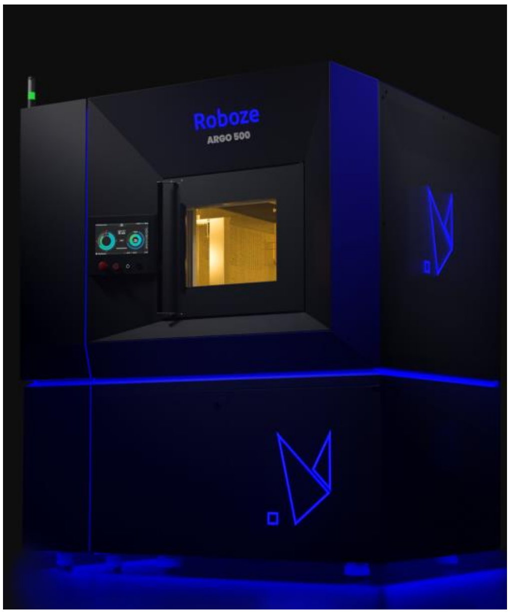

Figure 62 – Roboze Argo 500 [56]

This machine allows a high-precision FFF 3D printing with elevate levels of speed and repeatability, especially when speaking of low production levels [52], the field where Additive Manufacturing can compete on equal terms with traditional manufacturing. All these has become possible thanks to the patented Roboze technology called "Beltless System™", which substituted the traditional adoption of rubber belts with a racks and pinion system [55]. Another feature of the Argo 500 is the so-called "HVP (High Viscosity Polymer) extruder", able to sustain temperatures in the range of 550°C; this consents the use of (also but not only) the Roboze techno-polymers such as PEEK, Carbon PEEK, ULTEM and so on; also the printing volume is controlled from the point of view of the temperature: it possible to reach temperatures up to 180°C and to completely dehumidify the ambient [52], since the absorption of water from the filament can alter the final mechanical properties of the parts, as will be also discussed in the next paragraph when speaking about the selected materials for the case study. Moving to the more technical side of the machine, some of its characteristics, provided by the Roboze website, can be seen here [55]:

Whole system dimensions	1935x1436x2375 mm
Printing environment dimensions	500x500x500 mm
Precision	10 µm
Weight	1700 kg

Compatible materials	PEEK, Carbon PEEK, ULTEM, Carbon PA, PP, Strong-ABS, FUNCTIONAL-NYLON, ULTRA-PLA, etc.

Table 2 – Roboze Argo 500 characteristics.

The Roboze Argo 500 is well-known and adopted in the Additive Manufacturing world; this is confirmed by the fact that it is possible to find lots of examples of its usage (being them virtual or effective) in the literature; with a particular focus on the automotive field, it is possible to mention:

- Acanfora et al. [56] produced some samples made of PP (Polypropylene) and PP-CFRP (Polypropylene combined with carbon fibres) through Roboze Argo 500 in order to check the correspondence between virtual and real experimentation for the design and study of an automotive shock absorber for safety purposes.
- Kessentini et al. [57], in a similar way, printed specimens made of Carbon PEEK using the Roboze Argo 500, this time for the design and optimization of a mono leaf spring.
- Another study on shock absorbers for safety purposes, this time specifically focused on the upper roof zone of the vehicle, was performed by Riccio et al. [58]; in this case the study was only at a theoretical level, so the shock absorbers are supposed to be printed through Roboze Argo 500 using again PP (Polypropylene).

It is worth to mention again, like previously done in Chapter 3, that, when possible and considering the availability of data, case studies always benefit, from a validity point of view, of the usage of "real" homologation values when performing testing and simulations.

4.3 Additive Manufacturing materials

Some of the material available in the market, which are usually included with the purchasing of a Fused Filament Fabrication machine, are: ABSi, PC-ISO, ABS-M30i, FDM Nylon 12, ABS-ESD7, ULTEM 9085, PC-ABS, ULTEM 1010, ASA. All the aforementioned materials are thermoplastics, with the ABS which is probably the most adopted one in the automotive industry, especially for the production of functional prototypes, small production batches or stamps for production to be used instead of the silicon ones. In general, all the polymers adopted in Fused Deposition Modelling share a common base of characteristics, but it is possible to make a distinction especially regarding the mechanical properties.

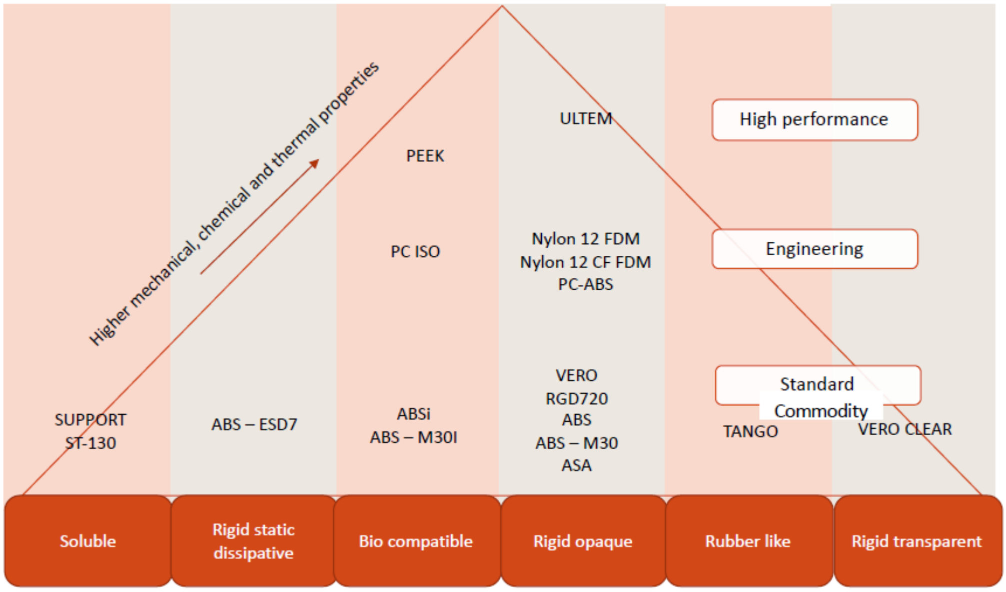

Figure 63 – Classification of the materials used for FDM/FFF.

For this case study it is necessary to look at the top of the pyramid, since the final objective is to assess whether it is possible or not to replace a component which is initially made in metal. For this reason, two high-performance materials have been selected, also taking into account the compatibility with the Roboze Argo 500: Carbon PA and ULTEM 9085. Both are developed by Roboze itself, an Italian company specialized in Additive Manufacturing and 3D printing.

4.3.1 Carbon PA

According to its technical data sheet [49], Carbon PA is realised starting by Polyamide and adding in its matrix structure a 10% in weight of carbon fibres. The main molecular group representing the structure of the Polyamide is the CO-NH one; being the main one, it is also the one which has a determinant importance in the definition of the characteristics of the material. Polyamide is a semi-crystalline polymer, so the "geometry" of the polymer will be regular and constituting crystalline zones. This ordered distribution is ensured by the sequence of the aforementioned CO-NH groups, particularly by the interfacing of a CO "subgroup" with an adjacent "NH" one. Polyamides as a whole usually find lots of applications in the manufacturing industries thanks to their properties like ductility, toughness, relatively economic prices and chemical properties. The addition of carbon fibres comes to compensate the main flaw of this family of materials, which is the not excellent mechanical characteristics [50]. Considering the specific case of the Roboze Carbon PA [49], adding the 10% in weight of chopped carbon fibres ensures an increasing in all the main mechanical features of the material, such as stiffness, thermal endurance and mechanical strength, other than good resistance to a plethora of automotive fluids such as diesel, gasoline, esters and ethers. Despite this and also a quite low level of moisture and water absorption level, the material is still hygroscopic, which means that the prolonged absorption of water may lead to deformations of the component after a certain amount of time; several case studies of this eventuality and how to prevent it have been explored in the literature. In general, all those features like temperature of the nozzle, thickness of the layer and so on have an influence on the final mechanical characteristics of the component. Finally, the material also ensures a good aesthetical aspect, and as already explained deeply in the previous chapters, thanks to the metal replacement and weight reduction application also embodies an answer to the more and more urgent environmental issues [51,52]. As regards the applications, the mechanical characteristics combined with its lightweight properties make Carbon PA very desirable for aerospace and automotive uses [53]. The company website of Roboze itself presents some automotive and motorsport applications [54]:

- Roboze has successfully printed a Carbon PA engine cover (which can be appreciated in the figure below), embedding the advantages of weight reduction with the ones of metal replacement and additive manufacturing.
- Another similar application regarded the production of a motorcycle clamp, with a saving of 50% on weight and of 60-70% on the cost (of course considering a batch made of a single component)

Figure 64 – Roboze Carbon PA engine cover [55]

Moving to more technical data, some of the characteristics of the Carbon PA are resumed in the following table [49]:

Property	Unit of measure	Value
Tensile Strength, ultimate, XZ	MPa	93
Tensile Strength, ultimate, XY	MPa	88
Tensile Strength, ultimate, ZX	MPa	69
Tensile Strength, yield, XZ	MPa	68
Tensile Strength, yield, XY	MPa	61
Tensile Strength, yield, ZX	MPa	54
Young Modulus, XZ	GPa	4.9
Young Modulus, XY	GPa	3.9
Young Modulus, ZX	GPa	2.7
Melting temperature	°C	200
Crystallization temperature	°C	162
Density	g/cm^3	1.17

Table 3 – Carbon PA main characteristics [49]

As it is possible to see, like the majority of the polymers Carbon PA is characterised by a certain level of anisotropy, and this should be taken into account when comparing the performance of the component made with polymers with respect to the one realized in metal.

4.3.2 ULTEM AM9085F

According to its technical data sheet [59], ULTEM 9085 is an amorphous polymer, realized through the blending of polyetherimide thermoplastics and polycarbonate copolymer, which improves its general characteristics. Thanks to its outstanding properties it belongs to the "family" of techno-polymers, also called super-polymers; this is mainly thanks to the mechanical and thermal performances, but also to the chemical ones, since it is able to resist to ultraviolet rays, acids and has a very good weatherability. It ensures good properties also from the electrical point of view, other than resistance to frequencies such as microwaves. Like in the case of Carbon PA, factors like nozzle temperature, layer orientation, printing speed and so on will have an influence on the final characteristics of the part, therefore also in this case it is fundamental to set properly these parameters. As regards the applications, all the previously listed features make this techno-polymer very attractive for aerospace ones: especially the high thermal resistance and the resistance to various fluids and different weather conditions are two desirable characteristics in this field; nevertheless, it is possible to find also some applications in the automotive world [60], where the needs are sometimes similar, even if in the automotive world it is quite difficult to reach the extreme conditions that are present in the aerospace one: for example, a need which is shared by the two fields is the resistance to flame and/or the self-extinguishing capacity: while lots of polymer don't have this property and need to be post-treated in order to artificially add it, ULTEM 9085 doesn't need this additional step since it is intrinsically Flame Retardant. In addition to that, ULTEM 9085 has reached official validations in regarding of self-extinguishing materials and FST (Flame, Smoke and Toxicity, meaning that the smoke produced during the ignition of ULTEM 9085 is not toxic). For example, all these characteristics, combined with the chemical ones referred to the resistance to fluids and so on, are suitable for the production of automotive ducts.

Figure 65 – Roboze ULTEM 9085 components [60]

To conclude, also in this case it is possible to resume the more technical characteristics of the filament in a table containing the information provided by the Roboze technical data sheet [59]:

Property	Unit of measure	Value
Tensile Strength, ultimate, XZ	MPa	98
Tensile Strength, ultimate, XY	MPa	87
Tensile Strength, ultimate, ZX	MPa	56
Tensile Strength, yield, XZ	MPa	83
Tensile Strength, yield, XY	MPa	63
Tensile Strength, yield, ZX	Mpa	40
Young Modulus XZ	GPa	2.9
Young Modulus, XY	GPa	2.6
Young Modulus, ZX	GPa	2.5
Density	g/cm^3	1.27

Table 4 – ULTEM 9085 characteristics [59]

5. Design of the component, analyses, redesigns

The design of the component has been brought on using the Solidworks software. Due to the fact that the Land Rover Discovery V was not available for taking the necessary measurements, another model of the same segment (SUV) was adopted, which is the Mercedes GLB. The analyses have been conducted with the Hyperworks software, in particular Hypermesh for the meshing and Optistruct for the structural analysis. In the end, it has been decided to bring on the evaluation considering ULTEM. This is due to the fact that Carbon PA properties strongly depend on the orientation of the Carbon fibres in the material, which is an information not provided by the Roboze technical data sheets and is also more challenging to implement it in the Hypermesh environment. The starting point should be the design of a component which resembles as much as possible the real one taken into consideration; after this first design is completed, it is possible to proceed with a first analysis on the component produced with the traditional material and method to understand its response on a simulation of working. After this analysis is completed, it is necessary to move to the Additive Manufacturing situation; it is crucial to exploit the advantages of the Additive

Manufacturing design, that is to get the possibility of developing more complex designs with a cost which is lower with respect to a traditional manufacturing operation.

5.1 First design

The starting point is a surface resembling the shape of the headlight taken into examination (the left headlight has been chosen):

Figure 66 – Contour of the surface resembling the headlight

The measurements have been taken considering the real vehicle. The first step is to realize a contour of a predetermined thickness which will constitute the edge of the grid. At this point the "grid" is drawn considering to follow both horizontally and vertically the already present contour; the "width" of the rows and columns constituting the grid are considered starting from the grid of the Land Rover Discovery V model. Here it is possible to appreciate the result:

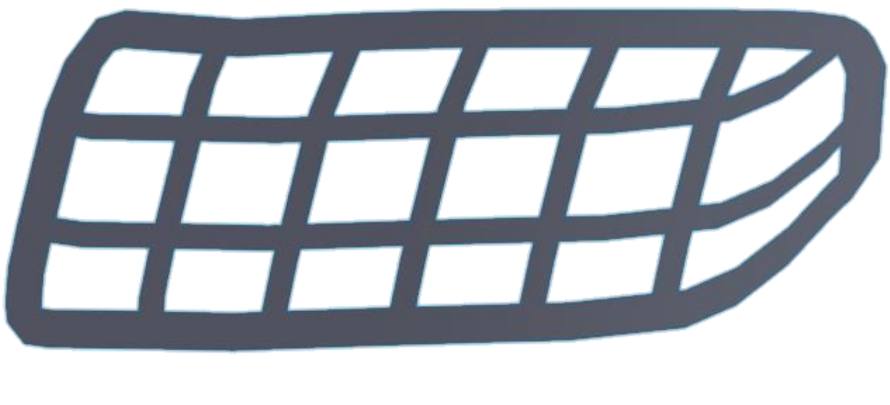

Figure 67 – Front view of the grid surface

At this point, some parts of the edges have been extended in order to get an area designated for the allocation of the screws, in order to allow installation and removal of the grid depending on the situation; the "clips" have been added taking into account the availability of space around the headlight zone.

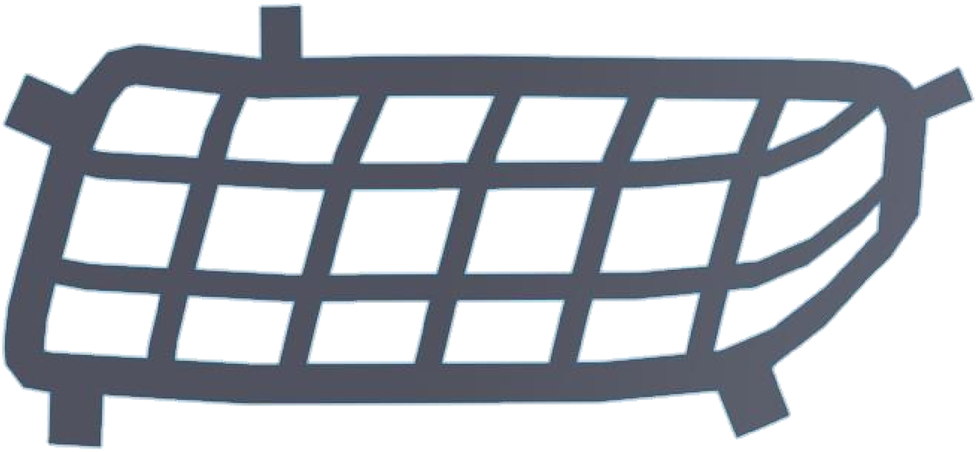

Figure 68 – Front view of the grid with clips for the holes

Since it is a surface, it is necessary to give it a thickness to turn it into a solid; The thickness has been selected taking into account the information given by the company Sperotto S.p.A. (2 mm):

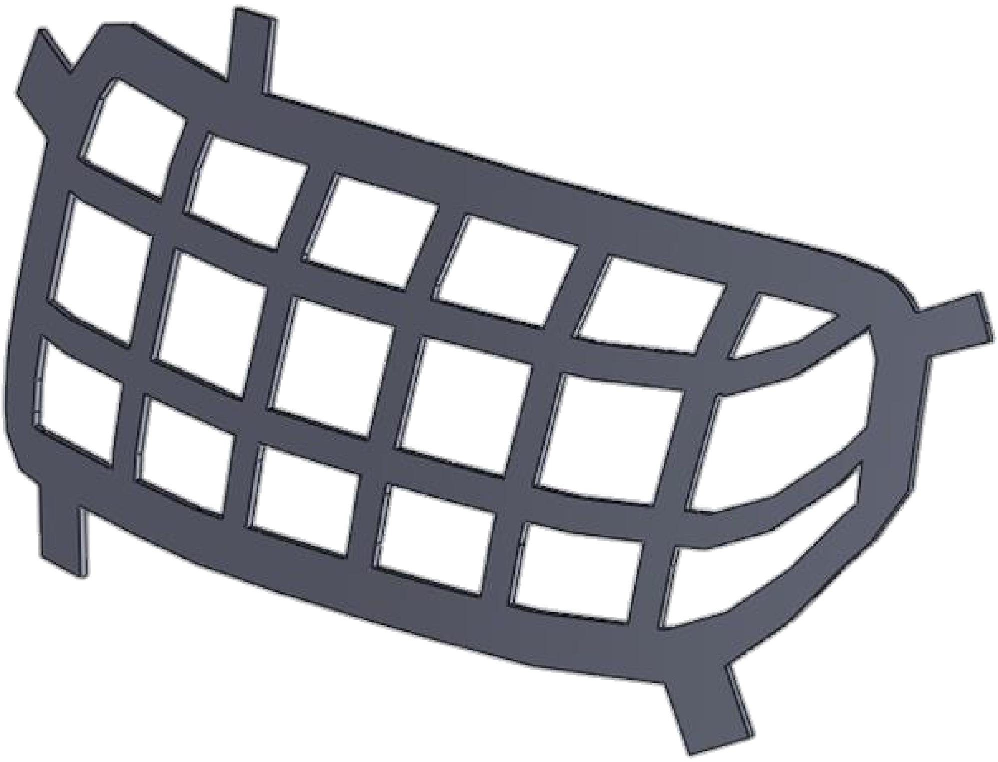

Figure 69 – Headlight guard with 2 mm thickness

Finally, holes have been added where the screws are supposed to be:

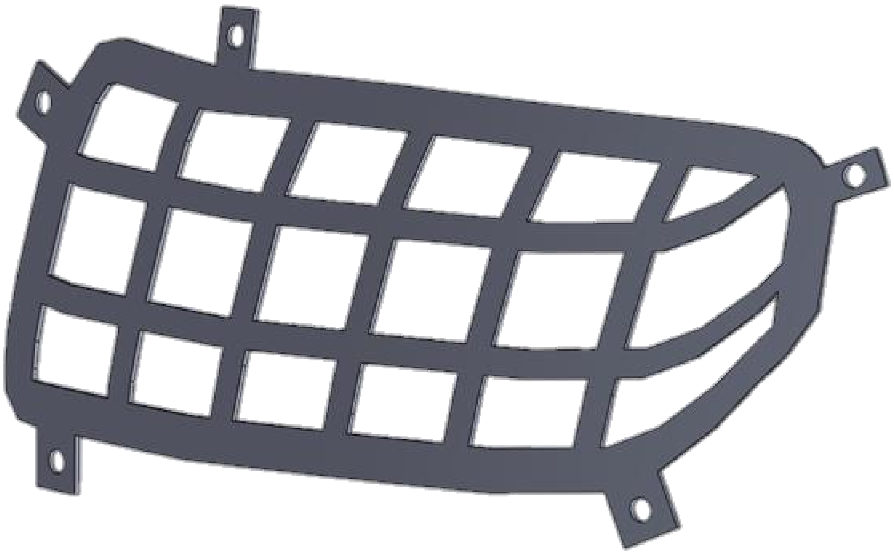

Figure 70 – Headlight guard, first design

This is the first completed design. At this point, it is possible to perform a first structural analysis to understand the properties of the finished component. Considering the shape of the component, 26 zones of the mesh have been selected on which select a node to apply a static force; the objective was to stay in a safety factor around 4.

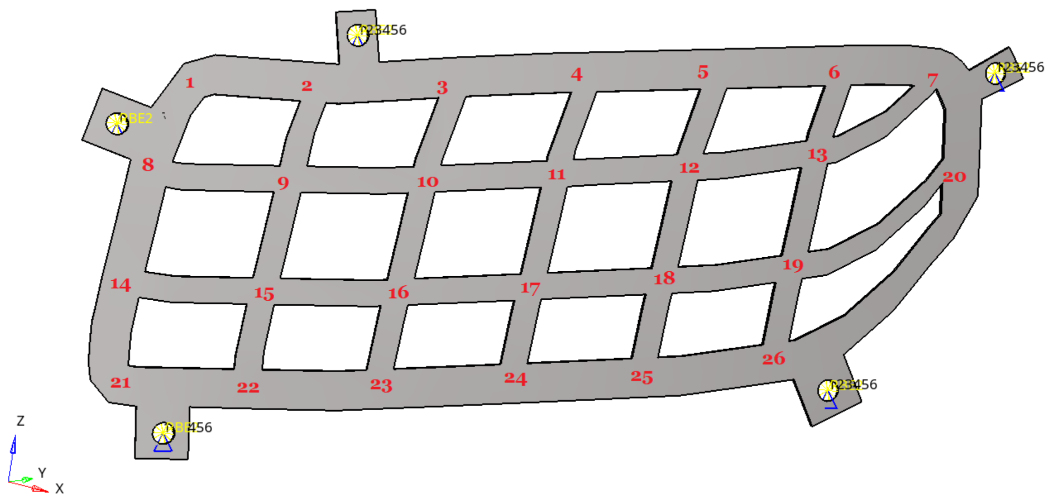

Figure 71 – Selected point for the structural analyses

Some other points in between the selected ones have also been tested, but they were judged as not critical for the Safety Factor; they instead gave relatively high values for the displacement, but due to the characteristics of the steel even the highest displacements are still far from the value of the clearance between the installed grid and the headlight, which has been measured in the real vehicle and corresponds to circa 10 mm. This should be taken into account when moving to the study of the polymer, which is characterized by higher levels of deformations. In the following table it is possible to appreciate the results of the simulations, considering the zone and the corresponding safety factor. Remember that the safety factor is characterised by the following formula:

$$SF = \frac{\sigma_{Rp,02}}{\sigma_{VM}}$$

Where $\sigma_{Rp,02}$ is the yield strength presented in Chapter 3, 235 MPa, and $\sigma_{VM}$is found after the simulation is completed. In the end, a force of 140 N has been selected.

Point	**Safety Factor (SF)**
1	5.04
2	6.25
3	4.95
4	5.29
5	4.98
6	4.45
7	5.32
8	7.34
9	6.93
10	5.77
11	5.84
12	5.76
13	5.51
14	6.26
15	6.52
16	5.64
17	6.76
18	5.93
19	4.85
20	4.40
21	4.08
22	4.61

23	4.27
24	6.21
25	5.51
26	6.05

Table 5 – Results of the simulations

As it is possible to see, the most critical point among the ones that have been selected is the number 21.

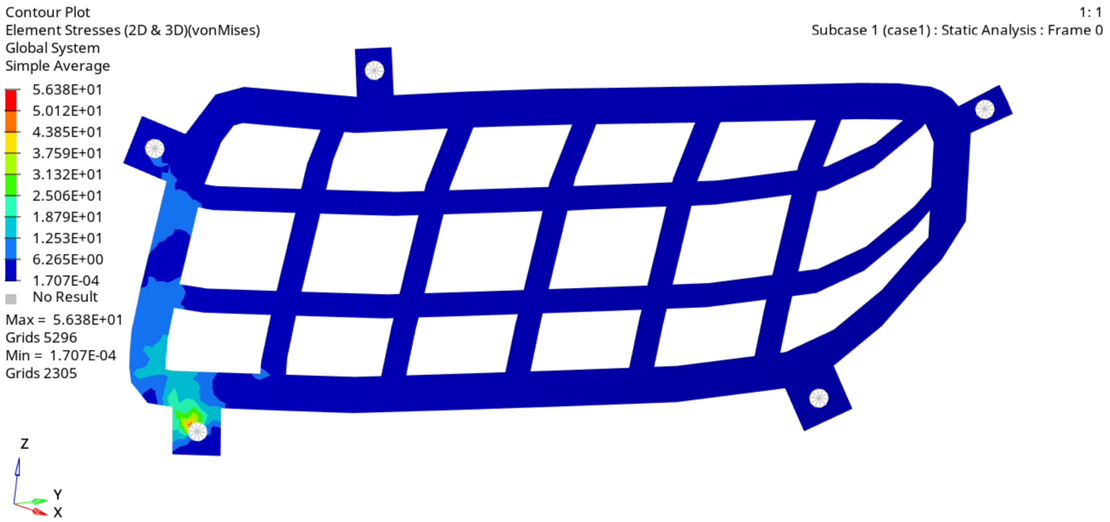

Figure 72 – Von Mises stresses evaluation for point 21

5.2 Additive Manufacturing redesign

Considering the component produced through Additive Manufacturing, it is possible to subdivide the study considering the three main objectives that have to be reached at the end with the final component:

- Competitiveness in terms of strength: the part should have the same or at least comparable performances with the one made with S235JR steel which has been analysed in paragraph 5.1.
- Exploiting of the Additive Manufacturing design in terms of lighting: despite the main objective of the component is to protect the headlight devices in case of shock, it should also interfere the least possible with the passing of the light.

- Exploiting of the Additive Manufacturing design in terms of aesthetics: as it is well-known, one of the biggest advantages of Additive Manufacturing is the possibility of rethinking completely the component without submitting to the constraints given by the traditional manufacturing.

After having taken all this into account, the redesign phase can start. First of all, it is necessary to understand which are the constraints that, independently from the modification, have to remain always the same; this can be done by looking at the operations performed to build the part according to a traditional manufacturing logic, which will make also possible to understand which are all the other variables that can instead be modified. Therefore, here are retraced the main steps done for the building of the part:

- Tracing of the contour and of the surface: since the surface must follow the contour of the headlight zone, it cannot be modified.
- Drawing of the contour for the edge of the grid: the shape of the contour is not a constraint, even though it is advisable to follow as much as possible the original one; also, it is possible to modify the width of the said contour.
- Drawing of the grid: the grid is one of the variables which can be modified the most, since it can be modified to exploit as much as possible the potentiality of an Additive Manufacturing design.
- Adding of the surfaces of the clip and related holes: while the holes are a constraint, since the position of the screws cannot be changed, it is possible to work on the surrounding clips.
- Thickness of the component: while this was a constraint in the traditional design, now it is necessary to consider it as a variable, because it is very likely that the performances of the polymer will be lower will respect to the ones of the metal and therefore this parameter can be fundamental to compensate the differences.

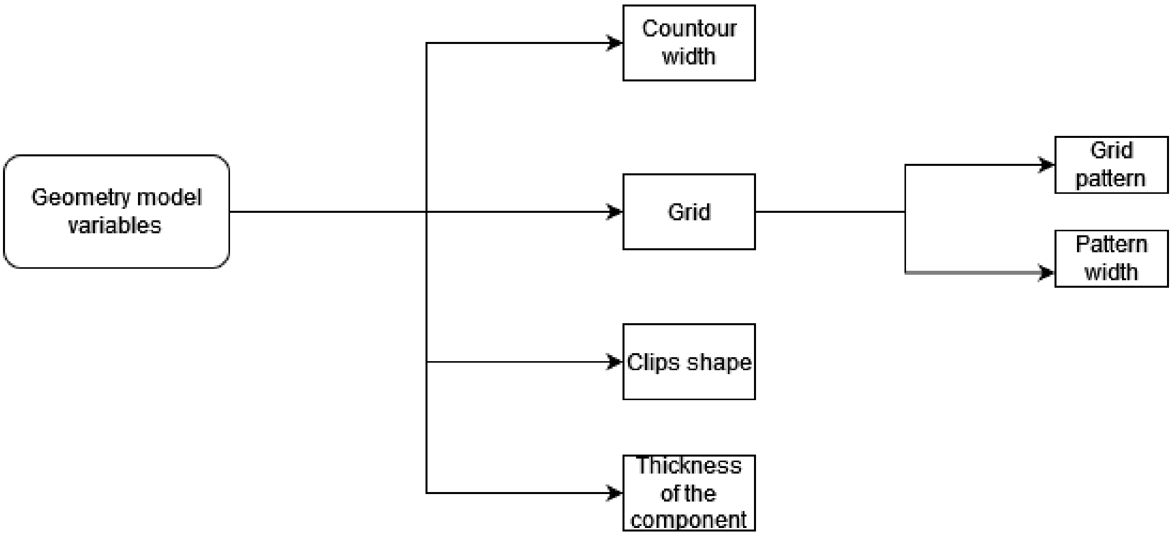

Figure 73 – Geometry model variables

It is also possible to build a graph representing the methodology that it's going to be applied on the redesign of the component:

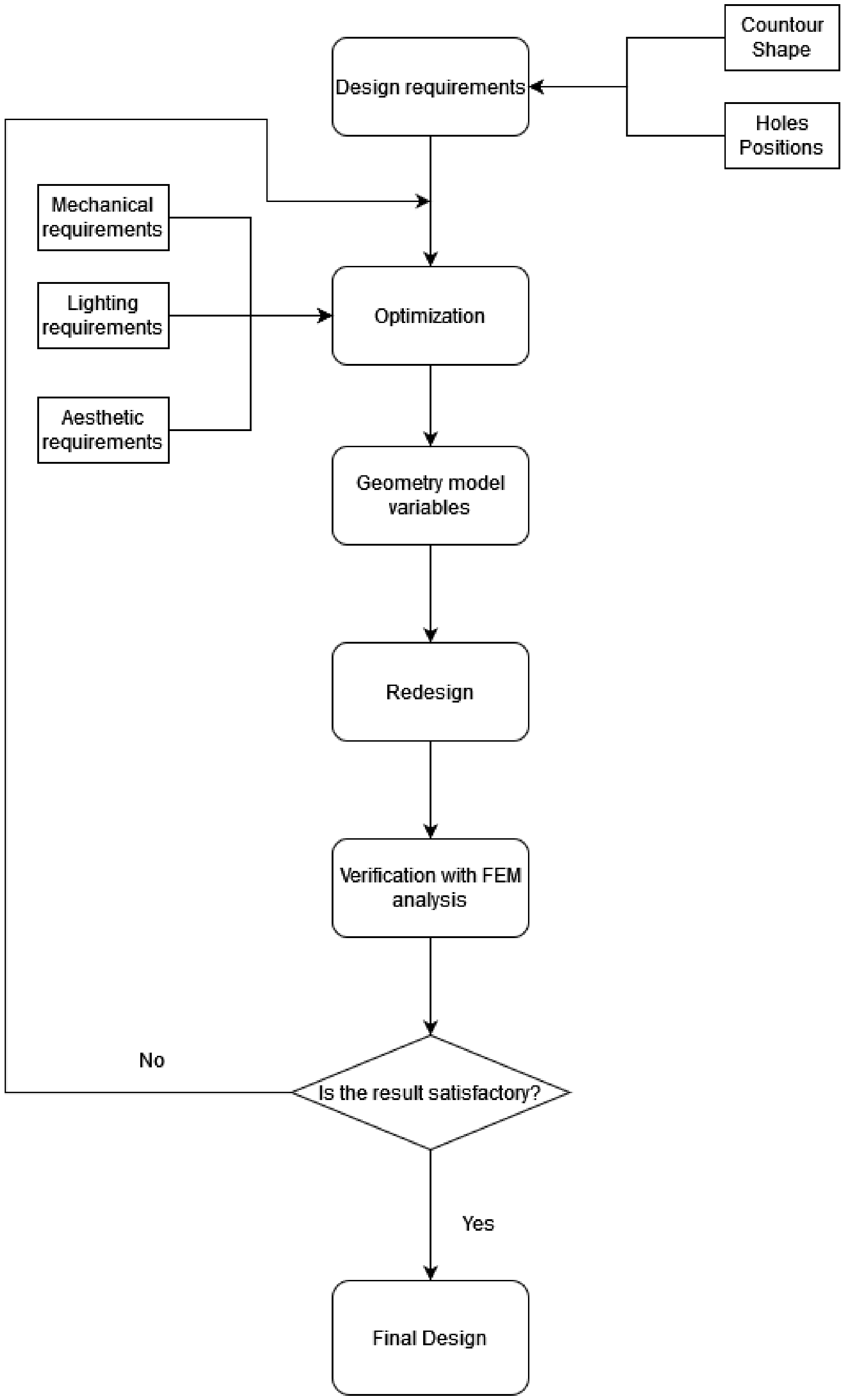

Figure 74 – Redesign flowchart

Considering the complexity of the model above, it is convenient to order the different variables in a sort of "priority scale", so that it will be possible to act on them separately until an acceptable result is reached; the priority is chosen taking into account the three requirements mentioned before (mechanical, lighting, aesthetical), and, from the most impacting to the less one, are listed below, along with a brief justification of the chosen position:

1. Grid pattern. Grid pattern (or shape) is selected as the most impacting variable since it has an influence on all the three requirements: for the mechanical one, the impact with an object has more probability to happen where the "pattern" of the grid is present, rather than in the edges; for the lighting one, the shape of the grid will for sure impact on the capacity of the headlight; for the aesthetical one, it is clear that, especially considering the Additive Manufacturing design, it is possible to obtain remarkable results choosing the most diverse designs.
2. Thickness of the component: despite influencing only one of the three requirements, which is the mechanical one, it has the highest impact on it, therefore a high priority is given to this variable.
3. Contour ("clips") shape: the impact of this variable on the three requirements is minimal, so it should have been placed relatively low in the priority scale; nevertheless, considering the Additive Manufacturing design, it is fundamental to modify it since the original design was explicitly oriented towards the traditional production methods.
4. Width of the grid pattern: depending on the chosen grid shape and/or pattern, it is possible also to act on the width. Like for the grid shape, this will have an impact on all the three requirements, but it is particularly important considering the mechanical ones: if it is not possible to act anymore on the thickness (for example because, by increasing it too much, the advantages of the polymer in terms of weight will be reduced), it will be necessary to act on this other parameter; of course, the downside of this action will be the reduction of the lighting action of the headlight, for this reason this variable has been placed relatively low in the priority scale.
5. Contour width: despite having an impact on the mechanical requirements of the component, it is chosen to give the lowest priority to this variable so that it will be changed only if strictly necessary.

Considering all this, in the end the following designs have been extrapolated, developed and considered as the best compromise between mechanical, aesthetical and lighting requirements.

5.2.1 First redesign

For the first redesign, the set of variables mentioned before has been developed in this way:

- Grid pattern: in this first redesign it has been decided to keep the classic grid pattern.
- Thickness of the component: it has been set to 4 mm starting from the initial value of 2 mm used in the metal component; this value has been chosen after a series of simulations to try to resemble as much as possible the mechanical resistance of the metal component.
- Contour shape: the shape of the contour has been changed to “incorporate” the clips in a single shape more suitable to the Additive Manufacturing design.
- Width of the grid: with respect to the original grid thickness, it has been increased to match as much as possible the mechanical resistance of the metal component; the final values have been chosen after a series of simulations and correspond to: 29 mm for the width of the vertical columns (the original value was 14.5 mm, so it was doubled); 23 mm for the width of the horizontal columns (the original value was again 14.5 mm, in this case the necessary increase was less with respect to the vertical ones); 52 mm for the distance between the middle of one vertical column and another (the original value was 58 mm); 53 mm for the distance between the middle of one horizontal column and another (the original value was 48 mm). The number of horizontal and vertical columns has been kept the same with respect to the original design.
- Contour thickness: due to the irregularity of the chosen contour shape, it is not constant anymore.

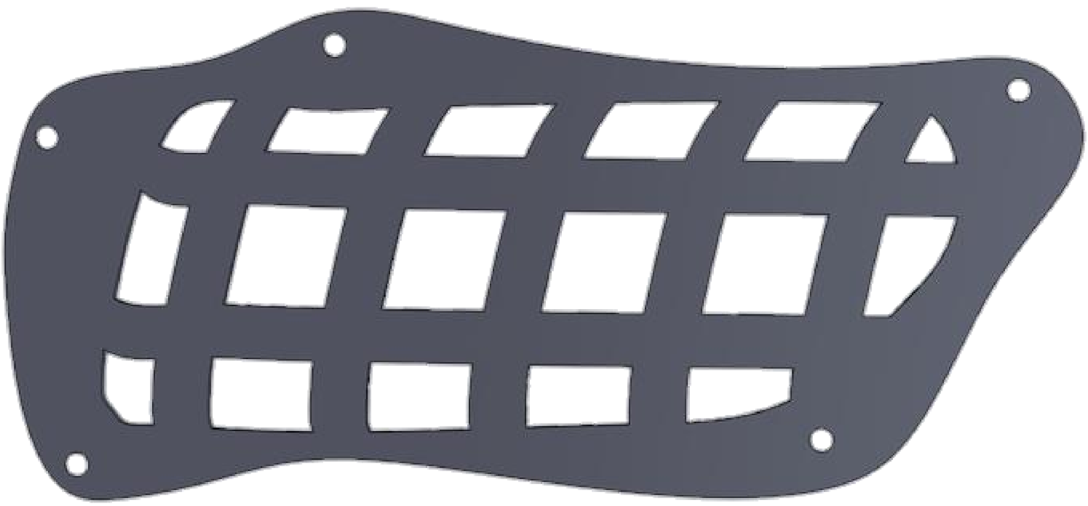

Figure 75 – First redesign

Due to the similarities between this design and the original one, it is possible to perform a similar structural analysis to the one done with the original component, where a series of zones are selected in which it is possible to choose a node and apply a static force. The force will be the same used for the simulations with the original component, which was 140 N.

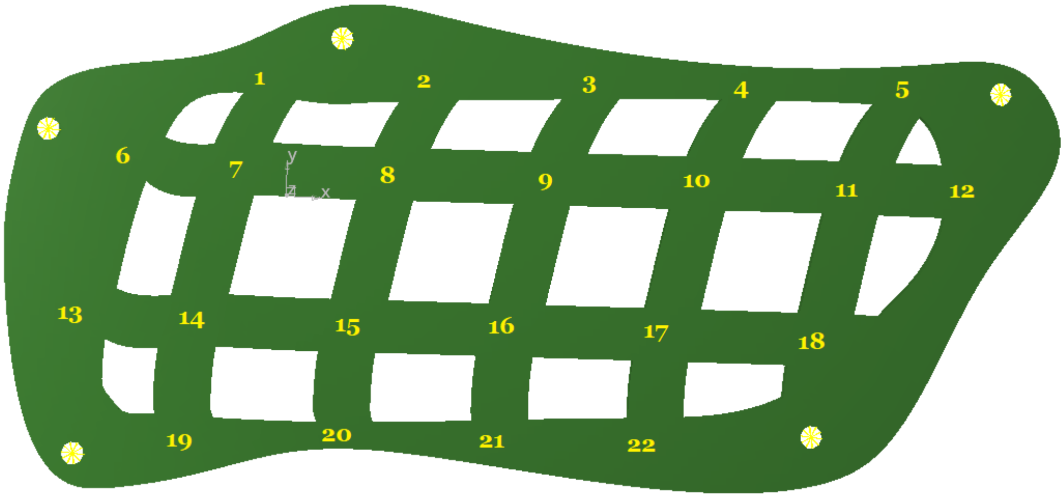

Figure 76 – Selected points for structural analyses of first redesign

Like in the case of the metal component, it is possible to find the Safety Factor for each of the selected points, of course taking this time into account the data of the ULTEM.

Point	Safety Factor (SF)
1	4.48
2	3.70
3	3.93
4	2.97
5	2.99
6	4.59
7	5.45
8	4.49
9	4.71
10	5.30
11	4.12
12	3.29
13	5.12
14	4.33
15	5.07
16	4.47

17	5.23
18	4.13
19	3.32
20	2.63
21	2.94
22	3.00

Table 6 – Results of the simulations, first redesign

As it is possible to see, in some critical points the Safety Factor goes below 4, anyway staying always around a value of 3, which is still considered enough safe. It is also interesting to note that the most critical point is the one where the contour of the guard is thinner; this has been done both to reduce the quantity of used material and to allow a more additive-oriented design, avoiding sharp angles.

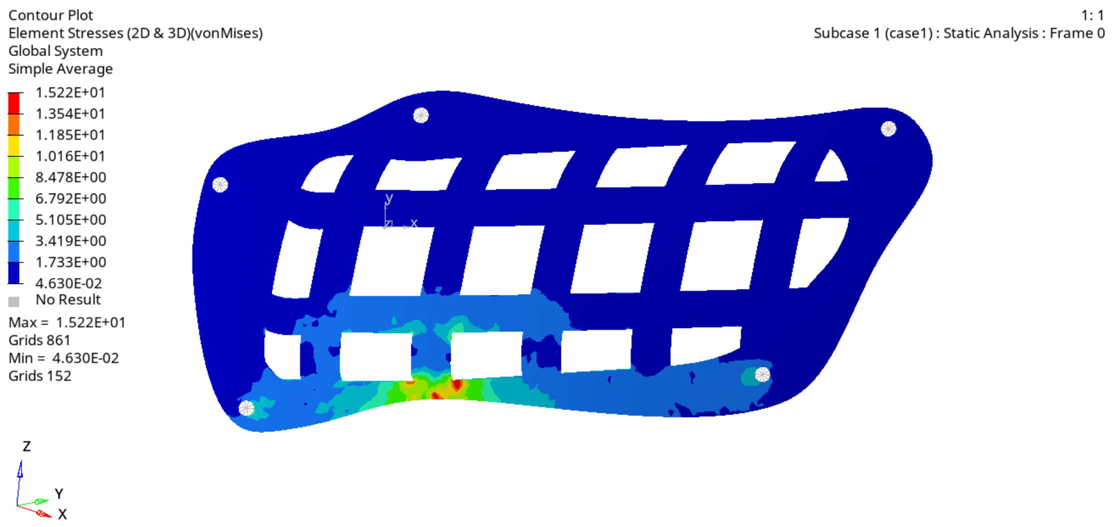

Figure 77 – Von Mises stresses evaluation for point 20 of first redesign

5.2.2 Second and third redesigns

The second and third redesigns share 3 of the 5 variables; starting from the second redesign, the variables have been set in the following way:

- Grid pattern: in this case the objective was to focus on the passing of the light priorly to the mechanical resistance; for this reason, a grid made of linked concentric contour shapes was designed.

- Thickness of the grid: increased to 5 mm due to compensate the lower mechanical resistance given by the grid shape.
- Contour shape and width: even in this case the contour was modified to “incorporate” the clips of the original design, but this time keeping a constant thickness of 20 mm (the original value was 22 mm).
- Width of the grid: determined by the distance between two concentric contours; for the “links”, a width of about 15 mm was chosen after some testing.

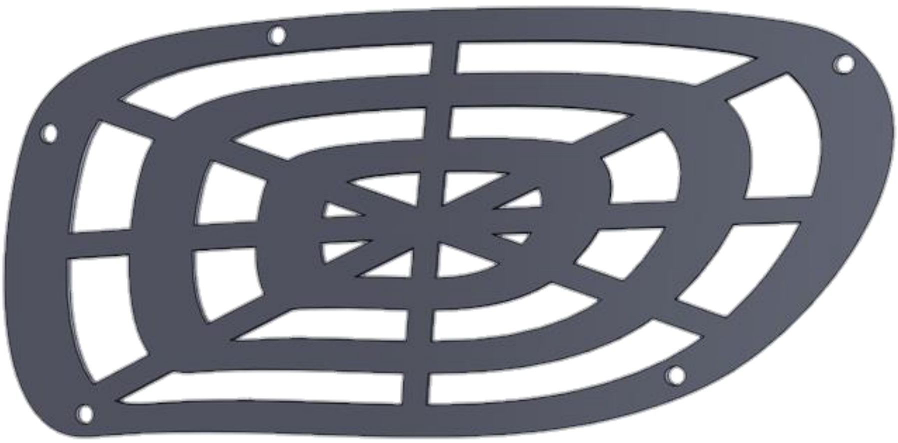

Figure 78 – Second redesign

Even in this case it is possible to perform a similar structural analysis to the one done with the original component and the redesign 1, where a series of zones are selected in which it is possible to choose a node and apply a static force. The force will be the same used for the simulations with the original component and the redesign 1, which was 140 N.

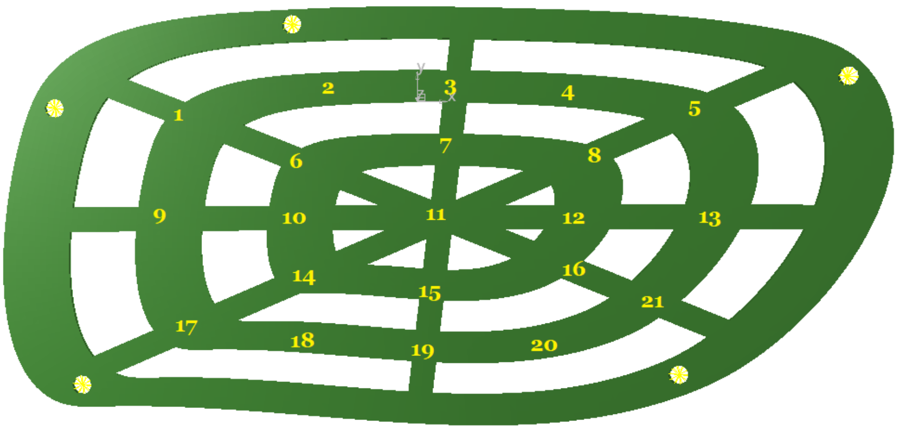

Figure 79 – Selected points for structural analyses of second redesign

Point	Safety Factor (SF)
1	4.10
2	2.71
3	4.48
4	2.56
5	4.37
6	4.03
7	5.69
8	5.44
9	5.26
10	7.03
11	4.87
12	4.64
13	5.41
14	5.06
15	4.90
16	3.56
17	3.95
18	3.03
19	4.66
20	2.39
21	3.17

Table 7 – Results of the simulations, second redesign

It is possible to see that the point with the lowest safety factor is the 20, but the value of 2.39 is still considered acceptable; nevertheless, this result was one of the reasons why it has been decided to increase the thickness to 6 mm in the redesign 3, as it will be seen later. In this case the high value of Von Mises stress is probably given by the length of the segment of concentric contour comprised between two links. As regards the displacement, it is still lower than 10 mm, which is considered the limit value.

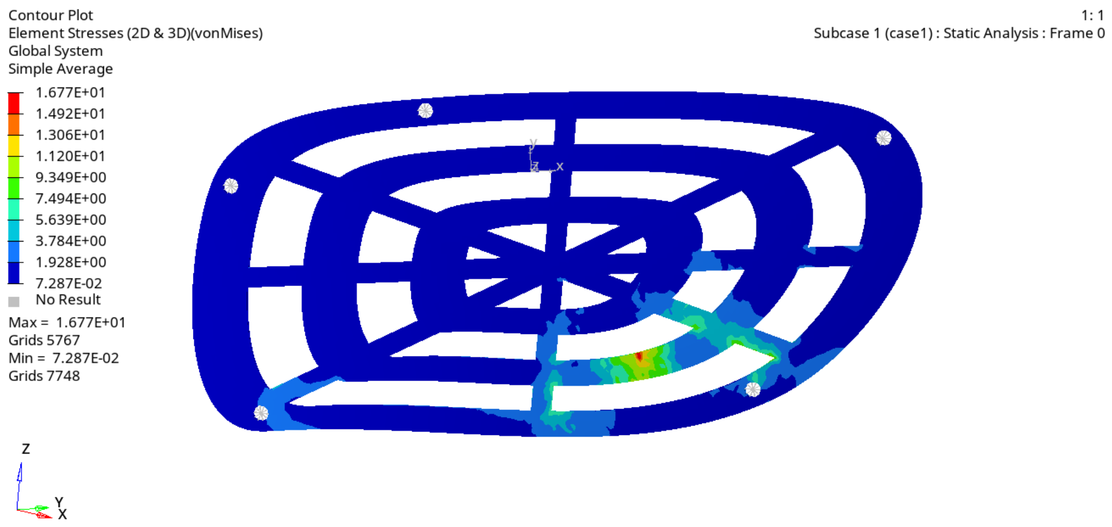

Figure 80 – Von Mises stresses for point 20 of second redesign

Redesign 3 is quite similar to redesign 2, except for two aspects where two variables have been changed:

- As regards the grid pattern, 4 of the 8 "links" in the more central part of the guard have been discarded, with the objective of improving the passing of the light generated by the headlights.
- Since this change worsened the mechanical properties of the component, the thickness was furtherly increased from 5 mm to 6 mm.

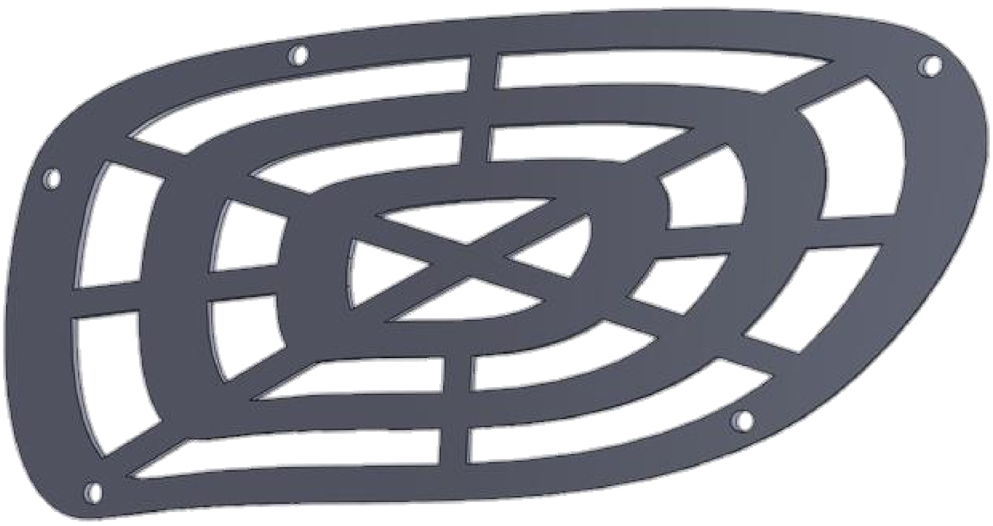

Figure 81 – Third redesign

The same structural analysis with the same zones of the redesign 2 has been performed also in this case.

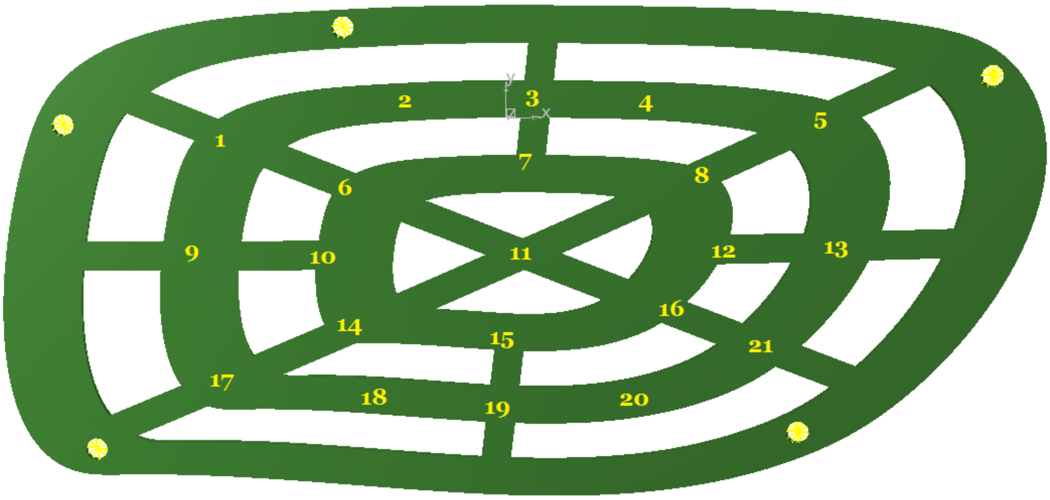

Figure 82 – Selected points for structural analyses of third redesign

Point	Safety Factor (SF)
1	4.08
2	3.76
3	4.93
4	3.33
5	5.03
6	4.90
7	5.22
8	5.05
9	7.05
10	4.07
11	3.56
12	5.72
13	6.48
14	5.30
15	5.06
16	4.25
17	4.53
18	3.35
19	5.06
20	3.23

21	3.66

Table 8 – Results of the simulation, third redesign

It is interesting to note that the point with the lowest Safety factor is again the same of the redesign 2, but the increasing of the thickness from 5 mm to 6 mm had as a consequence an increasing of about 35% of the Safety factor; this confirms what stated in paragraph 5.2 about the thickness of the component, which is one of the most impacting factors as regards the mechanical properties of the final component. The displacement also decreased, therefore staying again in the limit of 10 mm.

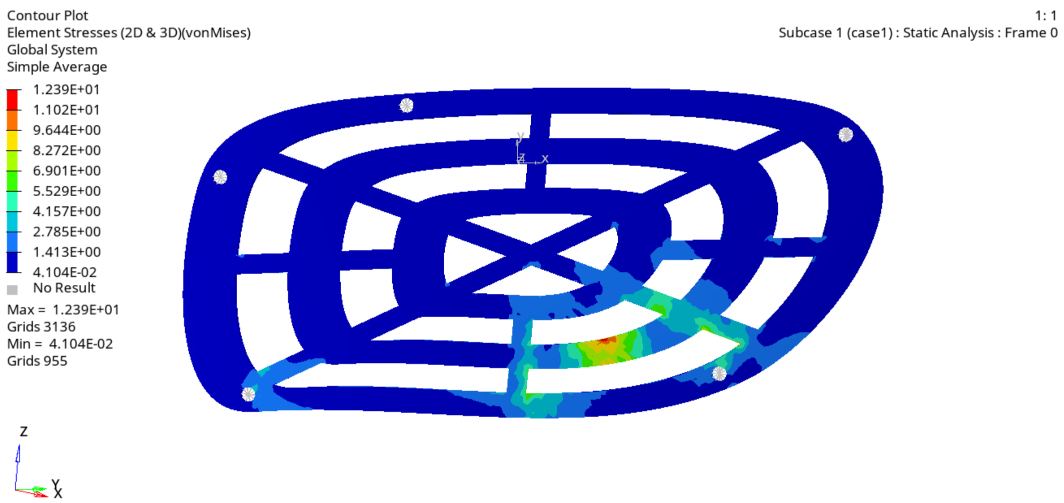

Figure 83 – Von Mises stresses for point 20 of third redesign

5.2.3 Fourth and fifth redesigns

The idea behind redesigns 4 and 5 was to exploit even more the possibilities given by the Additive Manufacturing design. It is known that one of the advantages of this technique with respect to the traditional ones is the possibility of obtaining "complexity for free", meaning that the more the shape of the component becomes particular, complex or convoluted, the more Additive Manufacturing results competitive. The main variable on which to act in this sense considering the case study is for sure the shape of the grid; for this reason, a honeycomb design of the grid was chosen for these two designs. Other than the honeycomb, also two slots have been added to the grid to favour the passing of the light. As regards the other variables:

- Thickness of the grid: even in this case this parameter has been set accordingly to the mechanical properties of the component; in particular, for both redesign 4 and 5 a thickness of 6 mm was chosen.
- Contour shape and width: the approach was the same of the thickness of the grid, but in this case the redesigns 4 has a constant contour of 28 mm which "incorporate" the clips, while in the redesign 5 there was an attempt of reducing the material usage adopting a non-constant contour thickness.
- Width of the grid: in this case it is determined by the distance between one hexagon and the other composing the honeycomb pattern, and, after some testing, it has been set at a value of about 8.7 mm for both the redesigns with a honeycomb grid. Each side of a hexagon is 14.5 mm.

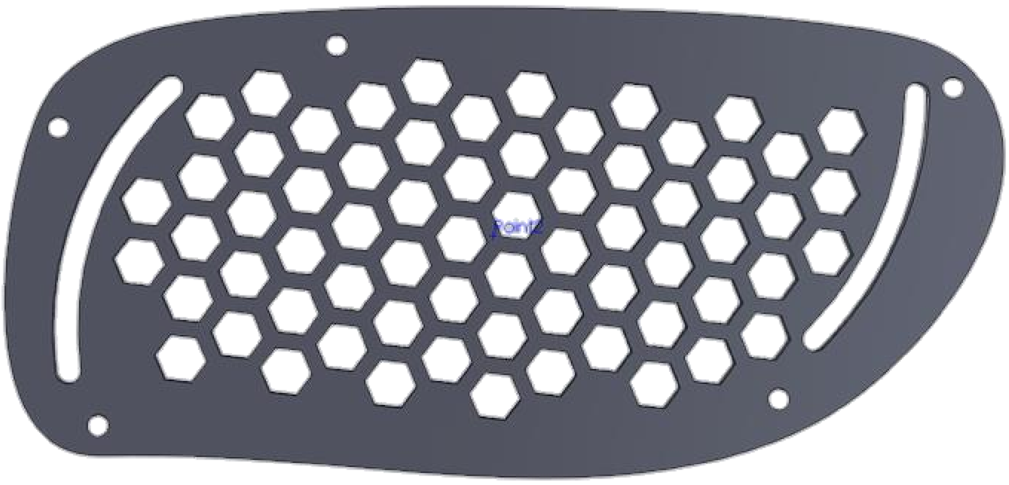

Figure 84 – Fourth redesign

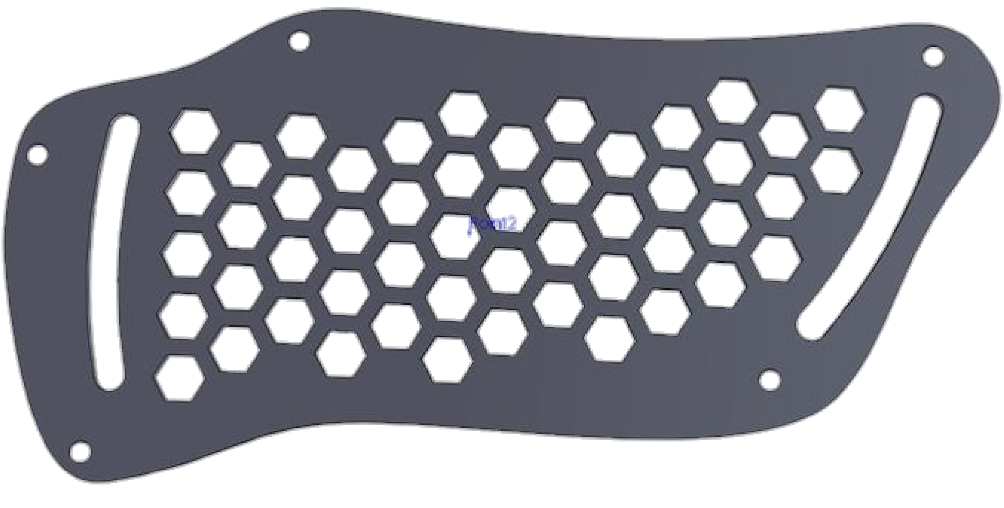

Figure 85 – Fifth redesign

In this case both due to the fact that there are too many differences between the original design and these ones and that the points to test would be too much, the structural analysis seen with the redesigns 1, 2 and 3 has not been brought on; nevertheless, in the next chapter these redesigns, together with the ones seen previously, will be compared with the metal component from various points of view, including the mechanical performances.

6. Comparison between traditional component and Additive Manufacturing component

6.1 Mechanical and physical comparison

The first comparison that can be made is the one regarding the mass of the component. The densities of the S235JR steel and of the ULTEM 9085 have been specified in Chapter 3 and Chapter 4 respectively:

Material	Density [g/cm^3]
S235JR Steel	7.8
ULTEM 9085	1.27

Table 9 – Material densities

As it is possible to see, the density of the polymer is much smaller with respect to the density of the metal. This has made possible during the redesign phase to increase the volume of the component (for example, acting on the thickness to improve the mechanical properties) without excessively impact on the final weight. The situation becomes even clearer looking at the final volumes of the original component and of the six redesigns (all the data are provided by the Solidworks software) and the corresponding masses:

Design	Volume [cm^3]	Density [g/cm^3]	Mass [g]	Mass saving [%]
Original	102	7.8	796	/
Redesign 1	325	1.27	413	48.1 %
Redesign 2	426	1.27	541	32 %

Redesign 3	500	1.27	635	20.2%
Redesign 4	515	1.27	654	17.8 %
Redesign 5	455	1.27	578	27.4 %

Table 10 – Mass properties of original component and redesigns

Even considering redesign 4, the heaviest one among the polymer ones, a saving of more than 15% in mass is reached; this percentage raises up to about 50% considering the lightest redesign, which is the first one. Considering instead the mechanical performances, they have been partially explored in the previous chapter, due to the fact that the redesign had also this parameter as input. Nevertheless, it would be beneficial to perform tests that find some feedback in the reality. Unfortunately, despite several companies have been contacted in order to get an idea of the official tests to which these grids are performed, none of them was willing to share this information. At this point a literature search was performed looking whether some official normative was available, but even in this case no specifications on the testing were made: this kind of grids are used by Italian Police in the "public order setup" (allestimento ordine pubblico), but no particular characteristics are requested in the tenders for their production. Since the objective of these grids is to protect fragile glass surfaces, a starting point can be referring to the homologation requests of this kind of components, which are internationally regulated by European normative. According to the "Regulation No. 43 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of safety glazing materials and their installation on vehicles" [67], different mechanical resistance tests can be performed on glazing materials according to their type; here are listed the main testing procedures:

- Uniformly toughened glass panes: a spherical object having a mass of 227 grams is dropped from a height of 2 meters; the test is passed if the surface does not break.
- Ordinary laminated glass windscreens: a spherical object having a mass of 2260 grams is dropped from a height of 4 meters; the test is passed if the spherical object does not cross the surface in 5 seconds, measured from the starting of the impact; another test consists in dropping a spherical object having a mass of 227 grams from a height of 9 meters, and in this case the test is considered passed if the spherical object does not cross the surface at all, if the surface does not break in more than one piece and if the fragments caused by the impact do not overcome a certain mass.
- Flexible plastic panes: same testing procedure of the uniformly toughened glass panes

- Rigid plastic multiple gazed units: a spherical object having a mass of 227 grams is dropped from a height of 5 meters; the test is passed if the spherical object does not cross the surface and the surface does not break.

In all the cases mentioned before, another requirement is that the impact point of the spherical object should be at a maximum distance of 25 mm from the centroid of the surface of the tested object. The data provided by the document are sufficient to evaluate the impact strength, taking into account that:

$$F_{impact} = \frac{m \cdot v}{t}$$

Where m is the mass of the object, in this case the spherical object used in the test, t is the time of impact (a value of 0.1 seconds can be considered as a realistic one) and v is the velocity of the object at the moment of the impact. This last term can be in turn evaluated considering the uniformly accelerated motion formulas:

$$v = \sqrt{2 \cdot g \cdot h}$$

Where g is the acceleration of gravity, considered having a value of 9.81 m/s^2, and h is the height from which the spherical object is dropped. All the available data and the final resulting forces are listed in the following table.

Test kind	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
Uniformly toughened glass panes and Flexible plastic panes	0.227	2	6.264	14.22
Ordinary laminated glass windscreens, breaking	2.26	4	8.859	200.21
Ordinary laminated glass windscreens, no breaking	0.227	9	13.288	30.16
Rigid plastic multiple gazed unit	0.227	5	9.905	22.48

Table 11 – Testing procedures for glazing surfaces

Another case which is partly ascribable to the one of the protection grids for headlights is the one of FOPS, an acronym for Falling Object Protecting Structure. The term is used when referring to the protection installed mainly on earth moving machines against falling objects and belongs to a family of other protection system such as ROPS (Roll Over Protection Systems, like the roll-cages), TOPS (Tip-Over Protecting Structures), and so on. It is another situation where a precise normative is present; for example, the ISO 3449-2005 normative [68] proposes two levels of testing for the homologation of these systems: the first level is for the protection against falling of small objects like bricks or tools used during the operations; the second level is for the protection against falling of heavy objects like trees or rocks. In this case it is decided to refer to the first level of protection since it is closer to the case study taken into examination. The test is similar to the one seen in case of the homologation of the glazing materials, in the sense that again a falling object is involved, but of course the values encountered in this case will be much higher: as a matter of fact, in this testing a spherical object having a mass of 45 kilograms is dropped from a height of 3.1 meters. These data allow the adding of a fifth row in the previously seen table, since it is again possible to find corresponding speed and strength of the impact in the same way.

Test number	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
FOPS, first level	45	3.1	7.8	3509.48

Table 12 – Testing procedure for FOPS

In the end, it has been chosen to simulate three of the six previously seen tests:

- Ordinary laminated glass windscreens, no breaking (from now on also named "Testing 1" or simply "1"): it has been chosen since it is the most critical among the ones involving the mass of 227 grams.
- Ordinary laminated glass windscreens, breaking (from now on also named "Testing 2" or simply "2"): it has been chosen since it involves a higher mass with respect to all the other testing sets on the glazing materials.
- FOPS, first level (from now on also named "Testing 3" or simply "3"): it has been chosen as a sort of "over-the-limit" test since it is thought that the force level is too high for both the metal and the polymer.

6.1.1 Testing results

Here are resumed the characteristics of the three testing procedures:

Test number	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
1	0.227	9	13.288	30.16

2	2.26	4	8.859	200.21
3	45	3.1	7.8	3509.48

Table 13 – Adopted testing procedures data

Other than this, as already said in paragraph 6.1, the impact point of the spherical object should be at a maximum distance of 25 mm from the centroid of the surface of the tested object (this is not specified for the testing 3, which is the one for FOPS, but it is considered reasonable that this requirement still holds). This is not a problem since through the Solidworks software it is possible to find the centre of a selected face. Once it is found, in the Hypermesh software a force of 30.16 N will be applied as close as possible to that point, and the structure will be solved through Optistruct. The procedure is therefore repeated with the force values of 200.21 N and 3509.48 N. Starting from the metal component, first of all it is necessary to find the centre:

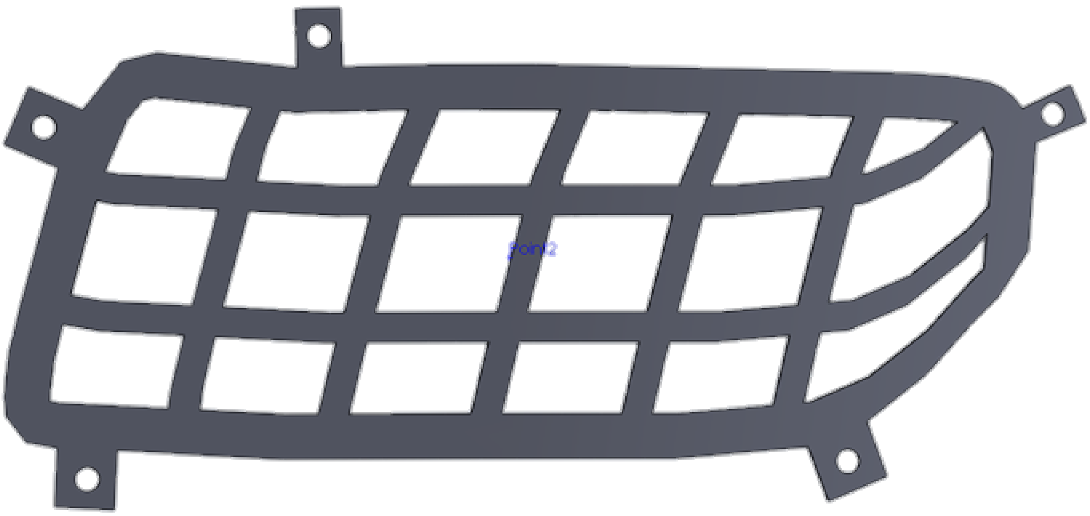

Figure 86 – Centre of the original component surface

Since the exact centre would not "hit" any physical part of the body, a close point in the margin of 25 mm is chosen. At this point the structure and loads are prepared in Hypermesh:

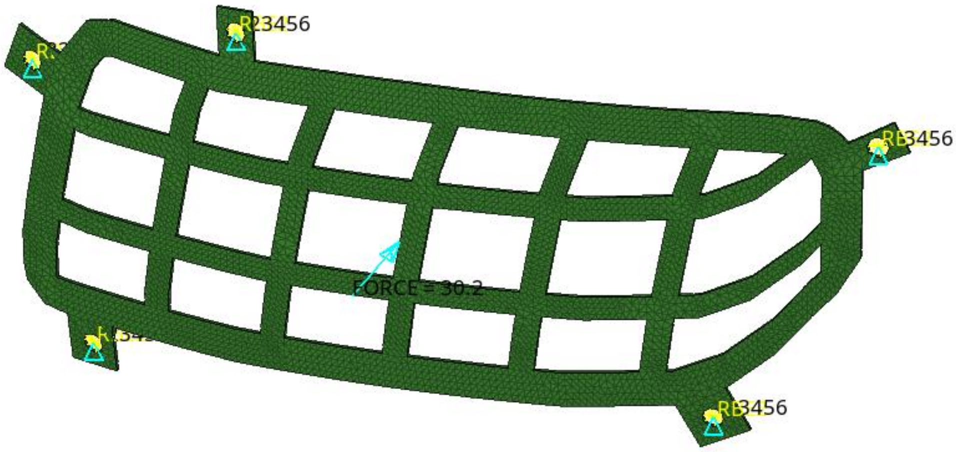

Figure 87 – Testing preparation, Hypermesh

The simulation performed through Optistruct solver will give some information such as the maximum Von Mises stress, which can be used to evaluate the Safety Factor as done previously in Chapter 5, and the maximum displacement. These operations are performed first for the traditional design and then for all the five redesigns; the results are resumed in the following pictures:

Testing 1 results

Test number	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
1	0.227	9	13.288	30.16

Design	Safety Factor, max	Displacement, max [mm]	Safety Factor decrease [%]	Displacement increase [%]
Original	26,34	0,03684	/	/
Redesign 1	17,87	0,5052	32,16%	1271%
Redesign 2	23,3	0,4356	11,54%	1082%
Redesign 3	17,26	0,4354	34,47%	1082%
Redesign 4	20,27	0,3795	23,04%	930%
Redesign 5	21,13	0,3501	19,78%	850%

Figure 88 – Testing 1 results

Testing 2 results

Test number	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
2	2.26	4	8.859	200.21

Design	Safety Factor, max	Displacement, max [mm]	Safety Factor decrease [%]	Displacement increase [%]
Original	3,95	0,2446	/	/
Redesign 1	2,69	3,354	31,9%	1271%
Redesign 2	3,51	2,892	11,14%	1082%
Redesign 3	2,60	2,891	34,18%	1082%
Redesign 4	3,05	2,519	22,78%	930%
Redesign 5	3,18	2,324	19,49%	850%

Figure 89 – Testing 2 results

Testing 3 results

Test number	Mass [kg]	Height [m]	Speed [m/s]	Force [N]
3	45	3.1	7.8	3509.48

Design	Safety Factor, max	Displacement, max [mm]	Safety Factor decrease [%]	Displacement increase [%]
Original	0,23	/	/	/
Redesign 1	0,15	/	34,78%	/
Redesign 2	0,20	/	13,04%	/
Redesign 3	0,15	/	34,78%	/
Redesign 4	0,17	/	26,09%	/
Redesign 5	0,18	/	21,74%	/

Figure 90 – Testing 3 results

Some considerations can be done looking at the results:

- It is possible to notice a big difference in displacement between the metal part and the polymer ones; this is given by the properties of the polymer and its molecular structure; the displacement is as important as the Safety Factor, since considering the component taken into examination, it is known that the clearance between the guard and the headlight once it is installed is limited, therefore a too high displacement can cause the contact of the two and the partial transmission of the force to the part to protect (the headlight).

- From the safety factor point of view, Redesign 2 seems to be the best; anyway, it should be pointed out that the test involved the centre of the surface, where the structure of redesign 2 ensures more resistance with respect to redesign 3; looking back to Chapter 5, in other point redesign 3 has proven more "resistant" with respect to redesign 2.

Taking into account this last consideration, it has been decided to conduct a final test, where the objective is to find the "limit" force for each redesign. This limit is determined by one of the two following conditions (the first one that is reached):

- Safety factor goes below 1.
- Displacement goes over 10 mm.

The second requirement is fundamental when considering the polymeric material, since it has been possible to see that it is characterised by higher levels of displacement with respect to the metal. As regards the point of application of the testing force, for the redesigns from 1 to 3 and the original design the most critical points found in Chapter 5 have been used; instead for redesigns 4 and 5 (the ones with the honeycomb patterns), some points which can be thought as critical have been explored, in order to avoid using again a point near to the middle of the surface. The preparation is the one seen before with the three testing procedures; therefore, it is possible to move directly to the results (all the pictures of the four testing procedures can be anyway found in the Appendix):

Design	Limit Force [N]	Limit Force Decrease [%]	Reason	Displacement with Limit Force [mm]
Original	565	/	Safety Factor	0.322
Redesign 1	340	39.82	Safety Factor	9.089
Redesign 2	295	47.79	Safety Factor	7.939
Redesign 3	450	20.35	Safety Factor	9.536
Redesign 4	325	42.48	Safety Factor	7.934
Redesign 5	330	41.59	Safety Factor	6.712

Table 14 – Testing 4 Results

Also in this case some consideration can be derived from the results:

- As it is possible to see, despite the adding of the displacement as limit factor, the limit in Safety Factor is always reached first.

- As regards the redesigns with the honeycomb pattern, the relatively low results have been found in proximity of the slots for the passing of the light, while in areas where the honeycomb patter was regular the performances where notably better.

Finally, it is also necessary to consider the results of Safety factor and displacement in relation with the other properties mentioned before, like the mass, which has already been analysed, and the performances in terms of lighting. To address this last parameter, a simple ratio has been chosen to highlight the percentage of guard which is not covering the headlight, allowing the passing of the light:

$$\%_{not\ covered} = \frac{A_{not\ covered}}{A_{total}}$$

Which is the ratio between the area which is not covered by the grid divided by the total area. The total area can be easily found through the "measure" instrument of the Solidworks software, as well as the not covered area which can be considered as the total area minus the covered one. The results are listed below:

Design	$\%_{\text{Not covered}}$	Δ%
Original	47%	/
Redesign 1	31.2%	-15.8%
Redesign 2	46.7%	-0.3%
Redesign 3	48.8%	+1.8%
Redesign 4	46.1%	-0.9%
Redesign 5	37.3%	-9.7%

Table 15 – Lighting performances

It is possible to see the results of the previous analyses in a more compact form in the following table:

Design	Mass saving [%]	Safety Factor decrease [average, %]	Displacement increase [%]	Δ%, lighting	Limit Force decrease [%]
Original	/	/	/	/	/
Redesign 1	48.1 %	32.95%	1271%	-15.8%	39.82%
Redesign 2	32%	11.91%	1082%	-0.3%	47.79%
Redesign 3	20.2 %	34.48%	1082%	+1.8%	20.35%
Redesign 4	17.8 %	23.97%	930%	-0.9%	42.48%
Redesign 5	27.4 %	20.34%	850%	-9.7%	41.59%

Table 16 – Overall mechanical and physical comparisons results

It is clear from the resuming table above that the choice of the final design is a matter of compromise; also, up to now the aesthetic criteria have not been taken into account, due to their subjectivity; despite this, an objective assumption is that redesigns 4 and 5 are the ones that exploit more than all the others the potentialities of Additive Manufacturing: redesign 1 is a simple grid that can be made also in traditional ways through laser cutting and punching processes; redesigns 2 and 3 are a bit more complex, but the concept still holds; as regards redesigns 4 and 5, it could be possible to recreate the honeycomb pattern through very precise laser cutting and/or punching operations, but this would likely lead to a general increase of the production times and costs. Taking into account all these aspects, it is possible to conclude that redesign 4 is the most balanced one: it is true that from the mass saving point of view it gives the worst result, but it is still a remarkable reduction; considering Safety Factor and displacement, redesign 5 is slightly better in both, but this comes with a significant reduction in terms of lighting performances; finally, as already said from the point of view of the aesthetics and the exploiting of the Additive Manufacturing performances it is the best approach together with the redesign 5.

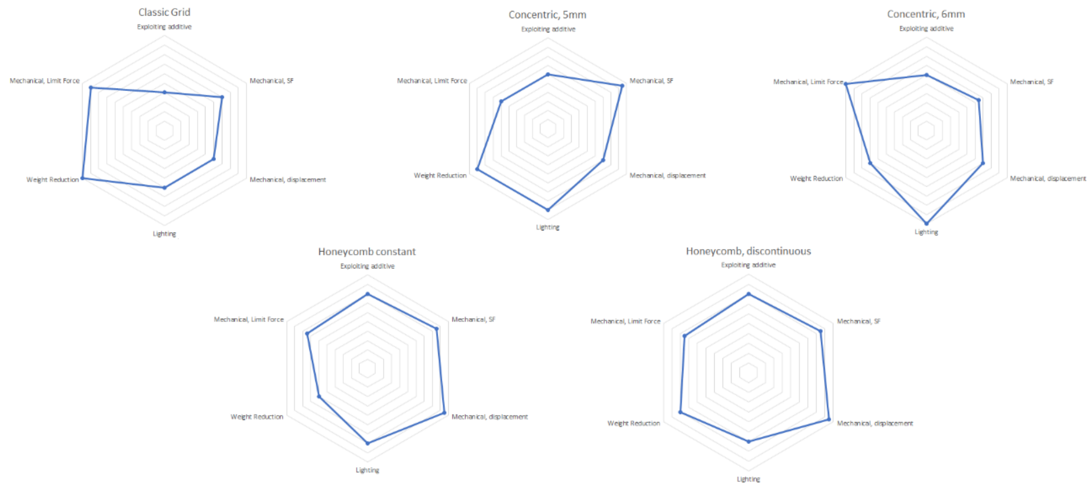

Figure 91 – Redesigns radar graphs

6.2 Cost comparison

Other than the mechanical and physical performances, it is fundamental to measure also the cost of production of both the traditional method and the additive one. The importance of this comparison is provided by the fact that it will give the possibility of finding the so-called Break-Even Point, that is the point in which the convenience of the Additive Manufacturing is surpassed by the one of the traditional processes. In fact, it is possible to divide the costs in two big categories, fixed costs and variable costs: the first ones are usually very high in traditional processes but can be shared among all the produced units, while the variable costs are usually lower and referred to a single unit. These aspects are the main reason why in traditional production Economy of Scale and Mass Production are two so important concepts: the production of a high number of units allows to divide the high fixed cost reducing the cost per component. On the contrary, taking into account Additive Manufacturing processes, variable costs usually prevail, mainly due to the high cost of the materials. Being this a preliminary cost evaluation, in the comparison between traditional process and additive one brought on in this case study only the production phase will be considered, therefore for the traditional process steps such as painting will be considered negligible on the total cost evaluation, and the same will be done with Additive Manufacturing with post processing and similar. Also, for both the techniques the initial investments consisting in buying the necessary machines to perform the various processes will not be taken into account.

6.2.1 Traditional production

For the traditional processes it is possible to recall the subdivision given by the company Sperotto S.p.A.; as already said, cataphoresis treatment, primer application and painting will be considered as negligible, therefore the processes that will be considered in the cost evaluation will be three: laser cutting, punching and cold stamping with mould. For sake of simplicity, it is possible to suppose that the punching process is replaced with another laser cutting operation. For this process, a search on the web and on the literature allowed to find some useful data to evaluate the impact of the first two steps in the cost per unit [69]: a 4-kilowatt CO2 laser has been taken into account, with a machine cost per hour of 23 Euros per hour. Considering a speed of about 185 inches per minute, corresponding to 4699 millimetres per minute and therefore approximately 282 metres per hour, knowing the length of the perimeter to cut it is possible to evaluate the necessary time to perform the cut and consequently the cost per unit. The perimeter is given by Solidworks, considering the original design, and corresponds to 1,3 metres for the external one and 3.727 meters for the sum of the "holes" of the grid. Multiplying these values by the speed of the laser it is possible to get the cutting time, which is 0.0046 hours (between 16 and 17 seconds) for the external contour and 0.013 hours (between 47 and 48 seconds) for the "holes", therefore the cost of this operation for each unit will be the sum of 0.106 Euros and 0.304 Euros, for a total of circa 0.41 Euros. It is also necessary to add the cost of the operator, which is possible to assume to be the same for both the operations of laser cutting, for a total working time per component of 0.018 hours (circa 64 seconds) which, considering a wage of 16 Euros per hours corresponds to about 0.285 Euros to add per component. For the process of cold stamping with mould, a realistic value for the cost of the mould itself has been given by the company Sperotto S.p.A., corresponding to 10000 Euros: considering the values obtained previously with laser cutting, it has been decided to neglect the cost of the operator and of the machine for this operation, taking therefore into account only the cost of the tool. Unlike the costs calculated before, the cost of the mould is a fixed one, and will be divided among the total number of produced parts. Instead, another important variable cost to consider is the cost of the material: after a search on the web a cost of 3.72 Euros per kilograms has been chosen. Through Solidworks a plausible value of a starting surface, having a thickness of 2 mm as the final part (considering buying the material directly in metal sheets of this thickness), has been found, and, considering the density of the S235JR steel, it has been estimated that approximately 8.323 kilograms of material are necessary to produce one part. The corresponding material cost of a single component will be therefore 30.96 Euros. It is possible to resume the found results in the following table:

Operation	Type	Cost per Part [€]
Laser Cutting, external contour	Variable	0.106
Laser Cutting, "holes"	Variable	0.304
Laser Cutting, operator	Variable	0.285
Cold Forming with mould	Fixed	10000/number of parts
Material buying (included scrap and over-material)	Variable	30.96

Table 17 – Traditional production costs

6.2.2 Additive Production

For which concerns the Fused Deposition Modelling or Fused Filament Fabrication, an estimation of the costs has been given by a company owning the Roboze Argo 500 machine (CIM 4.0); like it has been done for the traditional process, some aspects like the initial investment of the machinery, the post-processing operations, and so on are not considered; in this case all the main costs can be considered variable ones, since the use of material for the component and for the supports and the hourly cost of the machine and of the operator can be attributed to each single component. Starting from the cost of the material, it can be found simply multiplying the cost per kg of ULTEM 9085 by the mass of the component, which can be seen in Table 10; a similar reasoning can be used for the supports, given that the mass is provided by the company after a proper orientation and supports positioning has been decided. Hourly cost of the machine and of the operator are extrapolated by the information given by the company, combined with some web search, while the time to print the component is provided by the company itself (for example, it corresponds to circa 43 hours for the most bulky of the redesigns, which is the one with honeycomb pattern and constant contour); therefore, multiplying the hours to print with the hourly cost it is possible to find the cost of the machine for printing one component; the same can be done for the operator, assuming a wage of 25 Euros per hour and a setup time of 30 minutes. The results are resumed in the following table.

Operation	Type	Cost per part [€]
Buying of the material	Variable	94.83
Buying of the support's material	Variable	52.63
Printing	Variable	343.31
Printing, operator	Variable	12.5

Table 18 – Additive production costs

6.2.3 Comparison and Break Even Point

At first, it is considered a classic scenario: The cost for the production of a certain batch of headlights guards are compared as regards the traditional production of the traditional design and the Additive Manufacturing production of the "honeycomb pattern, constant contour" (redesign 4) redesign. It is possible to put in comparison the costs through the following graph:

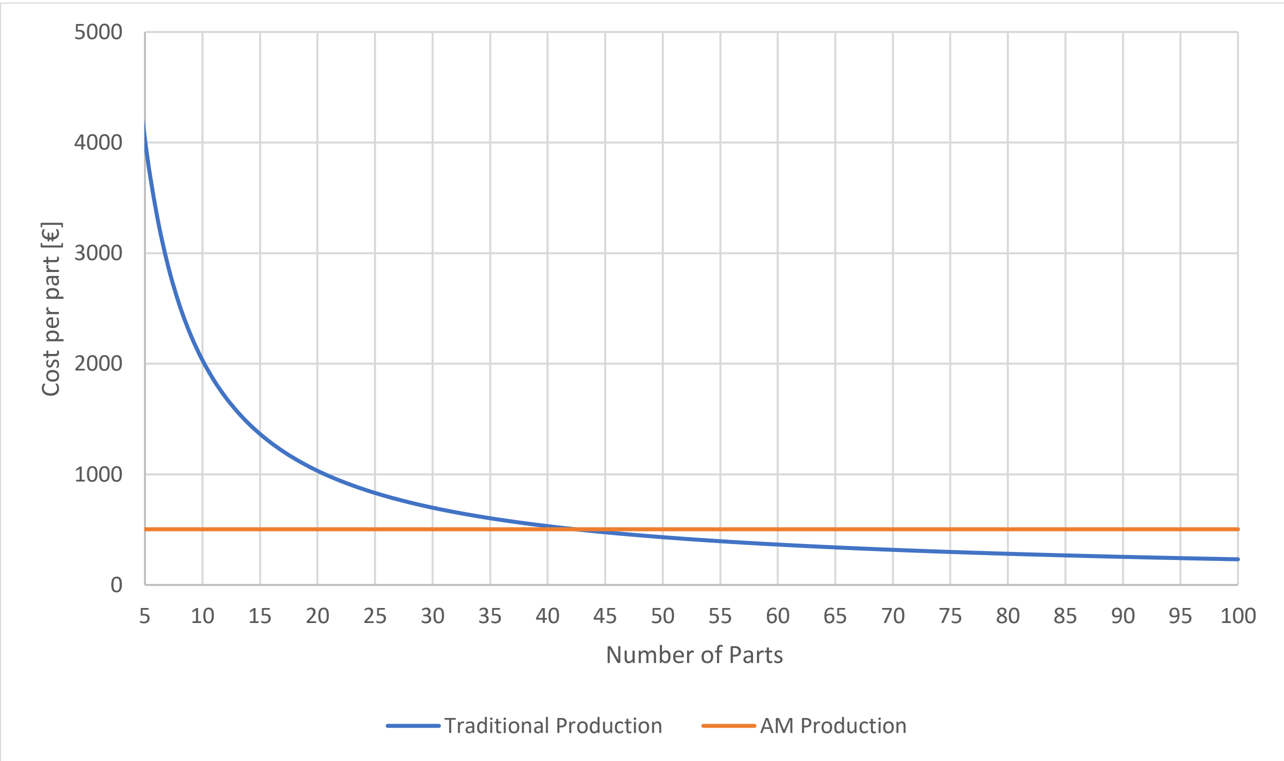

Figure 92 – Break Even Point, Scenario 1

It is possible to see that the Break-Even Point is between 40 and 45 units: this means that if the quantity of components to produce exceeds 45, the traditional method is still more convenient. Considering the specific case of the headlight guards to be installed on the SUV models used by Italian Police, since they are 30, the required number will be 60, making the traditional production slightly more convenient. Of course, it should be pointed out that probably the costliest among the redesigns has been considered, since it is the bulkiest one and therefore requires more material and supports with respect to the other ones. Other than this, it is possible to take into account a second scenario: consider a situation in which two different designs are produced, for example half of the vehicles will need grids more focused on aesthetics because it is known that they will not undergo too much "critical" situations, while the other half will need grids more focused on mechanical resistance: in this case it is supposed that another mould will be needed for the cold forming process in the traditional process, increasing the fixed costs; instead, considering the Additive Manufacturing process, it will be necessary only to sum the costs of production of the previous case with the ones of another redesign; in the following graph it is possible to see how this second scenario impacts on the Break Even Point.

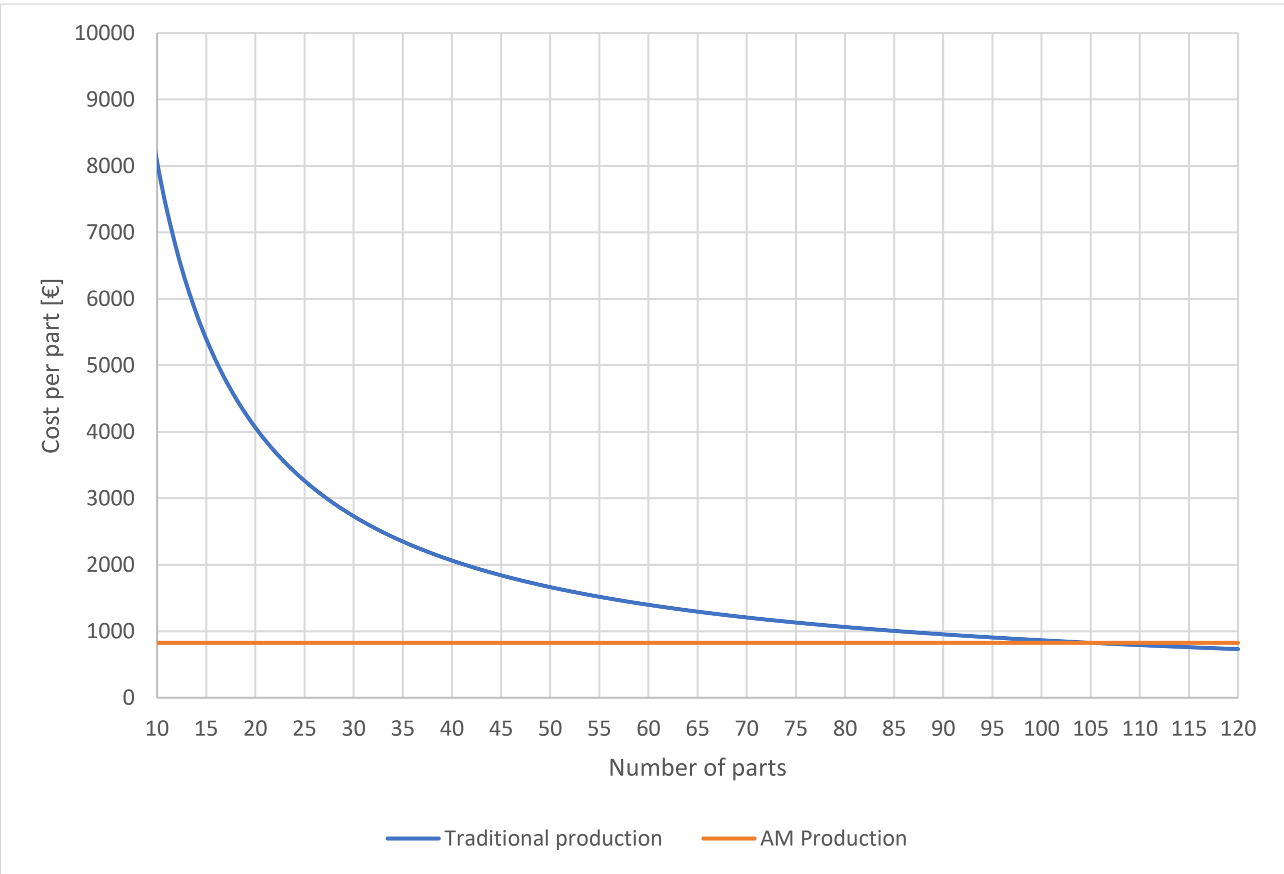

Figure 93 – Break Even Point, Scenario 2

It is possible to see that in this second scenario the Break-Even Point is shifted between 105 and 110 components, making therefore Additive Manufacturing processes more competitive with respect to the previous situation. This is compliant with the well-known concept of Mass Customization, which is one of the strong points of Additive manufacturing nowadays.

7. Conclusions and future developments

The work seen up to now aimed at individuating a potential case study where Additive Manufacturing performances could result competitive.

The selected component, a headlight protection grid, has been developed in a CAD software (Solidworks) at first following the traditional production design, then performing several redesigns which could result more suitable to an Additive Manufacturing production. The redesigns were developed following some different requirements like mechanical, aesthetic and lighting. Considering this step, it should be pointed out that the official data from a company which produces these grids could lead to more precise results in future developments of this case study.

Next phase was to perform a mechanical comparison between the traditional component and the redesigns. For both the mechanical requirements of the redesigns and the comparisons between traditional component and redesigns, Altair Hypermesh software with Optistruct solver were adopted. Some considerations for future works can be referred to the work performed on Hypermesh: it is true that Hypermesh and Optistruct have proven to be useful tools for the analyses, but it is worth to mention that only static analyses have been conducted, so also the use of dynamic ones could lead to results closer to the reality. Another aspect which has not been treated in this work is the fatigue resistance. This has not been done mainly because it is likely that the grids are replaced once a very "stressful" situation have been experienced by them, but it could be useful to add this aspect in further and more detailed examinations. Like it has already been said when considering the design phase, also in this case official data, this time about the testing procedures to which the grids are subjected, could lead to more realistic results. Finally, also dimension of meshing has for sure an influence on the accuracy of results. A consideration to do about the material, ULTEM, is about its anisotropy: its orientation is crucial for establishing the performances of the material; all the results presented before have been calculated taking into account the worst possible situation, so a situation in which the material is oriented such that its mechanical performances are the worst possible; the objective was to assess the worst-case-scenario, but further studies on ideal and optimal orientation could lead to even better results from the mechanical point of view and therefore more competitiveness with the metal component. Instead, considering the process, which is Fused Deposition Modelling or Fused Filament Fabrication, there are a lot of variables which could influence the final properties of the components such as building direction (related to the material orientation mentioned before), printing speed, post-treatments (or their eventual absence), infill of the material (which in this case has been considered to be at 100%, but can be reduced through different internal structures), therefore also from this point of view further studies will be needed. A proposal of building direction and support positioning given by CIM 4.0 can be seen in the following pictures.

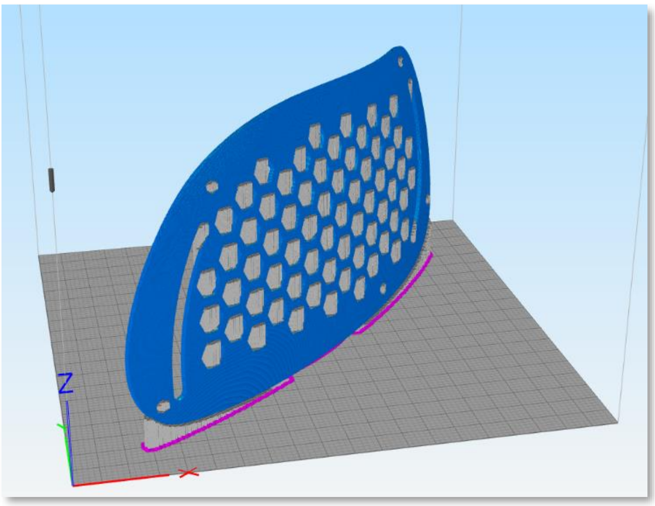

Figure 94 – Proposal of building orientation and supports positioning, front view

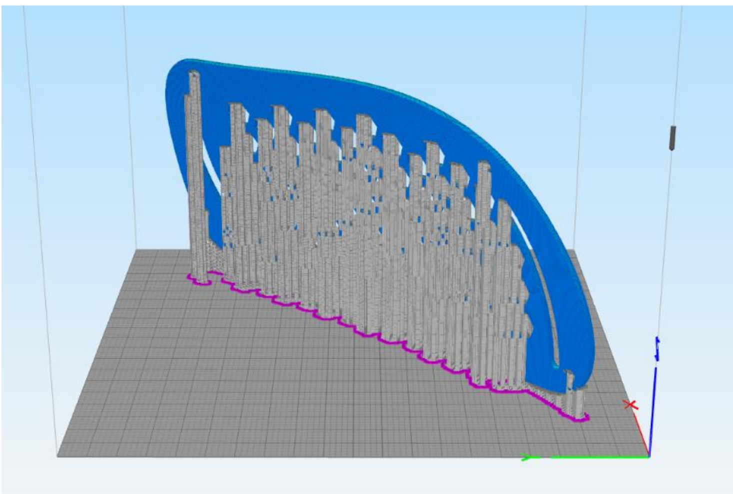

Figure 95 – Proposal of building orientation and supports positioning, rear view

As it has been possible to see during the comparison phase, there are still differences between metals and polymers, but the case study can be considered successful from different points of view. The reduction in terms of safety factor comes with a reduction on the mass, therefore, as it often happens in the industry, it is a matter of compromise to choose which component to develop. The same considerations can be done on the different redesigns, since each one has its peculiarities and potentialities, so accordingly to the necessities one of them can be selected. From the cost point of view the competitiveness of the Additive Manufacturing process strongly depends on the quantities to be produced: the case study has been conducted taking into account a low-volume production intended for a very niche application but can also be rethought to be applied in other applications such as aftermarket and/or personalization. A possibility for further cost reduction is using Carbon PA instead of the ULTEM as material to replace the metal; the composite material is characterised by a lower cost and density with respect to ULTEM, therefore even better results in terms of weight reduction and cost savings could be reached. The main issues could come from the mechanical point of view, since not only Carbon PA is an anisotropic material like ULTEM, but it is also strongly influenced by the orientation of the carbon particles inside the material; the behaviour of composite materials, like Carbon PA, can be simulated in Hypermesh, so further analyses can lead to the understanding of whether this material is another competitor for metal replacement or not.

In general, it is possible to assert that Additive Manufacturing, as already stated in Chapter 2 of this thesis, has not yet the potentialities to compete with Mass Production and Economy of Scale. Despite this, it is crucial to focus on the potentialities of Additive Manufacturing combined with Metal Replacement for the upcoming years: possibility of custom, complex designs, of competitiveness in terms of small batches, without renouncing to the “reliability” of some properties of metals thanks to innovative polymeric materials, is likely to push Additive Manufacturing and Metal Replacement from an industrial point of view. It is possible to extend what has been referred to the case study taken into consideration to several cases present in the Automotive industry and that have already been mentioned in Chapter 2, during the selection of the said case study. The headlight protection system that has been thought here for a particular car model can be redesigned to fit many different others, taking into account the shape of the headlight, the positioning of the holes for the installation, and so on, so this can be seen as a typical example of aftermarket. It has been found through market research [70] that customization through 3d printing is an upcoming reality in the ambit of personalization, where aftermarket companies can benefit from the Additive Manufacturing technologies to design and produce components chained to the inclinations and requirements of each single customer. Additive Manufacturing is at the moment one of the few technologies which allows to satisfy the specific requests of a customer with small-batches product at reasonable costs. All this is referred mainly to Additive Manufacturing, but the introduction of Metal Replacement can be linked to another trend of last years, which is the quest for “green” and sustainable solution: the combination of the possibility of developing designs that would not be convenient in the traditional processes with the light weight of the polymers could bring in the future to a notable reduction in fuel consumption, thanks to the concept of weight reduction; this becomes even more important considering the constant spreading of electric and hybrid vehicles, where the weight is dominated by new components which in the past were not present in the vehicles, starting with the large battery packs. Other than this, it is worth mentioning that Fused Filament Fabrication / Fused Deposition Modelling produced parts can be in the majority of cases fused again to be transformed into filament through special recyclers. An aspect which should always be taken into consideration from this point of view is the toxicity of the material: in this case study, ULTEM was taken into account, which is not toxic, but there are some cases in which the environmental and toxicological risks given by certain materials necessitate further research works since they are not sufficiently known.

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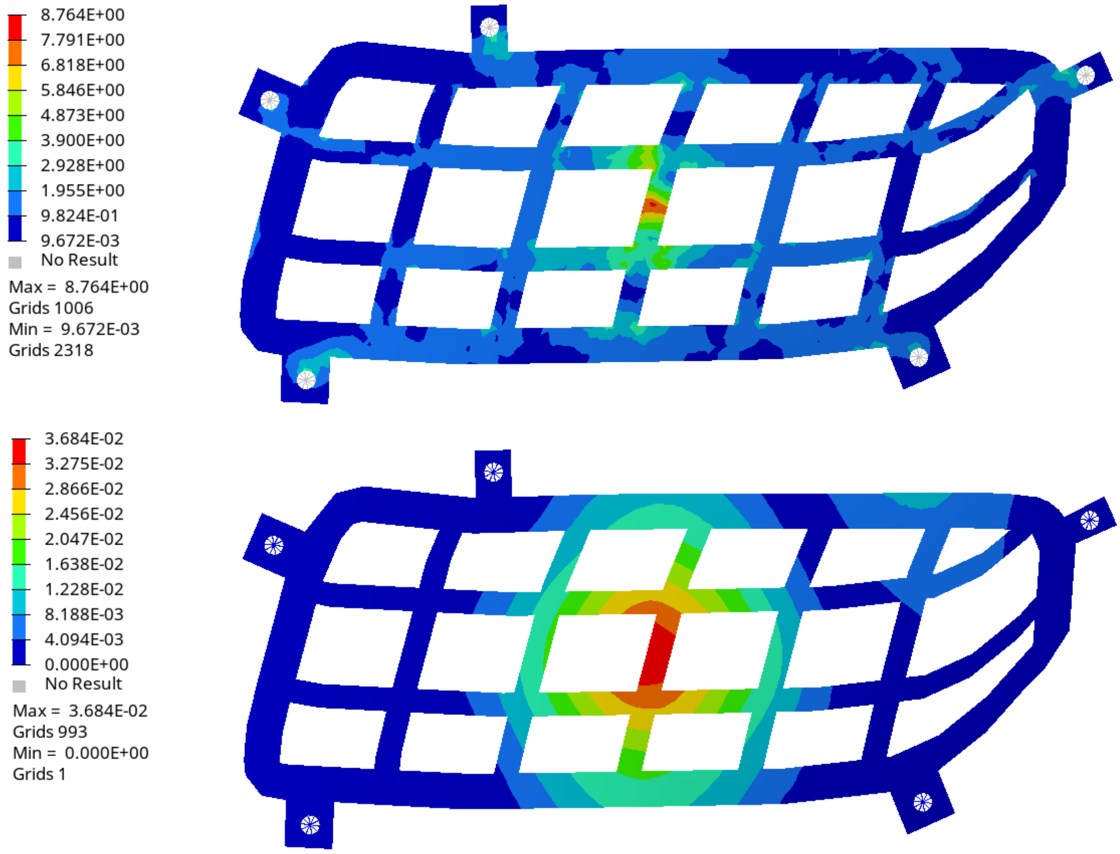
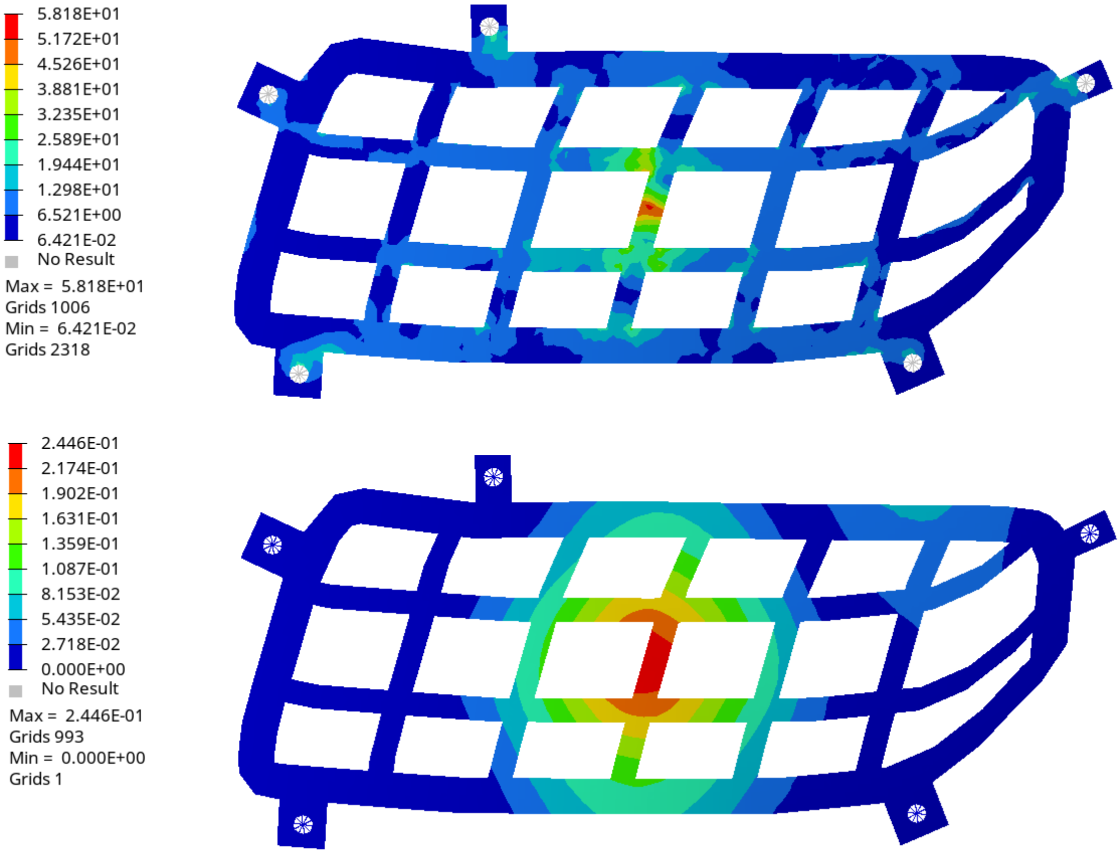
Appendix

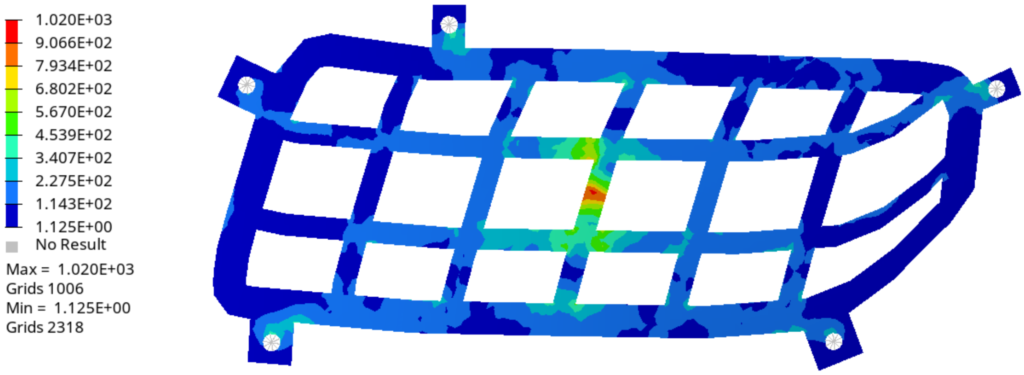
In the following appendix are presented all the images related to the testing mentioned in Chapter 6.



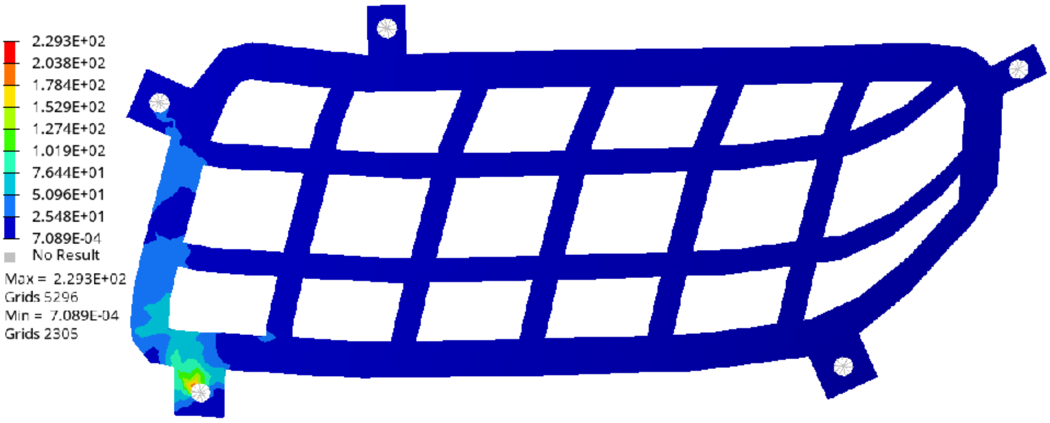
Figures 1 – Von Mises stresses (up) and displacement (down), testing 1, original design

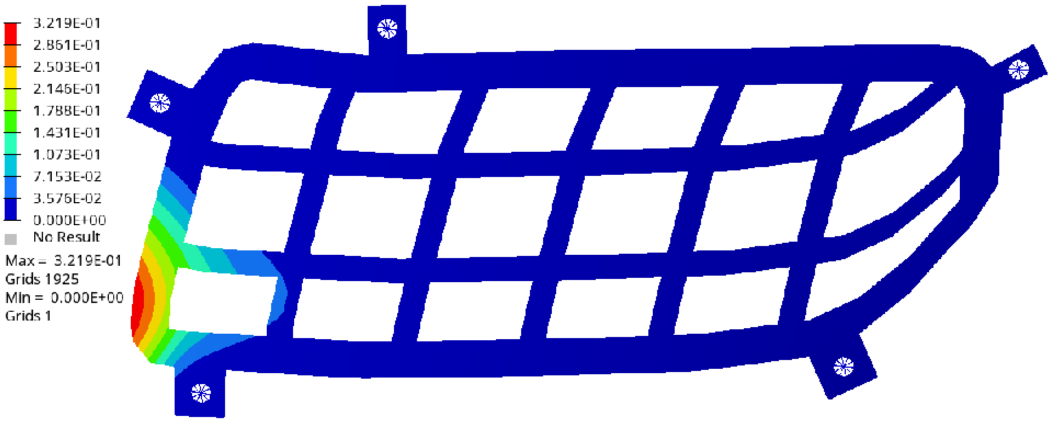


Figures 2 - Von Mises stresses (up) and displacement (down), testing 2, original design

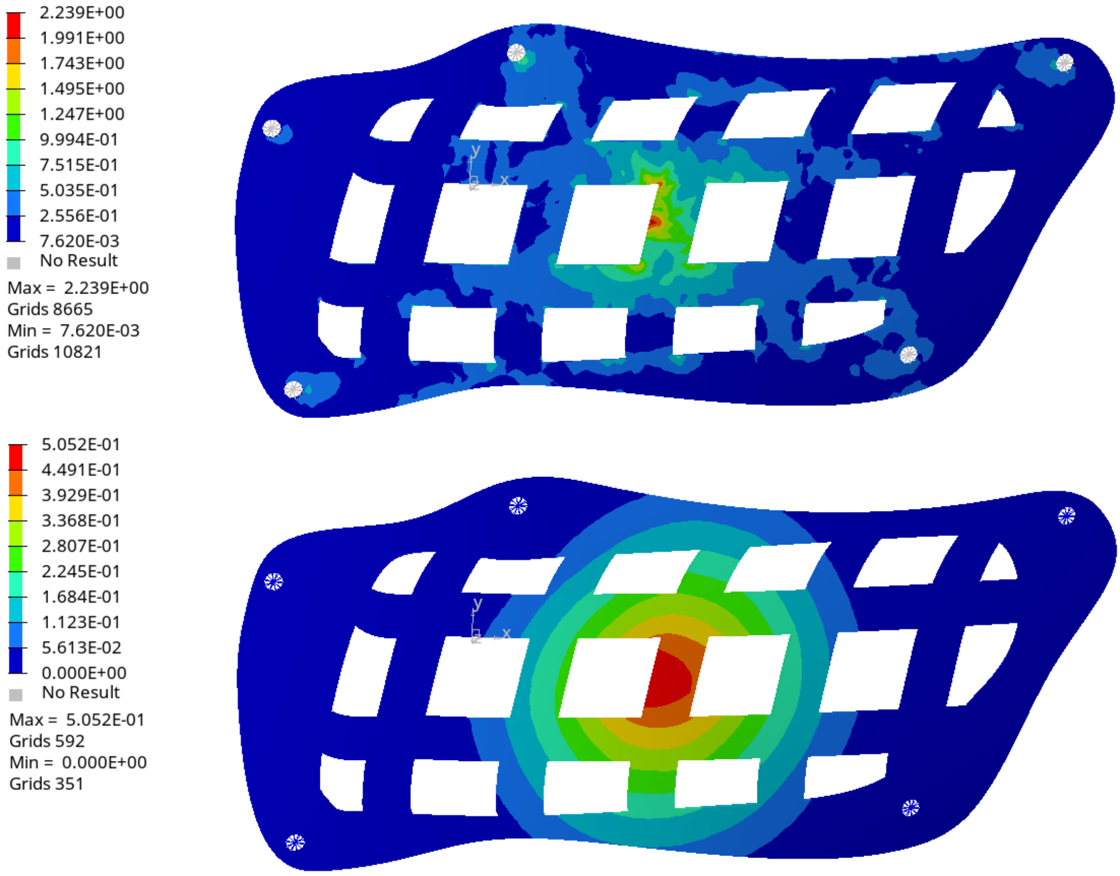


Figures 3 - Von Mises stresses, testing 3, original design

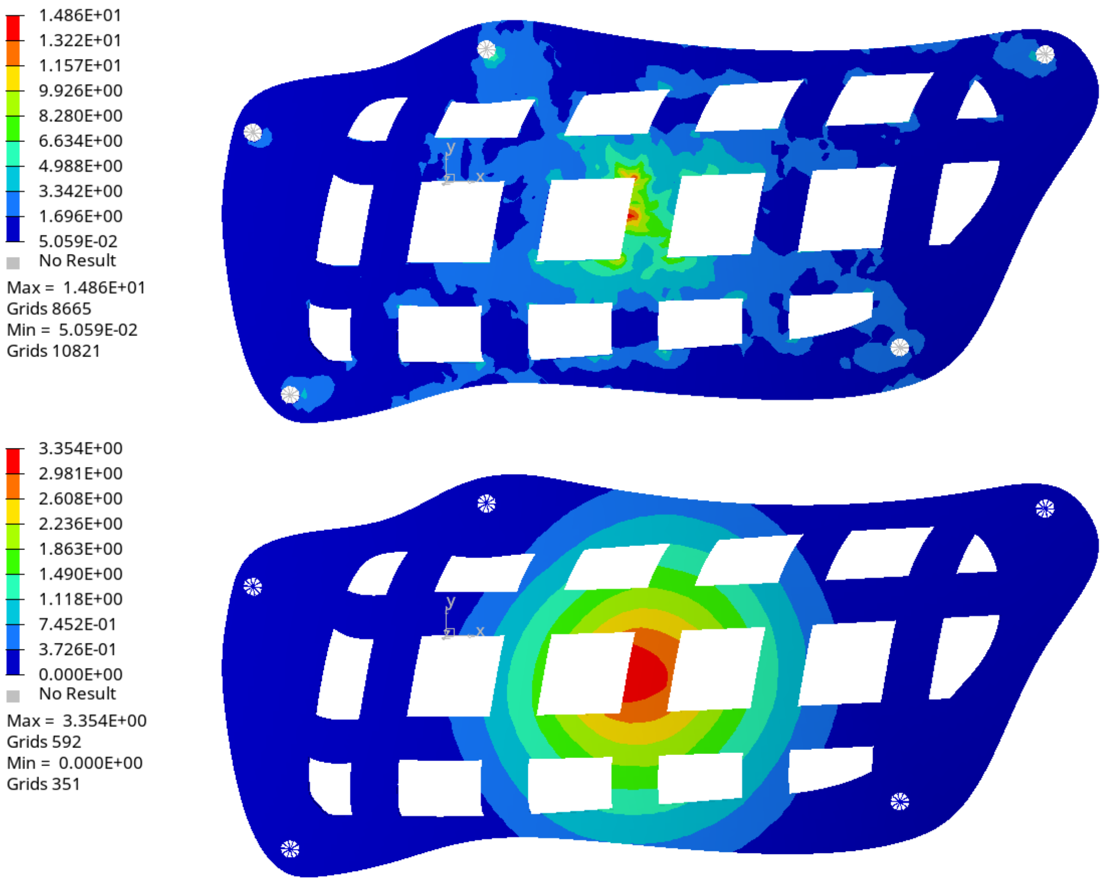




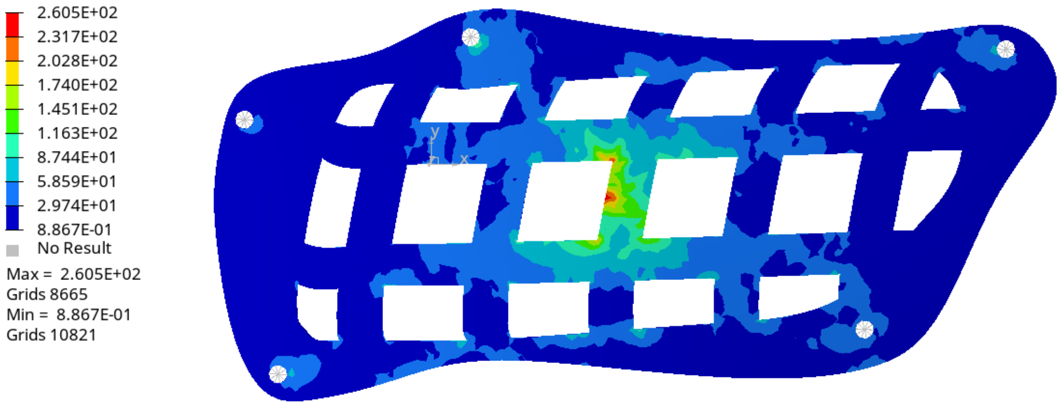
Figures 4 - Von Mises stresses (up) and displacement (down), testing 4, original design



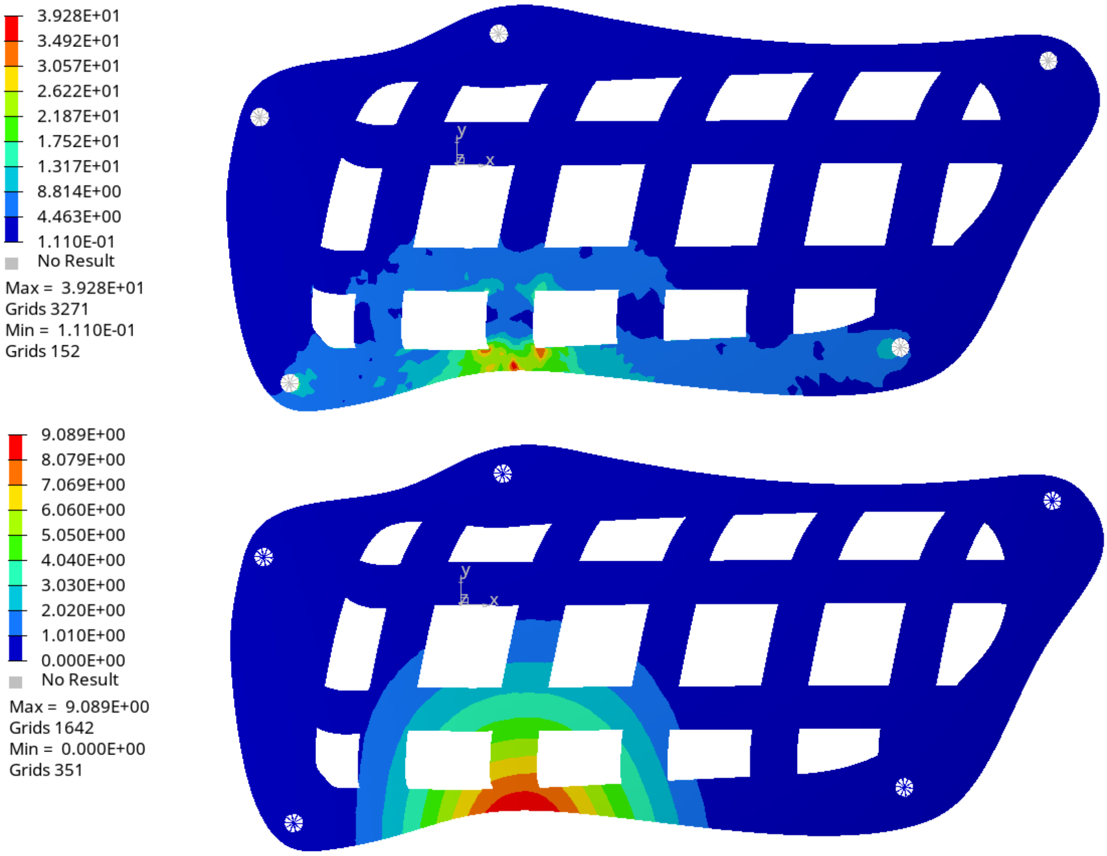
Figures 5 - Von Mises stresses (up) and displacement (down), testing 1, redesign 1



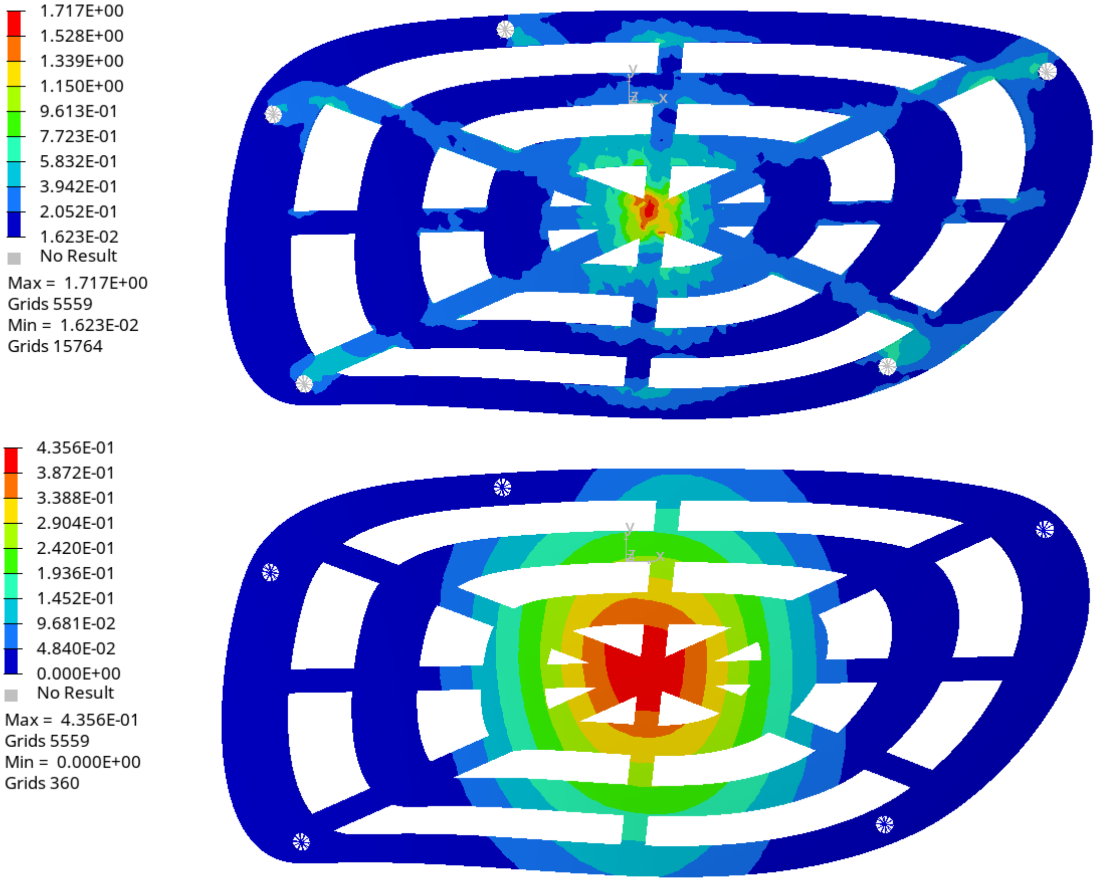
Figures 6 - Von Mises stresses (up) and displacement (down), testing 2, redesign 1



Figures 7 - Von Mises stresses, testing 3, redesign 1



Figures 8 - Von Mises stresses (up) and displacement (down), testing 4, redesign 1



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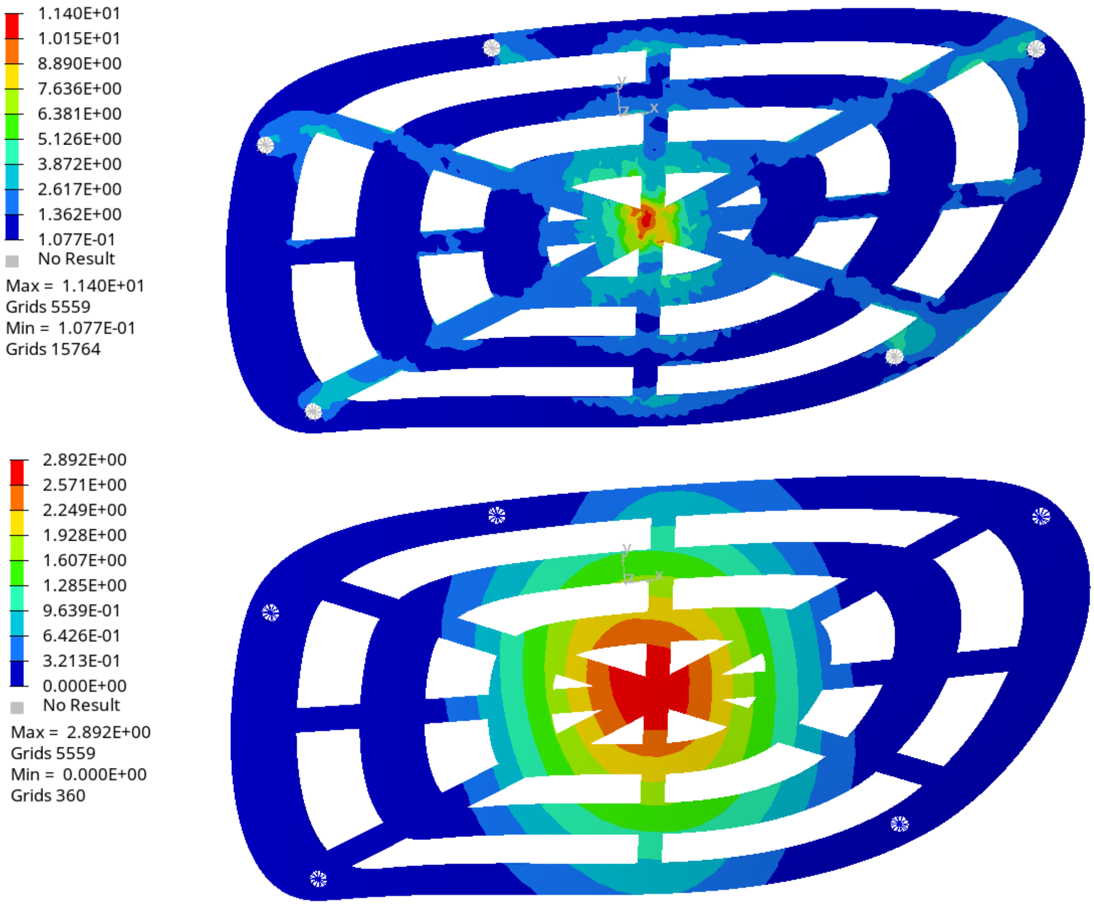
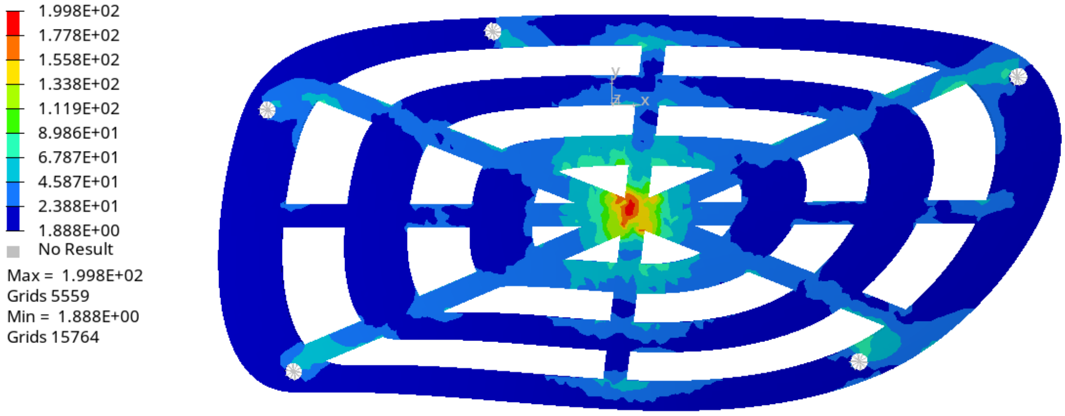
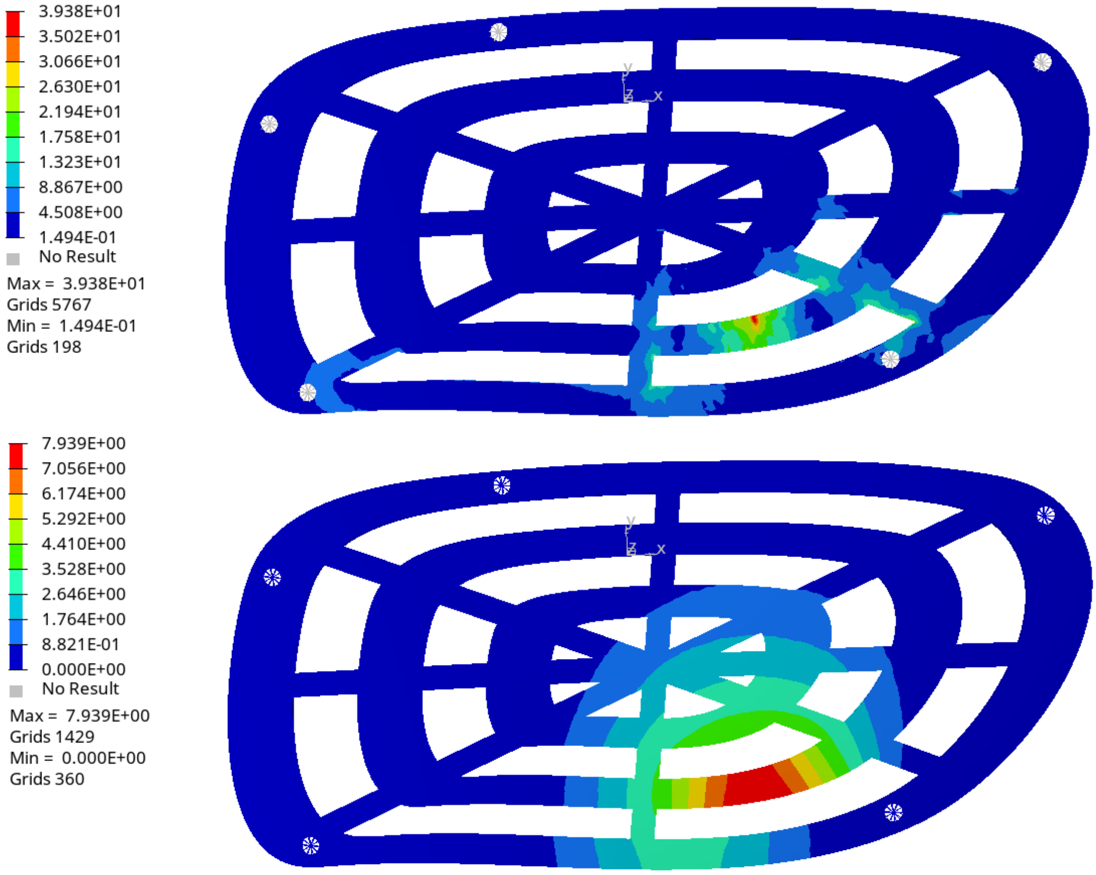


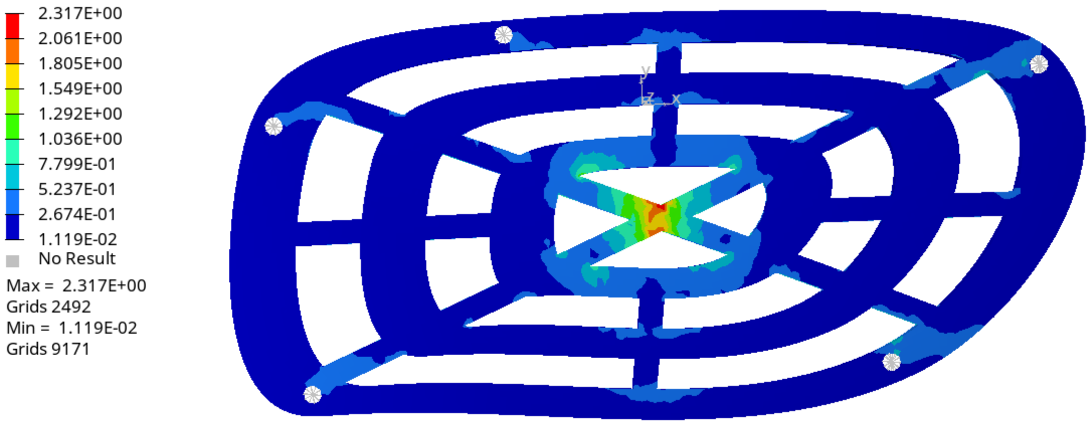
Figures 10 - Von Mises stresses (up) and displacement (down), testing 2, redesign 2

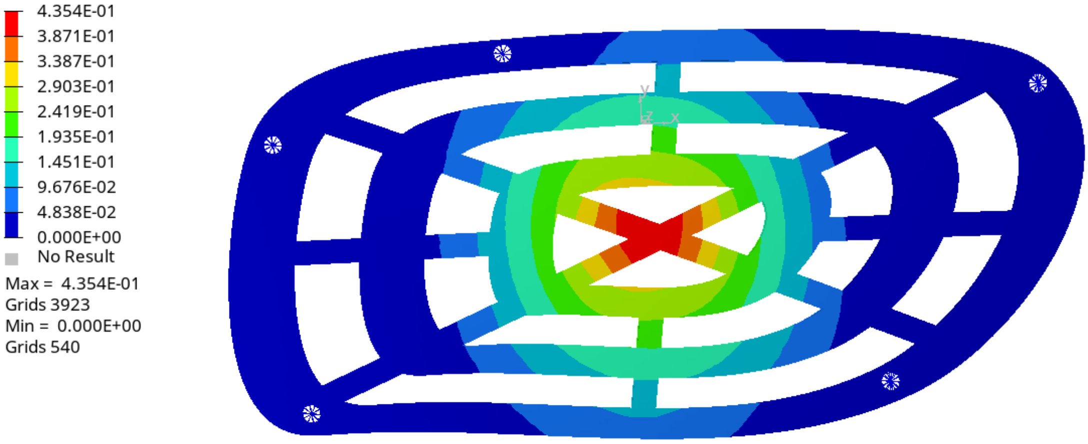


Figures 11 - Von Mises stresses, testing 3, redesign 2

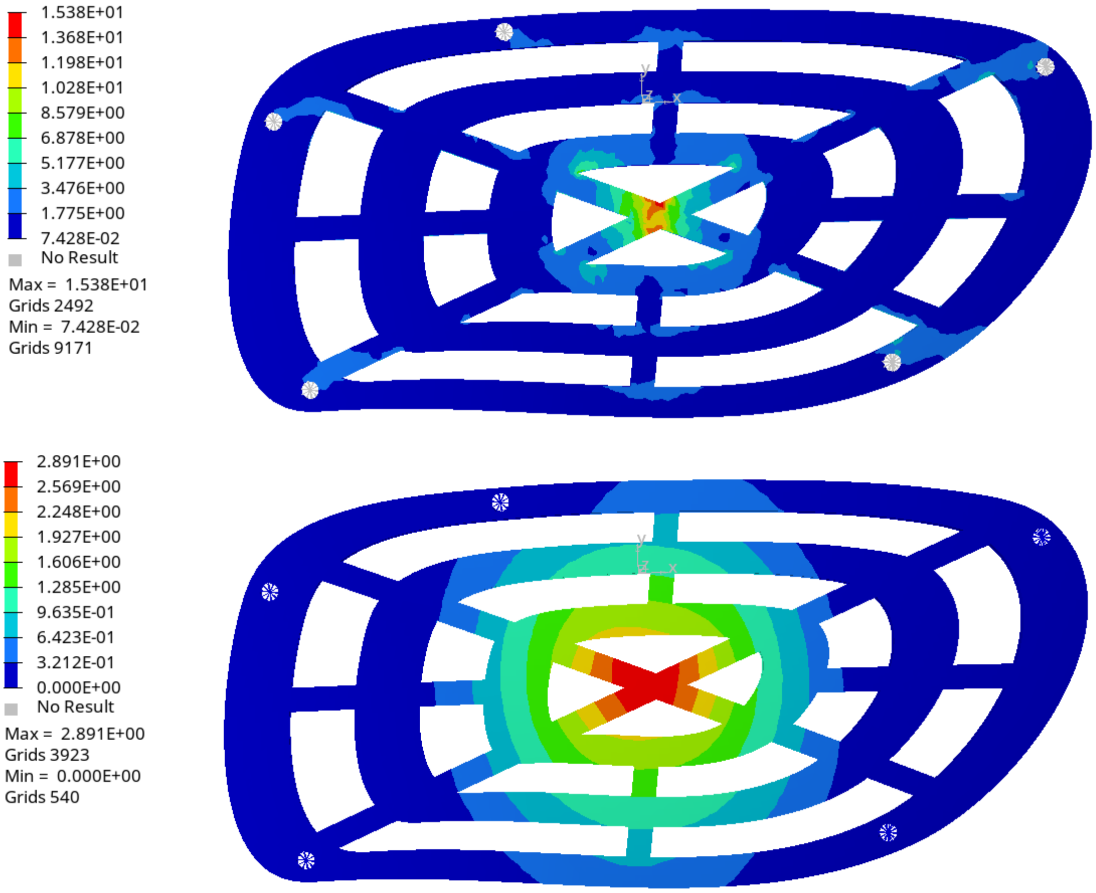


Figures 12 - Von Mises stresses (up) and displacement (down), testing 4, redesign 2

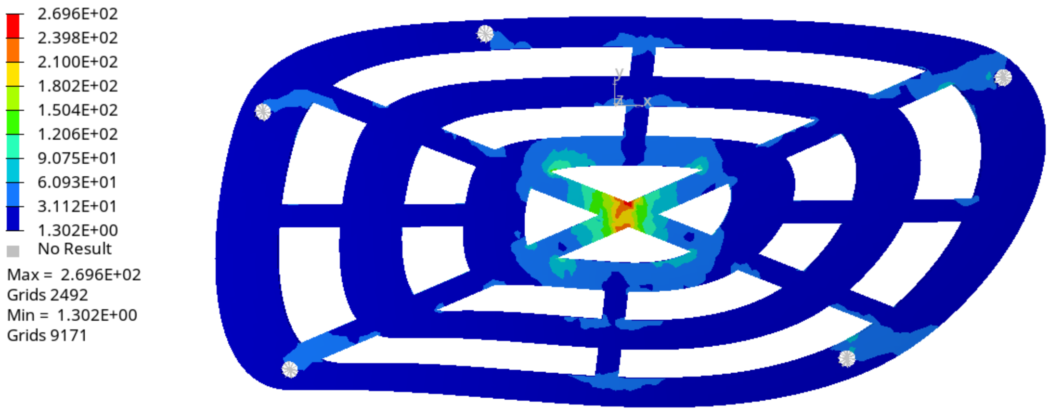




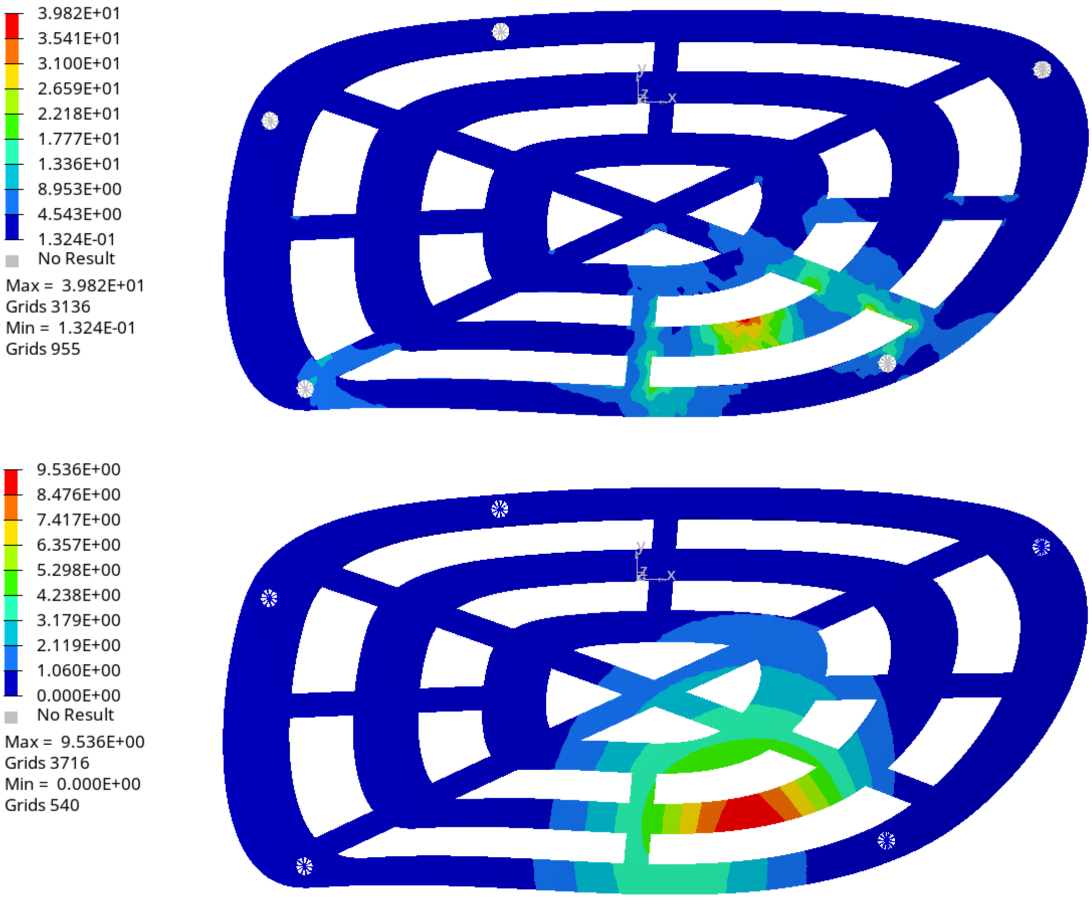
Figures 13 - Von Mises stresses (up) and displacement (down), testing 1, redesign 3



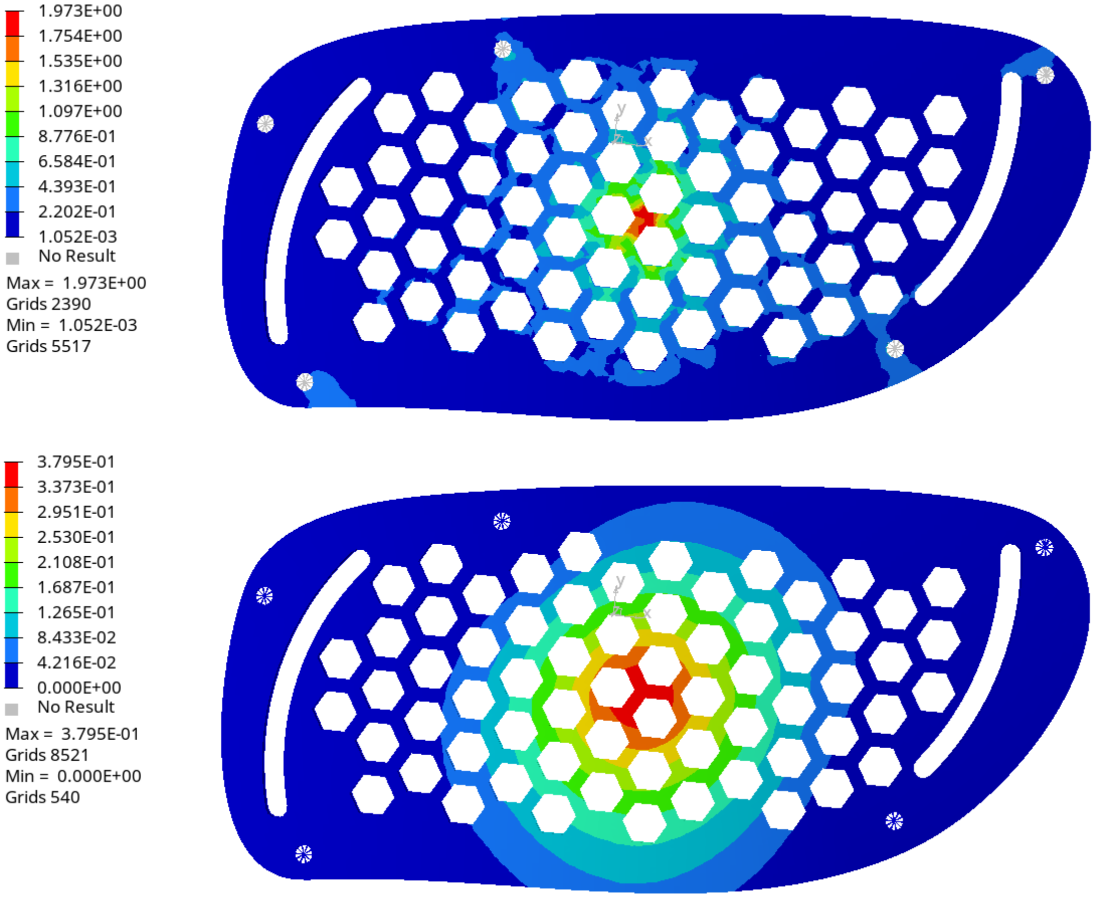
Figures 14 - Von Mises stresses (up) and displacement (down), testing 2, redesign 3



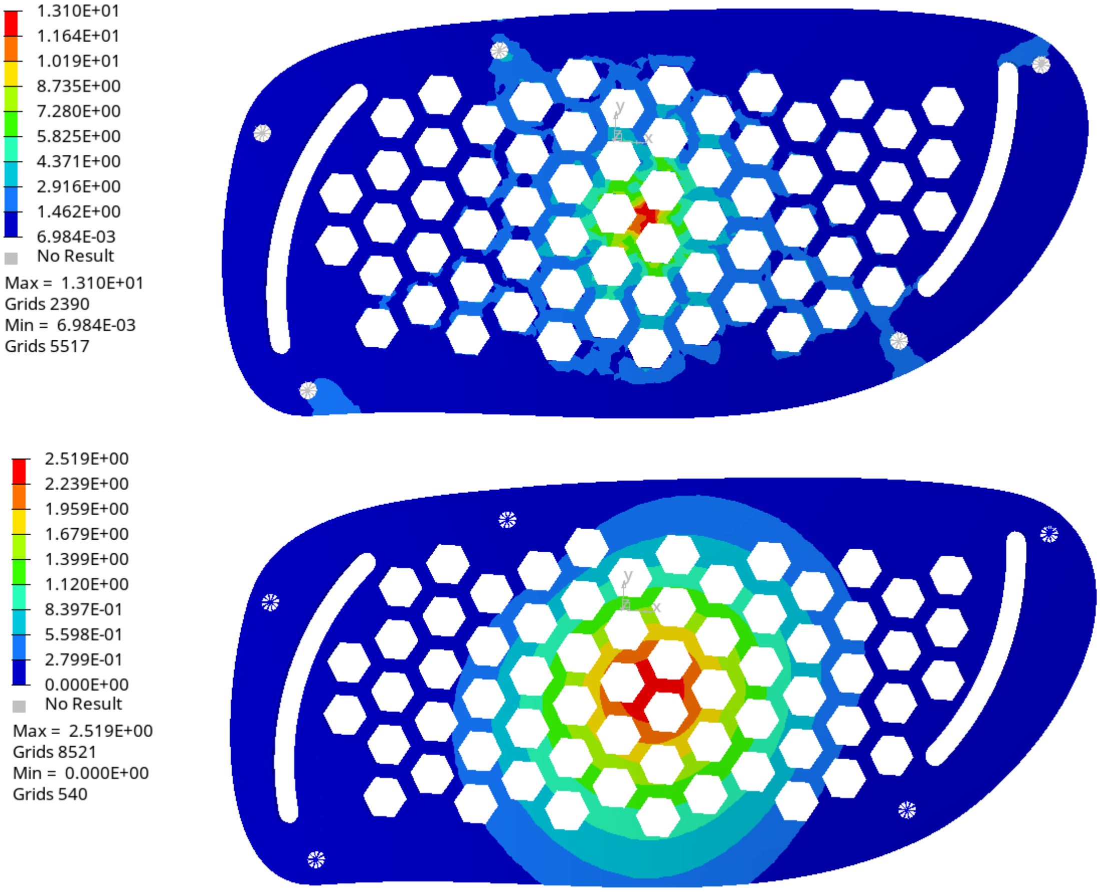
Figures 15 - Von Mises stresses, testing 3, redesign 3



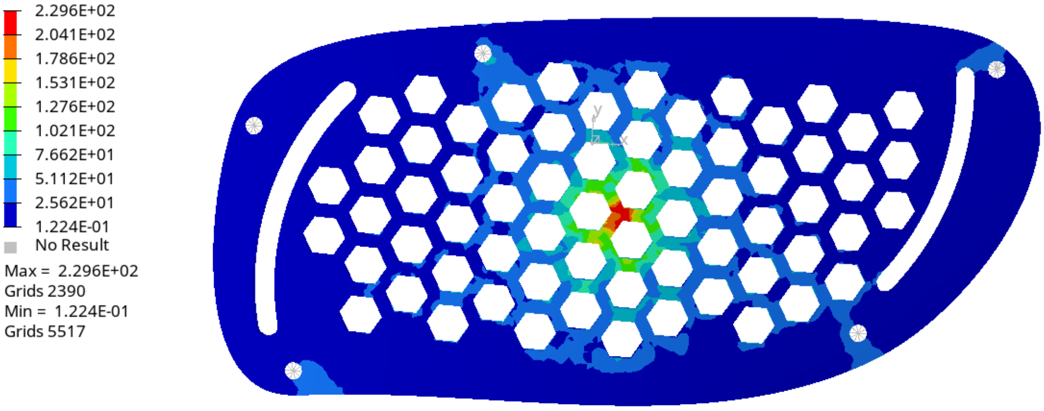
Figures 16 - Von Mises stresses (up) and displacement (down), testing 4, redesign 3



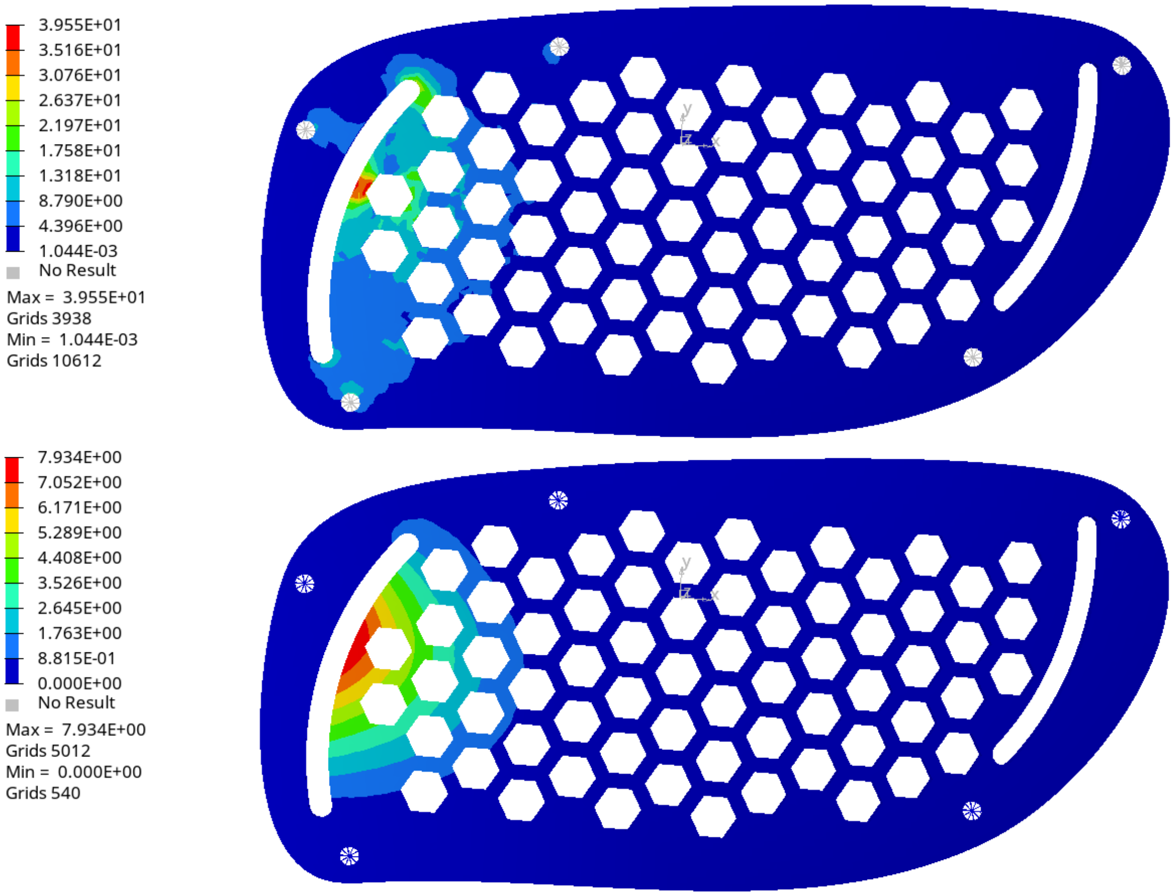
Figures 17 - Von Mises stresses (up) and displacement (down), testing 1, redesign 4



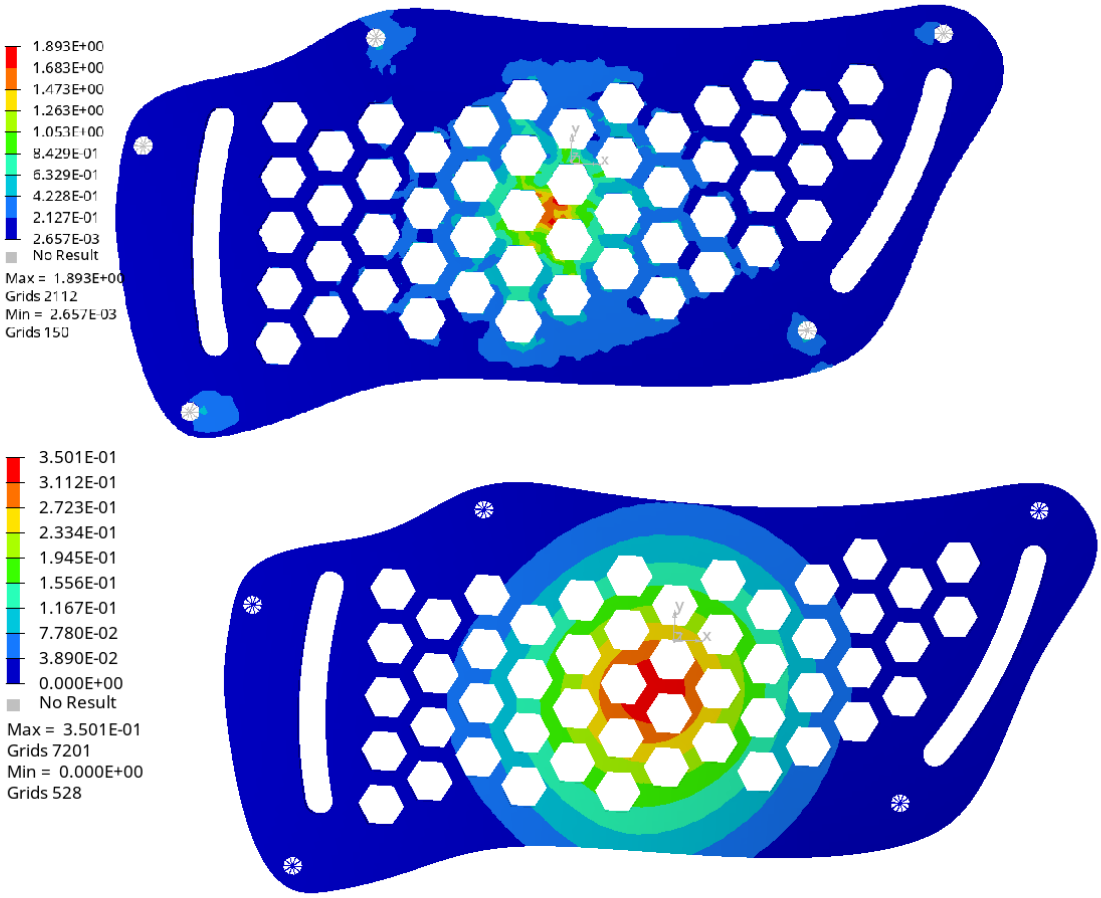
Figures 18 - Von Mises stresses (up) and displacement (down), testing 2, redesign 4



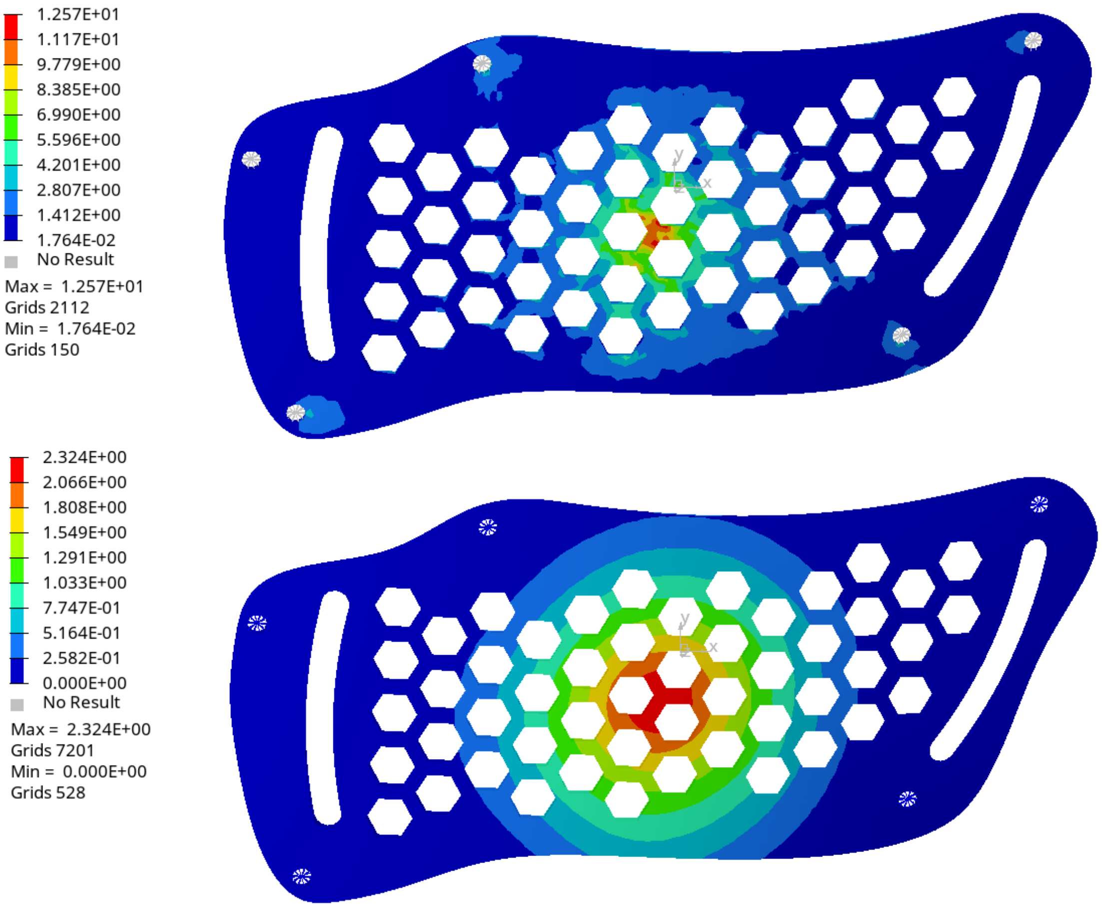
Figures 19 - Von Mises stresses, testing 3, redesign 4



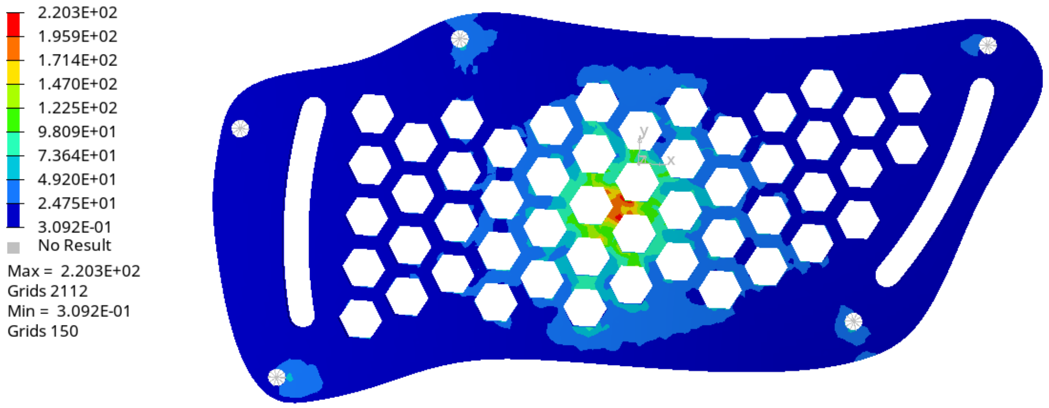
Figures 20 - Von Mises stresses (up) and displacement (down), testing 4, redesign 4



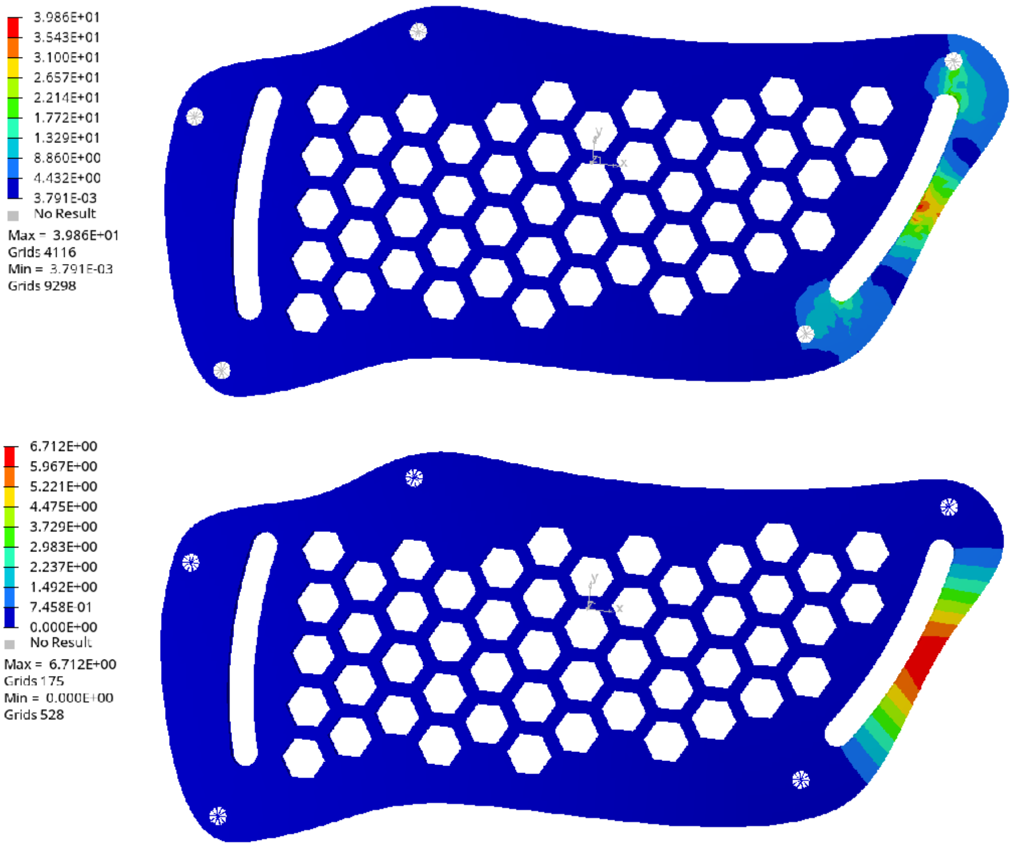
Figures 21 - Von Mises stresses (up) and displacement (down), testing 1, redesign 5



Figures 22 - Von Mises stresses (up) and displacement (down), testing 2, redesign 5



Figures 23 - Von Mises stresses, testing 3, redesign 5



Figures 24 - Von Mises stresses (up) and displacement (down), testing 4, redesign 5