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Contributions of Generative Design tools to Mechanical Design

Author: **Sébastien Schrurs**
Supervisor: **Bruno Dehez**
Readers: **François Heremans, Benoît Raucent, Aude Simar**
Academic year 2020–2021
Master [120] in Mechanical Engineering

Acknowledgements

I would like to thank the following people, without which this master thesis would not have been possible :

First of all, my supervisor Mr. Bruno Dehez, first of all for having accepted to supervise my personal thesis topic, but also for having offered me his time throughout the year with enthusiasm and consideration.

Mr. François Heremans for giving me his time and energy to discuss the technical aspects of his exciting PhD thesis topic.

Mrs. Aude Simar and Mrs. Camille van der Rest for their availability and their expert advice concerning metal additive manufacturing.

Mr. Thomas Servais for having taken his time to share with me his professional experience as a mechanical engineer, as well as his vision of technologies on mechanical design.

Mr. Vincent Musette, technician at iMMC, for having judiciously shared his expertise on machining techniques with me.

My parents and my two brothers for their presence and unconditional support throughout this year.

My uncle for the inspiration and advice, without which many things would have been less easy.

And finally, but not least, thanks to all my friends who helped me in the realization of this work.

Abstract

Mechanical design and manufacturing methods are adapting to the tools available. In recent years, technological progress has allowed engineers and designers to arm themselves with both new manufacturing techniques and new shape optimization methods.

First of all, this work describes what generative design is: a new type of mechanical optimization method that has appeared in the last few years, which uses the computational power of computers to reproduce evolution as observed in living beings.

These new methods call for modifications to the classic mechanical design process as we know it today and require profound changes in the organization of the companies that embrace them. However, this new way of designing shapes promises very interesting gains in time and performance.

After clarifying the general idea of the concept and giving some concrete examples, this thesis describes a practical case study in which an optimization study using generative design was conducted. The subject of the case study is the optimization of the mass of a part of the ELSA prosthesis, an active ankle prosthesis developed at the UCLouvain for lower limb amputees.

Finally, a critique of the different results is made, with a perspective of the contributions observed during the studies.

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1 INTRODUCTION

In recent years, technological advances have allowed engineers and designers to arm themselves with both new manufacturing techniques and new methods of shape optimization. Thanks to additive manufacturing, for example, the range of shapes that can be produced is expanding and becoming more widely available. It is therefore possible to use methods of optimization of the material in a freer way because we are much less limited by constraints related to manufacturing techniques.

Generative design is a new type of mechanical design method, which is based on a much greater collaboration between the designer and the computer. The designer relies on his imagination and critical thinking skills, while the computer uses its phenomenal computing power.

Engineering design methodologies have not fundamentally changed since the industrial revolution, and ideas for the evolution of these methods are slowly emerging. Certainly, as humans we use computers and computer systems to visualize certain shapes more easily, to exchange information and files better, or to run simulations. But we can ask ourselves if we are not currently under-using these technologies and are missing out on a much better efficiency. Until now, all the creative aspect has remained in the hands (or rather in the heads) of designers. In order to continue our exponential progress, we should probably resolve to review our methods of operation, and to delegate some of these steps to computer systems.

The first goal of this work is to define what generative design is. The EPL libraries do not have much information about generative design yet, so this thesis will have as main ambition to give an explanation of it, at least as it exists today.

Secondly, the idea will be to evaluate the interest of these methods and to try to perceive the different possibilities that it could offer us in the future. To do this, an application will allow us to have a practical example of implementation of one of these programs, and then to be able to discuss these results with those initially obtained via more traditional methods.

Finally, we will present some thoughts about the limits and possibilities that we encounter when using this kind of tool. Even though this technology is still in its infancy, it seems relevant to criticize the promises it makes.

2 STATE OF THE ART

2.1 EXPLANATION OF THE GENERAL CONCEPT

First of all, we will try to clarify what we mean by "generative design", and to explain what it consists of.

Generative design is a set of new technological means aimed at increasing the automation of engineering design processes, by incorporating the computer more into steps that were until now almost exclusively managed by the human brain.

The main principle is the following: To use the technological means currently at our disposal to try to approach the optimization methods of nature, in other words to reproduce the evolution of the living.

Until now, engineers have been limited to considering very simple forms because of the tools available. Even if it was proven that some less regular shapes were better, ease of fabrication always came first, as making a more complex shape would require a considerably larger investment of time and energy. This is especially true in the industrial world, where large quantities of parts must be manufactured.

However, in recent years, great advances have been made in mechanical manufacturing methods, now making it possible to consider the production of much more complex shapes at increasingly competitive prices. In particular, 3D printing is constantly progressing and allows the production of very complex shapes much faster than before, in an automated way, and with increasingly high levels of precision.

With almost unlimited manufacturing possibilities in shapes now available, we can then look at the means to generate these optimal shapes.

Roughly speaking, the current way to design an optimized part is as follows: A first draft of the part is drawn by the designer, according to his inspiration and personal experience. He then models it in a CAD (computer-aided design) software and launches an optimization program that will simulate the forces present in the part according to a certain load case for example. In a nutshell, this simulation will inform the user about the areas that are not subject to any or very little mechanical stress, meaning that we can then freely remove material from these areas without changing the overall functioning of the part in this given situation. These mathematical optimization methods are called "topological optimization" and are already present in most CAD software. For information, we will not explore these methods in this thesis, because they are already well defined and developed in many other works. Therefore, we will consider them as known for the following.

In opposition to this "optimization by subtraction", generative design proposes an optimization by addition. Conceptually, the idea is to no longer optimize from a previous part, but rather to design it directly in an optimized way without having to remove material afterwards. In other words, to add material only where we need it, a bit like living organisms do in nature.

In practice, generative design consists of a system in which the user defines the limit volume of a part, as well as the constraints and loads that apply to it. The system will then "generate" (hence its name) according to very precise algorithms tens, hundreds, even thousands of different results satisfying these input parameters. This multitude of results will then be available to the user, who will be able to sort or classify them according to various criteria allowed by the system (e.g. mass, deformation, manufacturing cost), to finally choose the solution which seems to him the most adapted to his needs.

The generation of such a large number of different solutions requires considerable computational forces, especially if we want to have these results in a few hours. This is why these methods generally use what is called "cloud computing", which consists in organizing via a cloud a large number of computing systems connected online so as to obtain much greater computing capacities than with a single computer.

In short, we could define generative design as a computer system with a large computational capacity, taking as input a whole series of user-definable input parameters, and returning as output a multitude of solutions meeting these same criteria.

Finally, let us note that generative design methods can be used in a whole range of disciplines, such as art [1], architecture [2], or even urban planning [3]. However, in this work, we will limit ourselves to their application in the world of mechanical engineering.

2.2 MAIN OBJECTIVE : MIMIC NATURE

The idea of these methods is to widen the field of possibilities, and to free ourselves from the limitations imposed by our human mind. Even if our mind has an incredible capacity of imagination, we are still limited in the forms we can consider. Typically, if we were to connect two points together, we would undoubtedly start with a straight line, and then consider a circular arc, or other regular or periodic shapes. If we then specify that the problem can extend in three dimensions, we would continue to consider simple and regular solutions, and would have difficulty conceiving more complex shapes. However, if we look at nature, there are few examples of structures with regular and straight shapes. The most telling example is the branches of trees, which are never quite straight. However, after studying the shape of the structure, it often turns out that these solutions found by nature are generally the most optimal solutions for this given situation.

Thus, for each of our mechanical engineering problems, we could try to be inspired by the shapes we find in nature. It is on this approach that the discipline of biomimicry is based, which studies the solutions found by nature in order to inspire new solutions to human problems [4]. One of the most famous examples is the aerodynamic fuselage of the front of the Shinkansen (Japanese high-speed trains), whose shape was directly inspired by the morphology of the kingfisher's bill. As this bird needs to enter the water with the least possible resistance, evolution eventually provided it with a beak having the optimal shape to enter the water in the most efficient way.

Figure 2-1 The shape of the kingfisher's beak inspired the design of the train fuselage to make it more aerodynamic [5]

However, even if nature remains the best engineer on Earth, the approach adopted by biomimicry is not always the most efficient in terms of time. Indeed, if for each problem to be solved we had to find a similar situation in nature to see what solution has been found, it would undoubtedly take us a considerable amount of time each time. Especially since some mechanical situations are probably not even found directly in nature. This is why it might be interesting to try to imitate the process by which nature finds its solutions, or at least to be inspired by these natural processes in order to find one that we could apply to our situations.

So the idea would not be to imitate nature's results, but rather to try to generate results as nature would. But how exactly does nature do this?

Since Darwin, a lot of paleontological studies have led the world scientific community to a consensus about the evolutionary model of Life. According to this model, evolution works by trial and error, with each modification taking place as new generations of individuals are born through random genetic mutation. When a new individual is born, it will be endowed with characteristics that are mostly identical to those of the parent, except for some that will differ more or less significantly. These changes will then influence a whole series of physical, chemical or other parameters of the individual child, who will survive differently from the other individuals of his family. If these differences give him an advantage over the other individuals of his generation, he will survive better and will have a better chance to multiply his own genetic heritage through a new generation.

Overall, nature proceeds by trial and error, on gigantic time scales. Since evolution is a continuous phenomenon taking place over periods of millions of years, any change takes a considerable amount of iteration before it becomes established in this environment over other possibilities.

The reason these processes sometimes take millions of years is that each new generation takes a certain amount of time to emerge. For the human being, for example, each generation takes on average between 15 and 25 years to appear. If we multiply this by the number of iterations needed before we can notice evolutionary changes, we arrive very quickly at periods corresponding to the results observed by scientists.

However, if we reduce the time of these generations with the help of computer simulations, and if we use sufficient computational forces to simulate tens or even hundreds of them per second, we can arrive at solutions quite quickly according to models inspired by evolution. This is the ambition of generative design: to try to imitate evolution through a trial-and-error process by considering a maximum of possibilities, and to evaluate the performance of each one to choose the direction to follow.

An interesting example was obtained by a team of designers led by Maurice Conti, then Director of Applied Research and Innovation at Autodesk.

Their goal was to design a structure for a quadcopter (flying drone with 4 rotors) using generative design methods. After identifying the different mechanical stresses and loads that the structure would face, they ran the simulation and finally arrived at a certain shape that was optimized for this use. Only, after observation, it turned out that the structure looked suspiciously like another shape found in nature: the pelvic bone of the flying squirrel.

Figure 2-2 Similarities between the shapes of a quadcopter obtained by generative design and a flying squirrel pelvis [6]

And indeed, it seems that the pelvis of this animal meets mechanical conditions very similar to those of the quadcopter as developed by the team. This result could have been obtained directly through biomimicry if these similarities had been noticed. That said, the fact that nature arrived at a very similar solution can to some extent reassure the team on the more or less optimal character of their design.
This is indeed a single example that was later confirmed in nature, but it seems logical that we would approach similar results if we follow the same basic rules and principles.

2.3 CLASSICAL ENGINEERING DESIGN METHODOLOGY

Currently, almost all of the parts engineered and produced come from one source: the designer's imagination. We use our human creativity to come up with all the initial ideas from which the rest of the design process will flow.

During our engineering training at university, we learn the engineering methodologies to be followed in mechanical design. In particular, at UCLouvain, the course LMECA2801 Machine Design [7] (given by Pr. B. Raucent and T. Servais), which is compulsory in the common core of the civil engineering masters in mechanics and electromechanics (specialization in mechatronics), teaches future engineers the different steps to follow in the design of a part or a machine in a given situation.

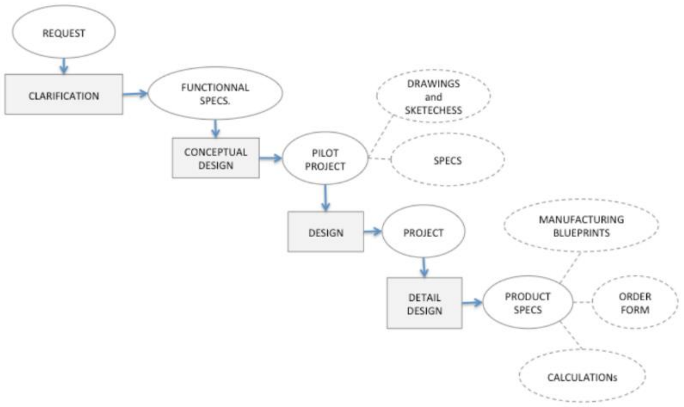

Figure 2-3 "The stages of a design", chapter 1 of the Machine Design course given by M. Raucent at UCLouvain [7]

The design process is therefore as follows:

1. Project Definition phase:

    1. A need emerges from the requester (aka client) who wants a solution to a given problem.
    2. The designer (aka engineer) clarifies the request in order to identify the situation and the gap to be filled.
    3. From this step emerges a first important document: the specifications. It consists of a description as exhaustive and objective as possible of the needs, limits and functionalities that the future solution must satisfy.
    4. Once both parties (the client and the engineer) agree on the description of the specifications, the design stage can begin.

2. Implementation phase:

    1. Typically, this starts with a first brainstorming phase during which research on already existing solutions for similar problems is carried out. This is also where human imagination and creativity take place: if new ideas and non-existent solutions emerge among the participants, these are added to the raw material panel that will be used to create the solution.
    2. All the solutions are then combined and evaluated according to the different criteria previously specified in the specifications.

   3. The engineer arrives with one or more final solutions ready to be tested in the next phase

3. Validation phase:

   1. Tests are carried out on the different design solutions chosen, in order to objectively and formally validate that these solutions do indeed meet the specifications previously defined in the first phase.
   2. The results of these tests are then discussed between the engineer and the client, who then decide whether or not the final solution is suitable for the situation.
   3. If the solution is not deemed sufficient, a new design iteration is carried out, starting from the definition of the initial specifications.

More generally, this working method is more often known as "V-model", and can obviously be applied to all types of projects.

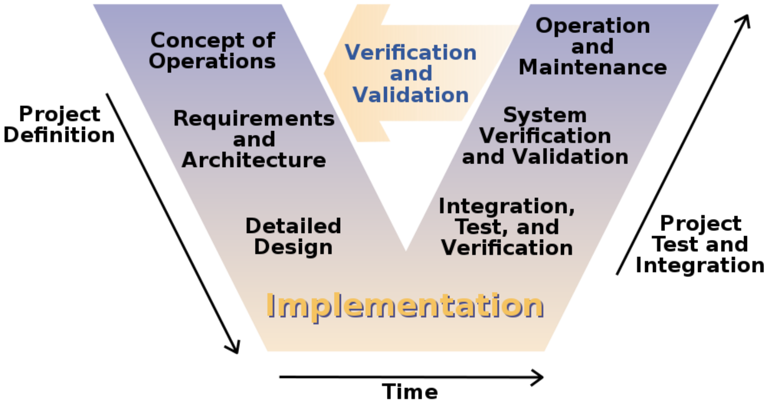

Figure 2-4 V-model methodology scheme [8]

Throughout this process, the engineer's experience and human creativity are the main drivers for the project's progress. Of course, computers and computer systems are useful in the first phase (Project Definition) in order to be able to manage the countless criteria and references that the project often has to deal with. Similarly, computers are of course used in the third phase (Validation), by calculating numerical simulations of effort or fatigue for example.

However, the second phase (Implementation) uses the computer in a very limited way. The first ideas usually come directly from the designer's hand, based on external inspirations, or from his own imagination. The computer is then used only after the solutions have been imagined, and this mostly for 3D visualization and sharing purposes.

Even if the computer is later used to optimize the design via various simulations, the starting shape will remain a shape thought by a human being. It then includes all the subjective biases related to the human's own judgment, which means that there is a good chance that the final design will have significant differences depending on who is doing the thinking. Since we get different final solutions depending on the designer, we are entitled to wonder if the solution a designer arrives at is really the best one. Then, no matter how the validation phase is conducted, the starting point will remain a less than optimal solution.

2.4 SOLUTION PROVIDED BY GENERATIVE DESIGN

It is to this lack of human creativity that generative design tries to bring a solution. Its ambition is to bring the computer much earlier in the process, and to use it for what computers are very good at: doing a lot of calculations very quickly and without distraction. This changes the role of the designer because he no longer directly manipulates the part to be designed, but must now create and modify the rules of the system that will generate the final design. [9] Of course, he retains his ability to judge and his creativity when determining the starting rules, as well as at the end when interpreting and verifying the results.

The design process is therefore as follows:

1. Project Definition phase:

   Almost exactly the same as in the classic design process as mentioned above. The only difference is that at this stage, the engineer must have a very good understanding of the mechanical situation of the part to be designed in order to be able to translate the real situation into parameters that can be understood by the system.

2. Implementation phase:

   1. The user enters the objectives and constraints (material used, manufacturing method used, volume available, contact zones, exclusion zones, applied loads, etc.) into the generative design system. The goal is for the system to have all the relevant elements at its disposal so that the proposed solution meets all the criteria of the specifications.
   2. The generative system is launched. It will then -using an algorithm specific to the system- consider a whole series of shapes meeting the criteria specified in the input.
   3. Once the system has converged towards solutions satisfying the criteria initially defined by the user, it stops and presents the different solutions it has arrived at. Depending on the system interface, the user can then sort and compare them according to certain criteria, such as total mass, maximum Von Mises stress, deformation, etc. Some systems even provide an estimate of the cost of manufacturing the part, based on partnerships with part prototyping companies.

3. Validation phase

   1. Among all these solutions, the user chooses one or more of those that best suit him. He can then directly make one or other modification if he wishes, concerning the aesthetic aspect for example, which is generally not easy to translate into a computer system.
   2. The next steps correspond to the validation phase of the classic design method mentioned.

This type of system promises a whole series of advantages over traditional design methods. In particular, in terms of the performance we can achieve. Indeed, the designs obtained by classical way (in other words, directly from the designer's imagination) are often not the most optimal in terms of mechanical resistance, mass optimization, etc. This is mainly due to the fact that, as mentioned earlier, the human being relies on his or her own imagination. This is essentially due to the fact that, as mentioned earlier, humans rely on their own experience and on what they can observe around them to imagine new solutions. The risk is then to take example on imperfect ideas, which will compromise the optimization of the final solution. Moreover, and perhaps more obviously, it is easier for a human brain to think of simple and regular shapes, and not of more "organic" and irregular shapes as we find them in nature. The computer obviously has no capacity for imagination, but the advantage is its speed in considering and testing many solutions very quickly. Coming back to the performance gains, as we will see later, there are many cases where for the same mechanical properties, a part optimized by generative design will have a mass 30 to 40% smaller, and sometimes even more.

The last big advantage put forward by the proponents of generative design lies in the expertise required from the user. Traditional design in industry usually requires years of training and experience on the part of the engineer to ensure that the solution is made according to industry standards. The designer must have enough experience to "feel" which design options will make the most sense, especially based on past mistakes. For example, to determine which material to use in which case. Here, although experience is of course highly recommended, the use of generative design programs try to reduce the skill requirements of the user to the strict definition of the input elements of the program. In other words, it is now no longer necessary to do a thorough search of what already exists in the field, the "only" thing the system needs is to be provided with the objectives, constraints and mechanical limits of the object to be designed. Theoretically, the use of this type of program would only require a "translator" who would translate the real situation into quantified elements understandable by the system. Then, and perhaps this step requires a little more expertise, the user must interpret the different results coming out of the system, compare them, choose one and even make some final modifications.

Given the automation of certain steps in the process, this kind of design method also promises much reduced development time: all the steps of researching the state of the art are no longer necessary, as well as the drawings and diagrams made by hand or on the computer, or the evaluations of the solutions between them. All of this saves a significant amount of time in the overall process of designing a solution. Some programs promise to reduce total design time by more than 20 percent. [10]

All this is of course very theoretical, but nevertheless seems to be in line with the evolution of the industry, where time and expertise cost money and where one of the main objectives is to reduce expenses and increase profits. It would be beneficial if, in addition to all this, the mechanical properties of the final solution were also improved.

2.5 EXAMPLES OF PRACTICAL APPLICATIONS

In order to illustrate the kind of results obtained by generative design, there is nothing better than to show some examples obtained through these methods. The list is obviously getting longer every day, and most of the design details of these parts are still rather vague, but this nevertheless gives a first idea of the results we can expect.

2.5.1 Aeroplane Seat (Autodesk and Airbus)

In 2017, then 3D Printing Research Scientist at Autodesk, Andreas Bastian set out to investigate the possibilities of generative design for a particular practical case: the structure of airliner seats. He quickly got in touch with the Innovation Department at Airbus, which provided him with the various information he needed. After a few months of research, he arrived at this result:

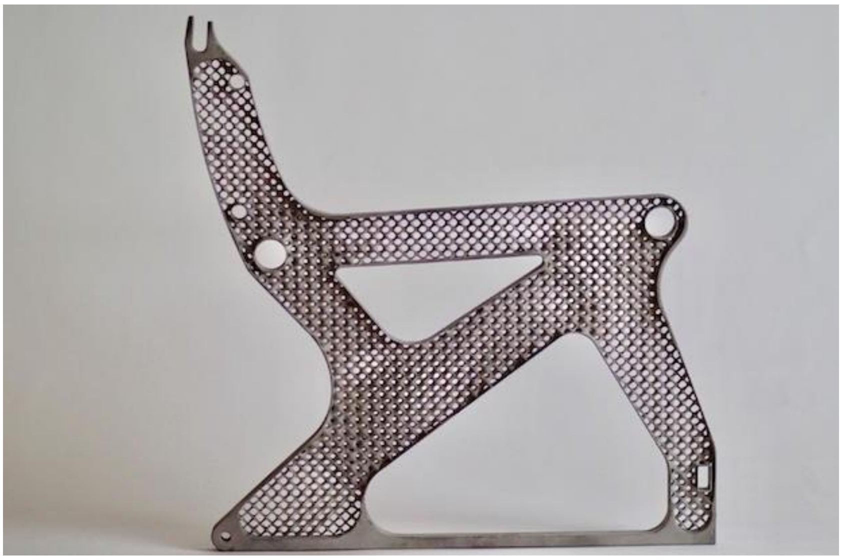

Figure 2-5 Airbus aeroplane seat optimized by generative design [11]

This 3D printed plastic model is used to make a ceramic mold, which can then be used to produce new metal seats by casting. The benefits of the new design are manifold: The seat has a weight saving of 30 percent due to the new, optimized design alone. In addition to this, the study showed that it was possible to use a certain magnesium alloy. Thus, by using this alloy instead of conventional aluminum, it was possible to lose an additional 24% of mass compared to the original design. Between the beginning and the end of this process, the mass of a seat went from 1672g to 766g, which corresponds indeed to a total mass reduction of 54%, while keeping the same mechanical properties as the original part. [12]

In this example, the final manufacturing method used is molding and not 3D printing. Indeed, 3D printing is used in the production of a mold, and not in the production of the final part. This is mainly due to the fact that additive manufacturing techniques are not yet advanced enough to offer enough different materials. On the contrary, molding is a well-known technique in the industry, and it was therefore possible to use the desired material for the production of this part. However, it is only a matter of years before additive manufacturing is a fully feasible option for a sufficient range of materials.

2.5.2 Steering Knuckle (ParaMatters, XponentialWorks and Arcimoto Inc.)

A second example of an object obtained by generative design is a steering knuckle for the performance cars of the American company Arcimoto. This company develops and produces Fun Utility Vehicles (FUV), three-wheeled electric cars. Currently, the challenge for electric car manufacturers is range. One way to improve this is to increase the capacity of the battery system, but another way may be to decrease the overall mass of the car.

So in 2020, the company is collaborating with ParaMatters (a mechanical design company) and XponentialWorks (a prototyping company) to optimize the design of certain parts. One of the parts that was optimized was the steering knuckle, shown in pink in the following image:

Figure 2-6 Steering knuckle optimized by generative design [13]

On the following image, we can see the original part on the right, and the optimized part on the left in pink.

Figure 2-7 Optimized part (left) and original part (right) [14]

The original part consisted of nine welded mild steel parts, with a total mass of 2.7kg. In comparison, the generative design optimized part consists of a single piece of MS1 steel produced by additive manufacturing, for a total mass of 1.7kg, which represents a mass gain of 37%. All this for a part that is three times stronger than the original structure.

3 GENERATIVE DESIGN APPLICATION CASE

3.1 CONTEXT OF THE CASE STUDY : ELSA PROSTHESIS

The best way to both illustrate and evaluate the relevance of these design methods is to put them into practice with a concrete case study and to observe the benefits that one gets from them.

In our case, we were lucky enough to be able to anchor ourselves to a project that is partly being developed at UCLouvain: this is the subject of the doctoral thesis being conducted at UCLouvain by François Heremans (and of which Pr. Dehez is one of the supervisors), which consists of developing an “ankle prosthesis, mimicking the complex biomechanics of the missing limb” [15]. The project is called ELSA, for Efficient Lockable Spring Ankle, and consists of an active prosthesis incorporating a clutchable parallel spring and an elastic series actuator, sized for the walking dynamics of a healthy ankle. The prosthesis aims to be sufficiently compact to fit into the volume of a conventional shoe. The idea is to miniaturize most of the elements and mechanisms composing the prosthesis in order to reduce its mass while coming as close as possible to the natural characteristics and functionalities of the human foot.

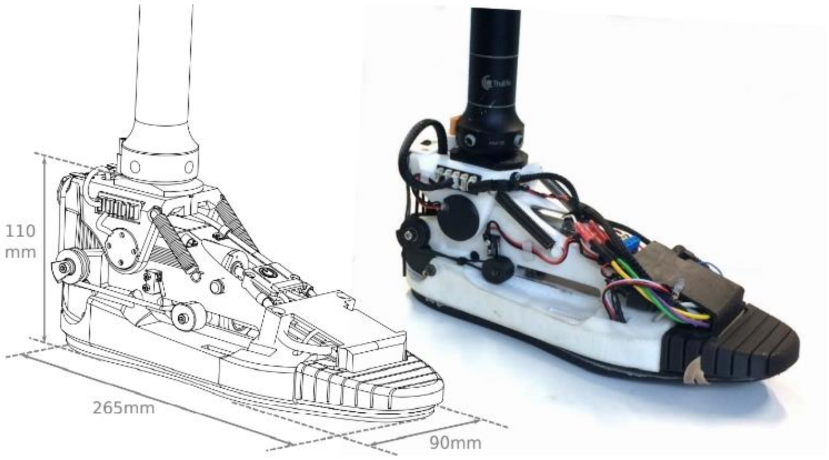

Figure 3-1 Schematic and photo of the ELSA prosthesis [15]

As a mechanical structure, the prosthesis comprises several 3D printed parts made of polyamide (PA12), which allows for rapid prototyping thanks to additive manufacturing, thus avoiding very costly machining methods while maintaining sufficient mechanical characteristics. The overall logic of the prosthesis is to keep the production cost as low as possible. Thus, the manufacturing price of a prosthesis is now about 1000 euros, which is very cheap compared to other equivalent prostheses on the market.

The prosthesis is now at a more advanced stage of development. Although it is therefore obsolete, the version on which we worked represents an example of application well known by the PhD student. The advantage is that we had access to someone who knew the prosthesis well, and he was then able to give feedback based on the experience he already had in developing this part.

By using this project as a subject of study, the idea is that in addition to being a very good example of practical application of generative design methods, it will eventually bring elements of reflection on the current design of certain parts composing the prosthesis, or even give leads for improvement on the overall design by approaching the question of mechanical design from another point of view.

The use of generative design having for main goal to reduce the mass while keeping at least as good mechanical performances, its recourse here seems quite relevant. Especially since the current parts have not been the subject of in-depth mechanical studies, it is then quite possible to find solutions even more optimized in mass than those currently used.

The part we were particularly interested in was the pin structure circled in red on the following figure:

Figure 3-2 Ankle structure to be used as a case study [15]

This structure is made up of two parts and is assembled using two pins and two screws passing laterally through one of the two parts to screw into the other. In reality, for reasons of bearing assembly, the current design of the part requires that the left and right parts be two separate pieces and can be assembled independently of each other before sandwiching the rest of the prosthesis.

In our case, we made the assumption that this structure could be made of only one piece and not two. As we will see later, the main reason for this assumption is related to the limitations of the software that do not allow us to design more than one piece at a time. On the other hand, it also allows us to challenge the current assembly and possibly consider a different assembly if the resulting design shows better characteristics than the old one.

Note also that the four holes located on the upper horizontal face are intended to fix a pyramidal connector from below using four screws. This pyramid connector will then be used to fit the prosthesis into the patient's tibial prosthesis. This is a generic type of adapter that is widely used in the lower limb prosthesis sector. Here is an example :

Figure 3-3 Pyramidal connector for lower limb prosthesis [16]

This adapter is not the exact copy that the ELSA prosthesis uses, the idea is simply to indicate the reason for the four holes on top.

In order to represent the size of the object, let us note that the structure fits in a volume of 80*60*60mm as indicated in the following figure:

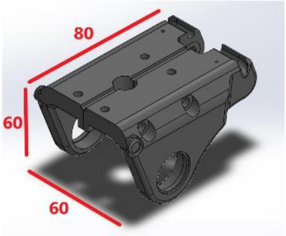

Figure 3-4 Dimensions of the structure we are interested in

Moreover, both parts are currently 3D printed (by Selective Laser Sintering, or SLS) in Nylon PA12 (with a MultiJet Fusion) and weigh 35 grams each. For your information, the production of these two pieces costs today about 50 euros in total. The idea of the studies carried out in this work will therefore be to try to see if we can obtain a coin lighter than 70 grams.

3.2 CHOICE OF GENERATIVE DESIGN SOFTWARE

Although the methodology has been known and applied for a longer period of time, CAD software offering commercial versions of generative design has only started to appear in the last few years.

Here is a non-exhaustive list of some software offering generative method functions, with their release date:

Software	**Company**	**Release year**
NX	Siemens PLM Software	2018
Fusion 360	Autodesk	2018
ParetoWorks (add-in to Solidworks)	SciArt Software, Inc.	2018
Truform SW (add-in to Solidworks)	GRM Consulting	2018
CogniCAD 2.0	ParaMatters	2018
Catia Functional Generative Design	Dassault Systèmes	2019
NTop Platform	nTopology	2019
MSC	MSC Software Corporation	2019
Creo Generative Design	PTC	2020

The year 2018 seems to have been the year that a lot of generative design features were launched for many companies. However, it had been a few years since we could hear about examples of generative design. Indeed, since generative design is a rather general methodology, it can be applied to other domains than the design of mechanical parts. For example, these methods have already been used in the field of art, notably by the Dutch designer Joris Laarman who designed the "Bone Chair" in 2006.

Figure 3-5 "Bone chair" made by generative design by Joris Laarman [17]

It is an aluminum chair obtained by casting, whose forms were generated by a program trying to imitate the generative process of human bones. This software was the result of a collaboration between the artist and the engineers of Adam Opel GmbH. The latter were already working internally on an optimization program for the design of car chassis structures, and then adapted the program for the artist.

This chair is often cited as one of the first examples of generative design applied to a mechanical structure.

Another area in which generative design has been applied for some time is architecture and urban planning. Indeed, in 2010 the company Rhinoceros 3D launched a VPL (Visual Programming Language) open source project called Grasshopper that allows parametric modeling to obtain interesting results in architectural projects in search of futuristic forms.

Figure 3-6 Example of architectural design obtained via Grasshopper [18]

Since we wanted to choose one in order to be able to carry out our different studies, we had to choose one from the list. Thus, among all these software offering generative design possibilities, the choice finally fell on Fusion 360 developed by Autodesk. And this, for several reasons.

First of all, it is the only software where all the generative design features are included for free in the academic version. In fact, the Generative Design Extension costs $1600 per year, in addition to the basic Fusion 360 subscription. And on top of that, there are variable costs for each model generation. But for students, all this is free, as long as it remains within the framework of academic research of course.

All other generative software is available through the purchase of very expensive licenses, or through trial periods of only a few weeks. For our studies, we needed it for a period of at least 6 months. Despite emails sent to various companies, no contact could be established to hope to have a version available for the research period.

Another decisive point in the choice of Fusion 360 as software: its userfriendliness. Given the relatively short time we can spend testing the software, it was necessary that the software be easy and quick to use. This is also the reason why we decided to focus on the results of a single software and not several.

A final advantage to using Fusion 360 is the large amount of content Autodesk publishes on generative design. Indeed, the company has adopted a strategy of communicating a lot about generative design applications and has done a lot of collaborations with different large companies (Airbus, NASA Jet Propulsion Lab, General Motors, ...). From all these collaborations came articles and videos praising the incredible advantages that generative design brings to mechanical design, so it was interesting to confront our own experience with these promises.

Unfortunately, despite all the research done on the subject, Fusion 360's solving algorithms remain unknown. We tried to contact Autodesk many times hoping to get some clues on how they perform generative optimization in practice, without success. So we had to run a whole series of simulations hoping to understand some logic behind the results we get.

3.3 DESCRIPTION OF FUSION 360

Now we will see how the generative study function works in Fusion 360, as we have used it.

The program looks like this:

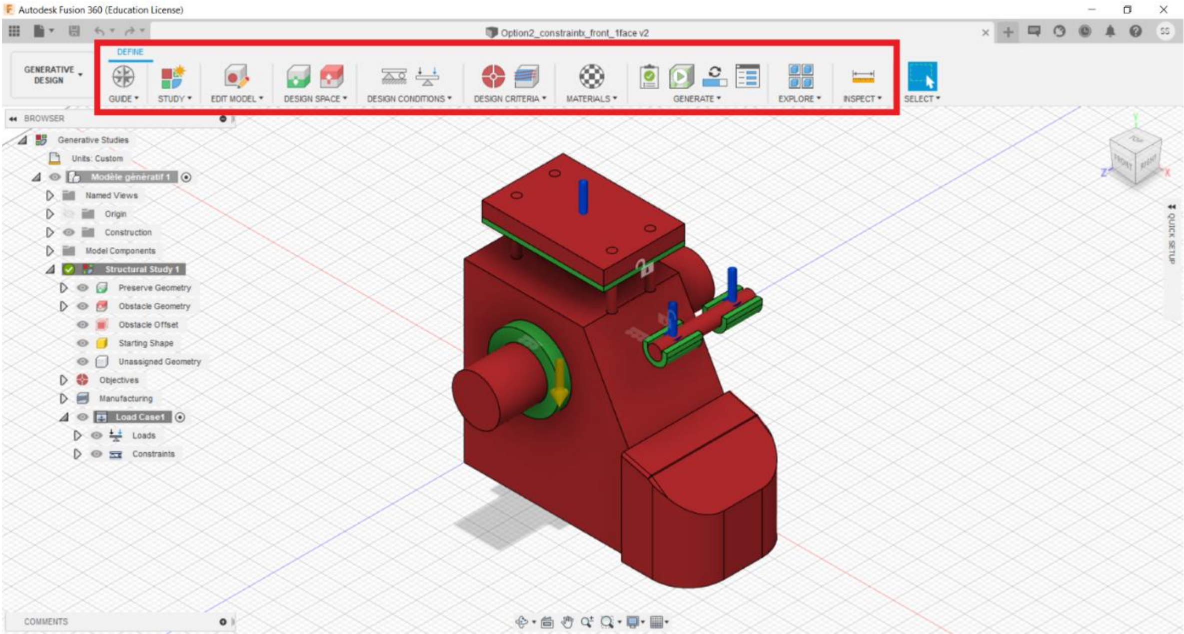

Figure 3-7 Fusion 360 generative design software window

Each of the steps to be followed is located in the top bar framed in red. You just have to follow them from left to right in order to define all the parameters necessary for the generative study.

Step 1: Guide: An interactive assistance guide, in which we can find additional information about different elements of the study.

Step 2: Study: Here it is possible to create a new study configuration. This allows the possibility to simulate several different load and stress cases for the same part configuration. Please note that it is only possible to run a generative simulation on one study at a time. Under this tab it is also possible to control the resolution and accuracy of outcomes.

Step 3: Edit model: Here it is possible to modify the part that has been previously designed for the study. This model must include both the volumes that will be kept when generating the new room, as well as the forbidden volumes in which the room cannot extend.

Step 4: Design Space: This is where we define the volumes to be kept and the forbidden volumes. The forbidden volumes (or "Obstacle geometry", in red in the design space) are the volumes in which the room cannot extend. Preserve geometry (green in the design space) are the starting volumes that the future generated room will have. Moreover, these preserve geometries are also the geometries on which the various loads and constraints will be applied, as we will see shortly.

Step 5: Design Conditions : Here the first tab allows to define constraints, and the second to define loads.

The constraint to be applied can be either :

- A fixed constraint applied to a face, an edge or a vertex. This will prevent the targeted item to move or deform in the specified direction (Ux, Uy or Uz).
- A pin constraint applied to a cylindrical face. This will prevent that cylindrical face from moving or deforming in the radial, axial and/or tangential direction depending on which of the three types of pin constraint we choose.
- A frictionless constraint applied to a face. This will prevent the targeted face from moving or deforming in the normal direction to the face. However, it can rotate, move or deform in the tangential direction.

The load to be applied can be either:

- A force applied to a to a face, an edge or a vertex.
- A pressure applied to a face.
- A moment applied to a face.
- Or a bearing load applied to a cylindrical face.

Step 6: Design Criteria: In the first tab, we can define both the safety factor, but also what is the objective of the optimization, either minimize the mass or maximize the stiffness. In the second tab, we must specify the manufacturing method(s) we want to consider for the simulation. Thus, it is possible to choose the following manufacturing methods:

- Unrestricted: without taking into account the limitations of the manufacturing methods. This is a good method to choose at the beginning in order to explore the different possible shapes while having a minimum of manufacturing constraints.
- Additive: we can define the orientation of the layers, as well as the overhang angle and the minimum thickness.
- Milling: we can choose between a 3-axis or a 5-axis machine. It is then possible to determine the direction(s) of the tool, as well as the minimum tool diameter, the shoulder length and the head diameter.
- Die casting: we can choose the ejection direction, as well as the minimum draft angle, the minimum thickness and the maximum thickness.

In addition to the manufacturing method, it is also possible to indicate a desired total production volume, and thus have an estimate of the unit cost of manufacturing the part. This estimate is based on data provided by an American company called aPriori [19] which specializes in the prototyping and production of parts. However, this feature is only available for a very limited list of materials.

Step 7: Materials: It is possible here to choose the different materials that the study will take into account, among a large list of materials of all kinds (metals, plastics, ceramics, ...).

Step 8 : Generate : The first tab makes a first pre-check and indicates if everything seems coherent. The second tab allows a rough preview of what the generated parts will look like. This can be useful to have a first idea of the look of the parts. The third tab allows you to launch the generation. Each generation costs 33 Cloud Credits, which corresponds to $33. The fourth tab shows the progress of the designs being generated. A generation usually lasts between 1 and 4 hours.

Step 9: Explore: Once the generation is finished, it is possible to visualize the results, and to classify them according to the manufacturing method, the material, the volume, the mass, the manufacturing cost, the Maximum von Mises stress, and the overall Maximum displacement.

Finally, the last two tabs Inspect and Select are only used for measuring distances on the part, and for selection options.

3.4 PARAMETERS OF OUR STUDY

After describing how the generative design program works, here is the application for the part we chose to study. All these choices of dimensions, loads, constraints, etc. are the result of many discussions and reflections. We will therefore only present here the final versions we finally arrived at.

3.4.1 Structure simplification and modeling in Fusion 360

As mentioned in section 3.1 the actual structure should normally consist of two parts that fit together and screw into each other. However, Fusion 360 does not allow to design more than one part at a time. Therefore, we will not take into account the constraints related to the mounting of the bearings inside the part, so that we can design the whole structure in one part.

A part with the same dimensions was then modeled in Fusion 360. The part was simplified to facilitate the overall mechanical situation, and the different contact points were defined:

- Two cylindrical rings (in green) are located on either side of the part to accommodate the two bearings of the pin.
- A flat surface on the top of the part (in green) to accommodate the pyramid connector. Note that since the thread is present in the connector, it is necessary to provide screw passages in the top plate, as well as the space needed to screw these screws from below (vertical cylinders in red).
- The central forbidden volume (in red) has been enlarged so that the final part can rotate +/- 20° around the axes of the bearings without being blocked by an internal structure.
- A cylindrical slot that can accommodate the traction system contained in the prosthesis was kept at the end of the part.
- A large cylinder-shaped forbidden volume crossing the whole design on its width has been added in order to guarantee that the circular passage in the rings.

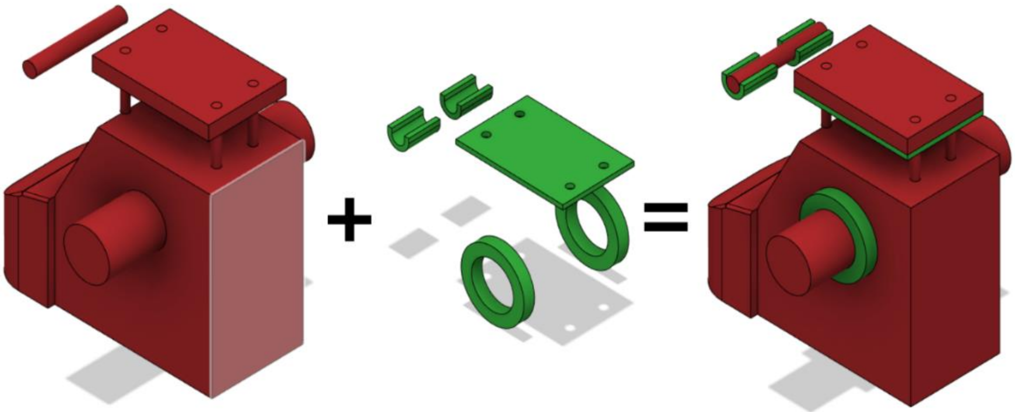

Figure 3-8 Assembly of forbidden and preserved volumes

3.4.2 Load modeling for base case

Before starting the simulations, it was necessary to define the mechanical situation of the part we wanted to study. So we talked with François Heremans so that he could explain to us the different functions that the part to be designed had to fulfill. He then gave us the SolidWorks model of the original part, and also gave us the different orders of magnitude of the loads that the part had to resist.

After discussion with the PhD student, it turned out that many forces could be neglected or put together. Thus, after simplifying the solution, two main loads could be identified:

- The patient's mass, evaluated at 1000N in the direction of the ground, which is applied to the upper surface of the pyramid connector (F1 in blue in the following image).
- The traction force generated by the active system included in the prosthesis, evaluated at 3000N in the direction of the ground, which is applied all along the slot located at the back of the prosthesis (F2 in blue on the following image).

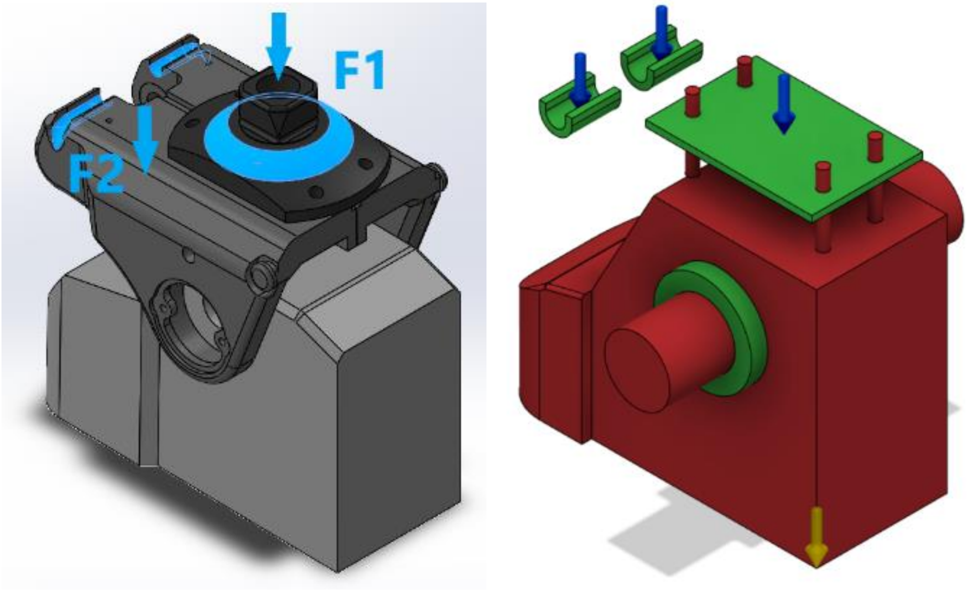

Figure 3-9 Forces applied on the original design (left) and on the new design (right)

We then transposed these loads on the part modeled on Fusion 360 like this:

- 1000N uniformly on the whole horizontal surface of the top with the four screw passages, in the direction of the ground.
- 3000N on the half-cylinders of the slot at the back of the prosthesis (so 1500N on each of the two parts), in the direction of the ground.
- In addition to these two loads, we also consider the effect of gravity on the whole structure, namely an acceleration of 9.807m/s^2 in the ground direction.

3.4.3 Constraint modeling for the base case

Regarding the constraints applied to the part, it was necessary to spend some time to make sure that the way the part is constrained is faithful to reality. Indeed, as we will see in the next section, the final design of the solutions obtained by generative design differ a lot depending on the configuration of constraints applied to them.

Since the solutions all have in common the preserved geometries (in green), the constraints that we can impose on the part will be on these surfaces. Before launching a simulation, the program checks if the system is not under constraint. If it is, it is not possible to run a simulation until it has been corrected.

In our case, we applied the following constraints:

- On both sides of the part, we first applied frictionless constraints on the inner faces of the two rings (in blue), to symbolize the contribution of the ball bearings present on both sides. This means that both faces can rotate, move or deform in the tangential direction.
- In reality, the two sides of the structure are fixed via two screws. Thus, in order to represent the fact that both rings are constrained in the axial direction, we constrain the external vertical faces of both rings in the direction normal to these faces. In truth, constraining only one of the two faces was sufficient to remove this degree of freedom. However, we wanted to have a certain symmetry of the constraints in the base case because it is the case in the real situation.
- Therefore, we now only have one degree of freedom to constrain. Indeed, at the moment, the part is still free to rotate around the axis of the two rings. So we decided to add a fixed constraint along the normal direction on the front vertical face of the top plate (in blue). This constraint finally prevents the final part from tilting forward or backward, and thus blocks the last degree of freedom of the future part.

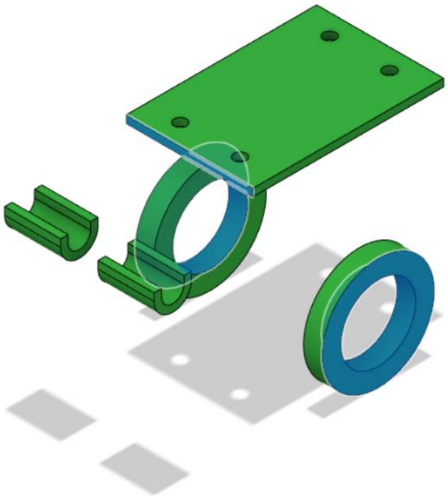

Figure 3-10 Faces on which we impose the constraints

3.5 RESULTS OBTAINED BY GENERATIVE DESIGN FOR THE BASE CASE

As a reminder, the goal here is to see what solutions we obtain for the study case described in this section, namely the structure making the contact between the pyramidal adapter and the bearings of the prosthesis pin. The results obtained here are already the result of an iterative process of numerous trial-and-error tests during which the parameters were modified each time according to the observations made. This version is therefore the last one we have arrived at, in other words the most successful so far.

3.5.1 Determination of the last parameters

All the parameters needed for the simulation of solutions by generative design have been defined previously in section 3.4, except for four: the manufacturing method, the material to be used, the optimization objective and the safety factor.

Concerning the manufacturing method, given that we want to produce a prototype of this part in limited quantities, and in a fast and relatively cheap way, additive manufacturing is the most interesting choice. Moreover, the parts constituting the structures of the original version of the prosthesis are 3D printed by a third company.

As for the material to be used, we have a little more freedom. The advantage we have here is that the structure is not in direct contact with the patient: it does not have to be biocompatible. We can therefore focus exclusively on its mechanical properties, as well as its cost. Of course, it is important to choose a material that can be printed, given the current technologies. Although the list of materials that can be used in additive manufacturing is growing every year, not all materials used in other manufacturing techniques are included. [20]

The original version of the prosthesis structures are currently printed in Nylon PA 12. This is a material that is already well known in the field of 3D printing, and we would therefore have liked to use this same material. Unfortunately, as we will see later in Section 4.1, simulations using this nylon as a printing material did not give convincing results.

Therefore, we opted for an aluminum alloy AlSi10Mg, a material that is already well known and often used at EPL for 3D printing by laser sintering (SLS).

Regarding the optimization objective of the part, we have the choice between minimizing the mass or increasing the stiffness. We choose the first option because we want to have the lightest part possible.

And finally, concerning the safety factor, we will keep a coefficient of 2 in order to respect good engineering practices. In fact, after discussion with the PhD student, it turns out that a lower safety factor could be acceptable for this application. However, we keep this coefficient of 2 for this iteration.

3.5.2 Results

So we have determined all the parameters needed to generate solutions. Now let's see the results we get.

The printing direction is as follows: The printing starts from the horizontal flat plate, and goes up to finish with the two circular rings.

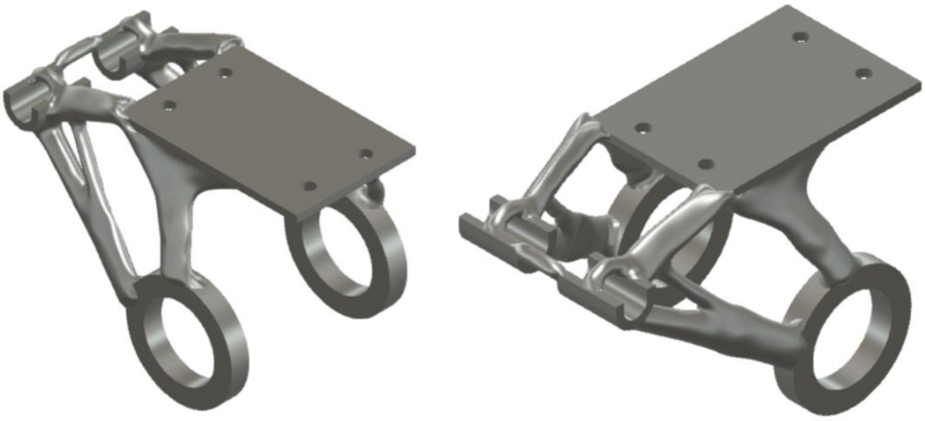

Figure 3-11 Isometric views

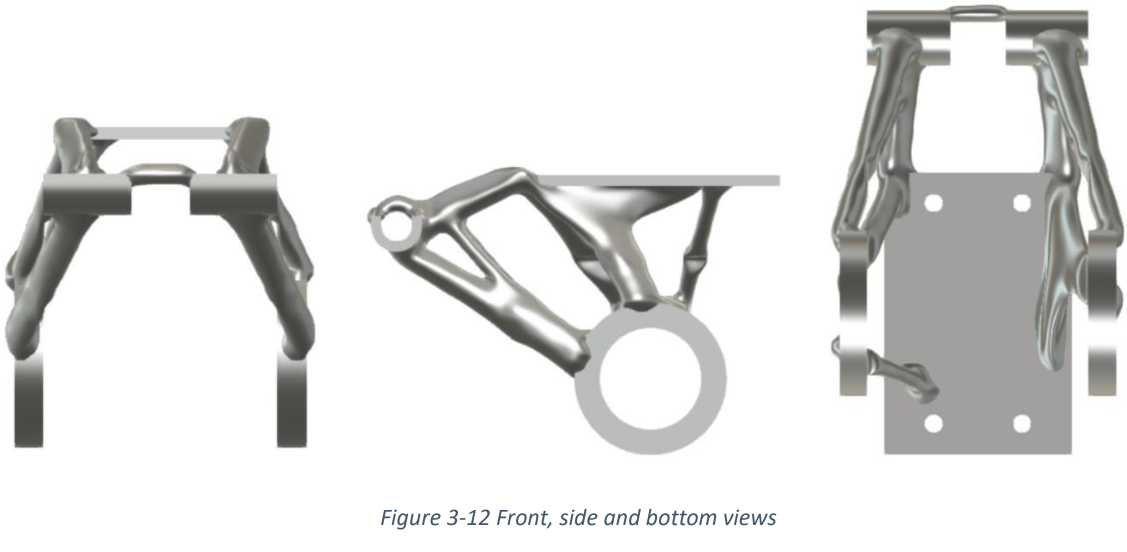

Figure 3-12 Front, side and bottom views

All this for a total mass of 39 grams, which corresponds to a reduction in mass of 44% compared to the original design.

3.5.3 Discussions

We can however observe that the part is globally symmetrical. This corresponds well to what we expected, given the stresses and loads applied symmetrically on the whole part. However, structures starting from the plate and joining vertically the two rings are not developed in a symmetrical way. This can be seen in the bottom view. In spite of the various tests carried out afterwards, we cannot give a clear explanation of the cause of this asymmetry. As we will see in the following, this asymmetry is not caused by the manufacturing method, because even when we choose to generate a part in an unrestricted way (i.e. without taking into account the limitations related to the manufacturing method), asymmetries of this type always appear.

Concerning the price, several solutions are possible. The first solution is to manufacture it at the university, with the printers we have at our disposal. After contacting Camille van der Rest of the IMMC at EPL, whose area of expertise is additive manufacturing with this aluminum alloy, it turns out that the cost of manufacturing a single part would amount to about 420 euros in total. This is justified primarily by the use of the machine, which is very expensive. Indeed, this one amounts to 80 euros per hour of use, cost of use and argon included. Still according to the specialist, given the dimensions of our part, we can expect it to take 5 hours to print. Finally, there is the price of the aluminum powder, which is 50 euros per kilogram. Given the important losses of powder linked to the machine, we can estimate that the printing of the part will require the use of 400 grams, that is 20 euros.

Another possibility is to use a third party company specialized in 3D printing for prototyping. In order to have an idea, we called the Chinese prototyping company SuNPe [21] to have an idea of the production cost of a single part. Thus, the production cost of a single part in this company would be 120 euros, for 80 euros of production and 40 euros of shipping costs, which would be a clear improvement of the price for a theoretically identical result.

Remember that these prices must be compared with the production price of the current design parts, which is about 50 euros.

3.5.4 Numerical validation

In order to verify the mechanical strength of this design, we will perform a static simulation of the part on SolidWorks, and compare the results with those of the basic design.

We apply loads identical to what we have already described above, namely:

- 1000N from uniformly over the entire horizontal surface of the top with the four screw passages, in the direction of the floor.
- 3000N on the half-cylinders of the slot at the back of the prosthesis (thus 1500N on each of the two parts), in the direction of the ground.

Concerning the constraints, we also applied similar ones, namely:

- Bearing support type stresses on the inner circular faces of the two rings.
- Roller/slider type stresses on the inner vertical faces of the two rings.

- Roller/slider stress on the front vertical face of the top plate.

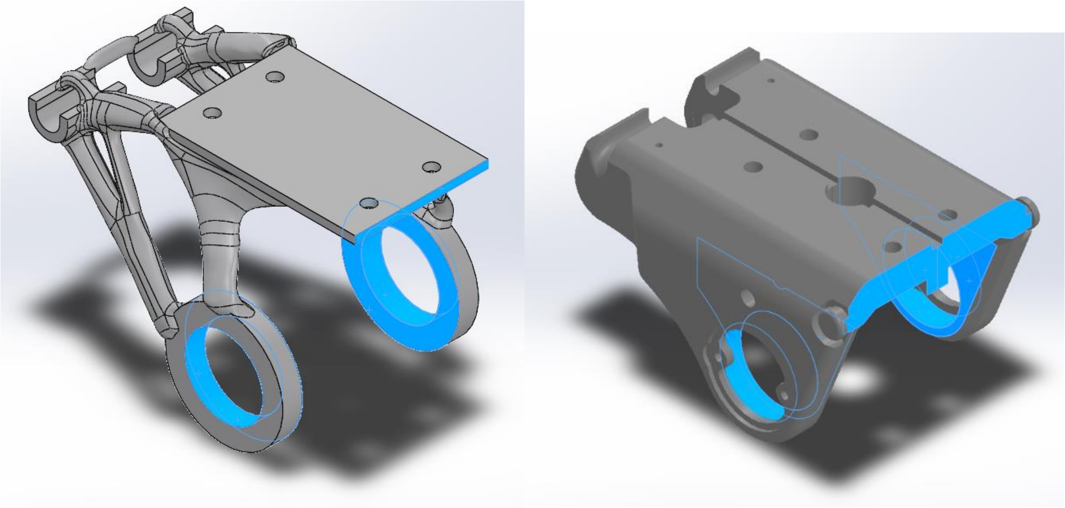

Figure 3-13 The 5 faces of the new (left) and original design (right) on which the constraints are applied symmetrically

After running the static simulation, we have the following results:

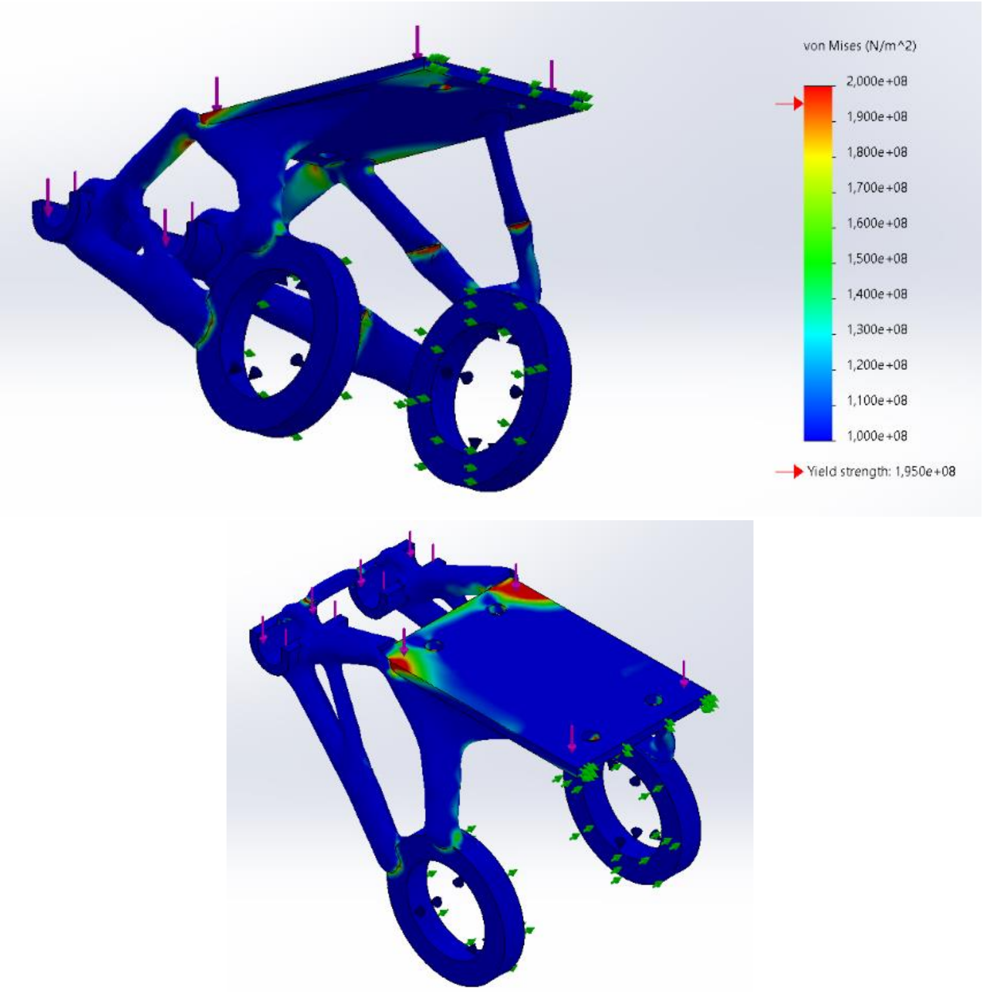

Figure 3-14 von Mises stress distribution on the new design

We can observe peaks of more than 230 MPa in the red areas, thus beyond the yield strength value for the aluminum alloy (195 MPa). This means that the part is likely to deform or even break in these areas, which we do not want. The hollows of vertical structures are therefore very sensitive areas, especially since they are not very thick at all.

Regarding the stress concentrations on the corners of the plate, we can expect that in reality the plate manages these stresses by redistributing them on the rest of its surface, which does not seem to suffer too much from mechanical stress.

Let us now run the simulation on the original part:

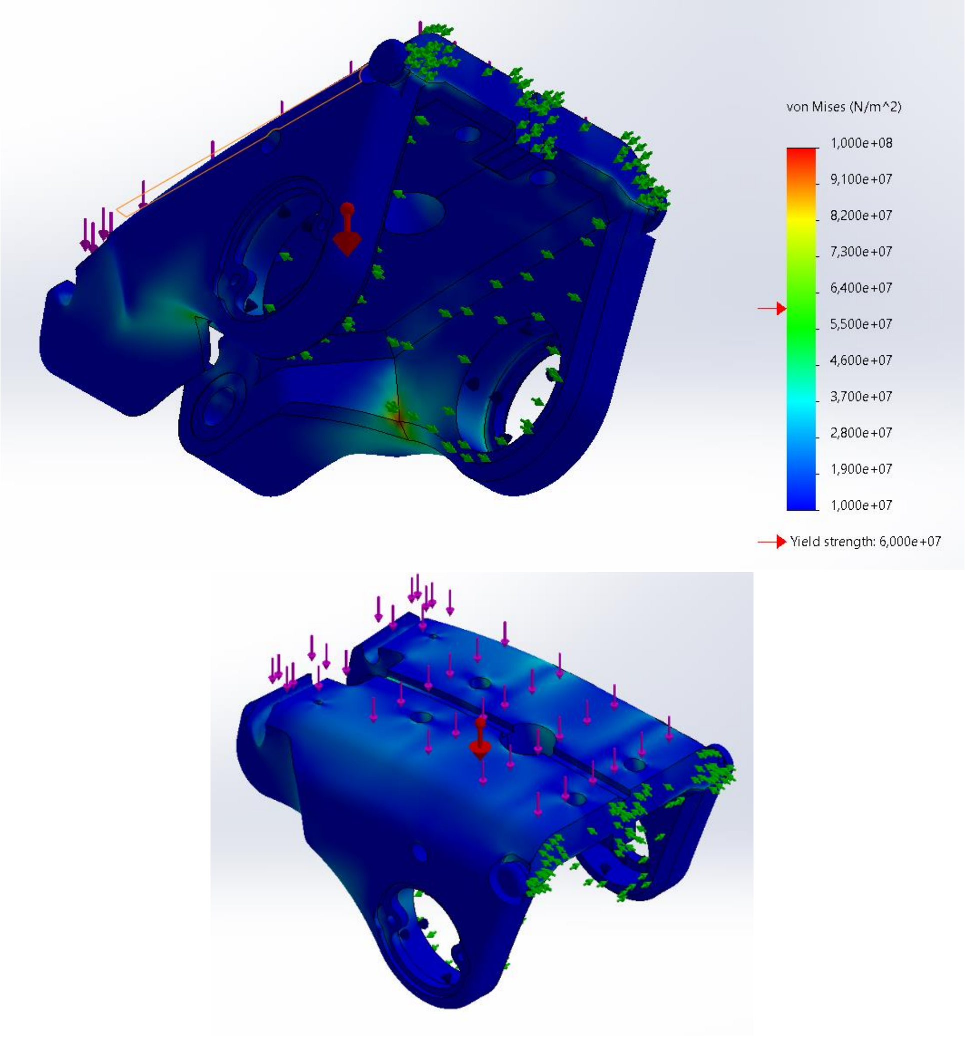

Figure 3-15 von Mises stress distribution on the original design

We can see that the structure resists very well to this load case in its almost totality, except for some small and very local areas in the bottom of the structure. Although these stress concentrations exceed very locally the yield strength of nylon (60 MPa), we can expect the whole structure to take these mechanical stresses without any problem thanks to the large volume of material around it.

3.5.5 Discussion of the results

We know very well that in practice the original part resists the forces we have defined. This has been tested and validated experimentally by François Heremans. Hence the interest of these simulations, to compare the results of the new design with those of the original design. And we observe that despite the fact that the new structure seems to resist rather well to the imposed load case, the small concentrations of forces in the vertical branches could worry us.

Thus, it might be worth considering touching up these areas by adding some volume, for example by making the diameter more uniform along the length.

That said, even if we do see these peaks in effort concentration, the values are still overall in the same order of magnitude as the yield strength. To do this properly, we would need to do some experimental testing to be sure.

3.5.6 Conclusions for the base case study

In conclusion, we can say that the result obtained here by generative design can be quite interesting, at least for a first iteration. Indeed, if we manage to rework the part in order to eliminate these in the vertical branches, and that we thus solve the problems of unwanted concentrations of efforts, this new design allows us to go from a mass of 70 grams to a mass of 39 grams, which corresponds to a reduction in mass of 44%.

In terms of manufacturing price, we saw that the difference was not huge: around 50 euros for the original design, against 120 euros for the new design. Especially since in these 120 euros, 40 euros are fixed costs corresponding to the cost of shipping the part. The cost being almost the same, it would not really justify the choice of one or the other.

However, there is still one major problem that would prevent us from using the part before we find a solution: the current mounting configuration of the part requires that the structure can be split in two, so that the bearings can be fixed inside and the rest of the prosthesis can be sandwiched.

Thus, even if it turns out that the part resists well to the experimental tests of loadings, it would be necessary to decide if the gain in mass interests us enough within the framework of this project to rethink the assembly diagram of the prosthesis. This one has however the main advantage of being very compact, and it is up to the PhD student to decide if it is worth considering mounting the bearings from the outside.

4 DÉMONSTRATION OF THE INFLUENCE OF DIFFERENT PARAMETERS ON THE DESIGN

In this section, we will observe the influence of some parameters on the shape of the solutions in the output of generative simulation. The idea here is to try to understand a little bit better the behavior of Fusion 360, and to see how similar the results are to what we would expect.

First of all, let's say that if we run two exactly identical simulations, we will get the same results twice. This means that the optimization algorithms used by Fusion 360 are indeed deterministic. In other words, the generation obviously does not use a random factor in the generation of the shapes.

4.1 INFLUENCE OF THE MATERIAL

For the record, we will still consider additive manufacturing as a manufacturing method here, and a printing direction whereby the plate is the first part to be printed flat.

The first material we wanted to use for our simulations was the one used in the original parts, namely Nylon PA12 produced by the MultiJet Fusion machines.

However, the simulations for the load and stress situation as described in the previous section for the base case did not give us any convincing results:

Nylon PA12 MJF

Figure 4-1 Design obtained by using PA12 MJF

This shape means that the program could not converge on a solution using this material.

Two other options are available in the list of non-metal materials for additive manufacturing, namely PA12 used by Orgasol machines and PA11 used by Rilsan machines. These give the following results:

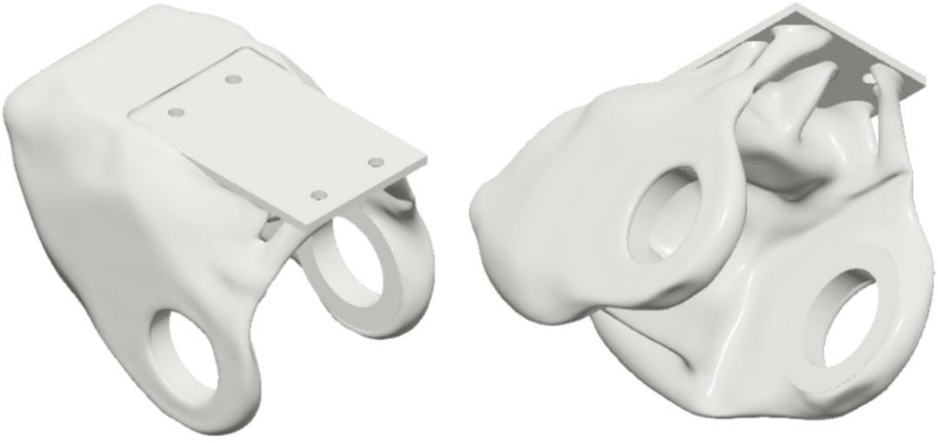

Figure 4-2 Design obtained by using PA12 Orgasol

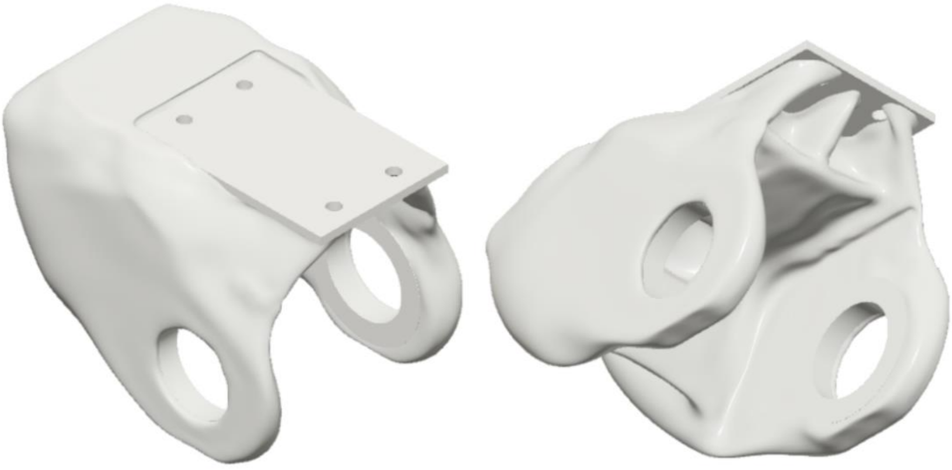

Figure 4-3 Design obtained by using PA11 Rilsan

These last two results are relatively similar in their shapes, but differ in their masses. Here is a small summary table with the mechanical property values as implemented in Fusion360.

Material	Yield Strength	Tensile Strength	Mass of the part
Nylon PA12 MJF	20 MPa	32 MPa	(153g)
Nylon PA12 Orgasol	47 MPa	48 MPa	71g
Nylon PA11 Rilsan	43 MPa	53 MPa	90g

Thus, the yield strength value would directly influence the amount of material that will be added to the part. This is logical, because the higher the yield strength of the material, the more it will be able to withstand a high mechanical stress before entering plasticity. Thus, for the same applied force, if we have a lower yield strength, it is logical to add material to increase the material section and thus decrease the stress.

In the case of Nylon PA12 MJF, this yield strength is much too low, and the software cannot converge to a solution that will resist the given situation, even if the volume is completely filled with material.

As a last example, here is a simulation made using a Titanium alloy:

Figure 4-4 Design obtained by using TiAl6-4V

And indeed, we observe that the mass is smaller for larger yield strengths.

Material	Yield Strength	Tensile Strength	Mass of the part
Ti6Al-4V	882 MPa	1034 MPa	54g

4.2 INFLUENCE OF THE MANUFACTURING METHOD: DIE CASTING

To date, casting is the most widely used manufacturing method in practical examples. Indeed, many different materials can be molded, especially when we consider the use of metals, and the technique is well mastered by the industry. Fusion360 has therefore incorporated this manufacturing method into its generative design features. When defining the manufacturing parameters, we can decide the direction of injection of the metal into the mold.

So let's look at the results obtained here by molding in the 3 different directions:

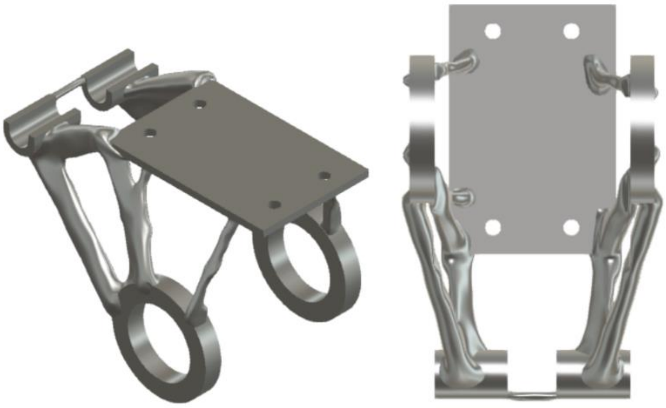

Figure 4-5 Die casting in the vertical direction

Figure 4-6 Die casting in the lateral direction (=direction of the ring axis)

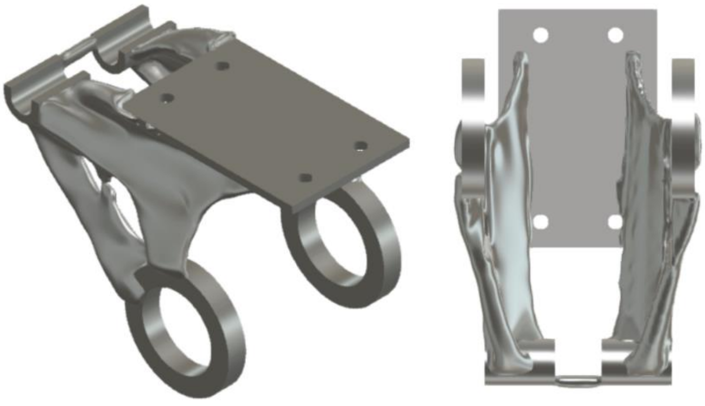

Figure 4-7 Dis casting in the longitudinal direction

We can observe that the parts are each time relatively symmetrical according to their direction of injection and that they all have approximately the same mass (respectively 37g, 46g and 47g).

4.3 INFLUENCE OF THE APPLICATION OF THE CONSTRAINTS

The final design is strongly influenced by the location of the constraints. So, let's see here an example of a different final design depending on the applied constraints.

To simplify the observations, we have decided to observe the effect only by playing on the fixed constraints of the inner faces of the rings.

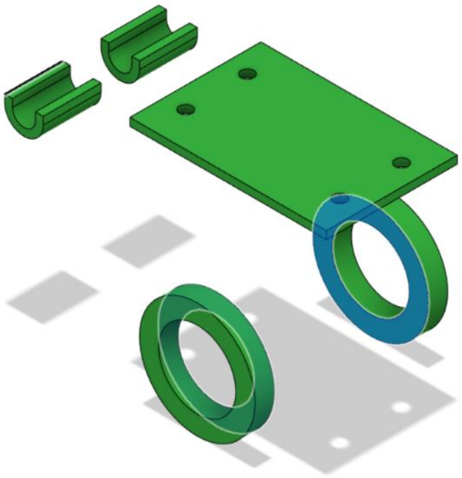

Figure 4-8 The 2 faces on which we apply constraints

As a reminder, here is what we get in the case where we constrain both sides simultaneously:

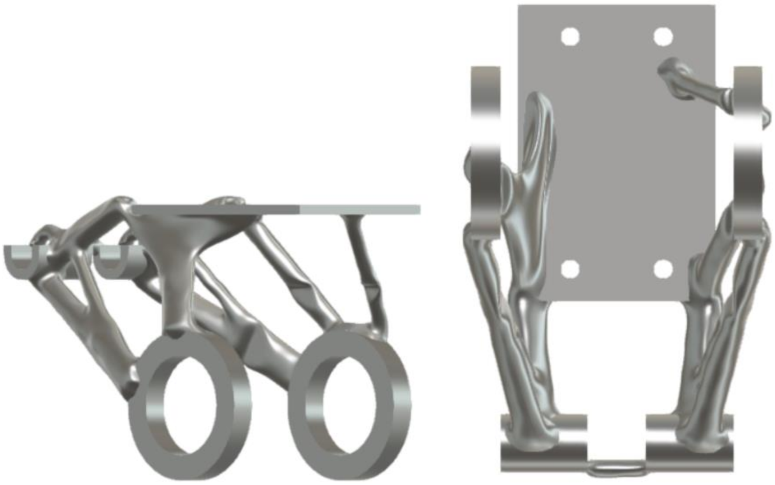

Figure 4-9 Design obtained when the constraints were applied symmetrically

In the case where we constrain only the inner face of the right ring, this is what it looks like:

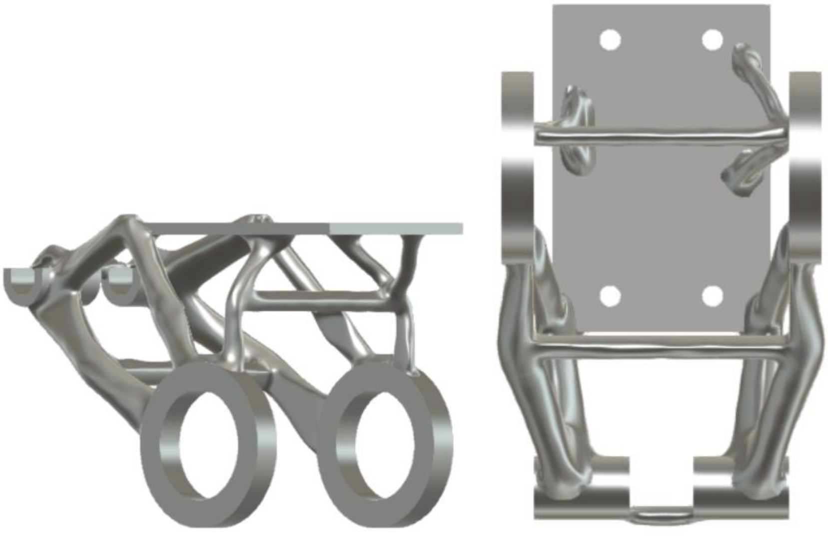

Figure 4-10 Design obtained when one constraint is applied on the inner face of the right wing

We can observe the appearance of transverse structures over the entire width. This can be explained by the asymmetry of the stresses, which forces the structure to find a way to distribute the mechanical forces so as to be able to resist the load case.

5 CONCLUSIONS

5.1 DISCUSSIONS OF THE RESULTS

After observing all these results, we can try to draw some conclusions about the use of the generative design function of a CAD software, in this case Fusion 360. However, as we have only worked with this program, the remarks will only concern the use of this one first. However, it is likely that most of the remarks we make to Fusion 360 will apply to most programs.

5.1.1 Limitations et deficiencies

First of all, the big negative point of this program is the lack of transparency of the company regarding the theory they apply. Since this is a company whose goal is to develop and sell its own programs, it is quite normal that they do not share all the details of their software development. However, here we are at the opposite end of the spectrum, where we have very little information about how the algorithms work. We therefore have to work a bit "by instinct", and then trust the program to give us optimal results.

Another disappointing aspect is the determinism of optimization systems. It is obvious that we are looking for the best solution, and therefore if the program gave us several it would mean that they would probably not all be optimal. However, it would be useful to be able to work with this degree of optimization, to perhaps have access to a larger number of different solutions. This could be useful, for example, if the user wants several examples of shapes to make an aesthetic choice.

Even if the first design using such a system does not require years of professional experience in mechanical design, it is nevertheless necessary to have well acquired basic mechanical concepts. Since the results are so sensitive to the definition of stresses, forces, etc., it is essential to have skills in theoretical mechanics in order to use the system in the right way. In our case, a lot of time was used to determine the most accurate way to describe the stresses and loads of our situation. Thus, mechanical design done with this kind of tool does not necessarily require a very experienced user in mechanical design, but rather a user who has a good understanding of the mechanical situation of the object to be modeled, as well as knowing how to identify the different constraints, loads, and limits of the situation.

Another noticeable limitation is the need for the user to edit the models of the solutions before they can be manufactured. Contrary to the promise made by most of these generative design software, the resulting solutions still all require modifications before they can be sent to production. This is undoubtedly part of the advances that will be made in the future, but it is nonetheless a disappointment that we have observed.

Finally, the biggest limitation of these programs today is that we can only model one part at a time. It is indeed impossible to model a whole assembly composed of several parts, even if it is sometimes necessary. In our case, this led to our final part design having to rethink the entire prosthesis assembly diagram if we wanted to incorporate our solution into this project. There are many situations where more than one part is needed, and it would be very interesting for these programs to be able to incorporate this feature in the future.

5.1.2 Benefits and prospects

Obviously, the use of these design methods does not have only limitations. In particular, the fact that despite all these limitations, we have arrived at a proposed solution that would save the structure a little more than 40% of its mass, which is far from negligible. And this, for a rather similar price. In certain fields where every gain in mass is sought at all costs, there is no doubt that this type of method will be highly appreciated. We can think in particular of the space sector, where each kilogram less represents tens, even hundreds of thousands of euros.

Another positive point is the fact that the user does not need to have special skills in finite element analysis methods or to be a specialist in the use of materials. Even if some mechanical skills are still required for a correct determination of the input parameters, it is perhaps not necessary to have as much experience as before to design an optimized part.

This may not be directly related to generative design itself, but the fact that these systems typically use cloud computing can be very convenient at the organizational level. Indeed, it is then possible to run several optimization simulations at the same time, and to save a considerable amount of time on these simulation times.

In the future, we can hope that these systems will improve by using the powers of artificial intelligence. In particular with regard to the "ready-to-go" character of the final parts, which would then no longer require reworking before being produced.

Another point of improvement that will undoubtedly take shape is a more accurate estimation of the production cost of designs. Currently, a very rough estimate is given, based on figures given by a single US prototyping company [19]. A practical feature would be for the software to be in direct contact with companies, and we could then directly get a customized quote for the production of our part.

5.2 CONTRIBUTIONS OF THIS MASTER THESIS

The writing of this master thesis was above all the occasion for me to take in hand a new technology, and to learn how to put it into practice on a real subject of study. Especially since there is a strong chance that this kind of technology will be used more and more in the future. Indeed, given the current trend, we can expect more and more engineering processes to be automated.

This work allows us to reflect on how engineers will have to rethink their way of working, even in a field as old and coded as mechanical design. It is also an opportunity to question our work methodologies, and to challenge them with new methodologies that appear in order to keep only the best of each way.

It was however quite frustrating not to have access to a lot of theory about the exact functioning of the software optimization algorithms. It is obvious that even if we had access to all this information, deconstructing and analyzing it would undoubtedly be very complicated. Nevertheless, here we found ourselves in the opposite situation, where we had almost no information about how the intelligence of the software worked, and where we had to try to understand this "black box" according to the results it gave us.

However, in spite of all this, we were able to make some observations that might merit further research. In particular, real experimental tests of these shapes obtained by generative design, but also to quantify and comment on the extent to which it is necessary to modify by hand the final solutions so that they can be sent to production while satisfying the initial objectives.

In addition, this work is also a good introduction to the subject of generative design, and anyone who wants to study this subject in the future will be able to start with a head start. They will already have an idea of what they can expect when using such software, and what performance and limitations they are likely to encounter.

This kind of technology will probably be inevitable in the future, given the race for constant improvement. Thus, this work can in the future also serve as a temporal witness about how we perceive the subject today in 2021, and compare it with the vision we will have in the future.

5.3 PERSONAL REFLECTIONS

Generative design seems to be a logical extension of engineering evolution. We get better results, in a shorter time. It remains for these methods to integrate in a much more direct way the different tests to be carried out for validation tests. Perhaps if the tests were automatically chosen according to the nature of the object to be designed as well as according to the definition of the various objectives and constraints, this could bring an enormous added value to the whole production process of a part.

After discussions with several people working in the industry, it appeared that generative design methods still need some improvements before convincing. As the cost of production is often a very important element in the decision making process, other criteria remain a priority in the adoption of this type of technology by the industry. In particular, the reliability of the part. When I spoke to engineers in the industry about these technologies, they did not seem to be willing to risk losing design control for the sake of a material gain, no matter how significant. In other words, the advantages that all these methods currently offer are not yet sufficient to decide to switch to a new operating model. Changing the entire organization model of a company requires a lot of time, money and energy to implement, which is why it is necessary that generative design methods offer significantly more advantages than the methods currently used. It is therefore necessary that the methods evolve and become more refined so that they begin to interest the industrial world.

Moreover, today's industry is also looking for more environmentally friendly manufacturing methods, whether it be through the choice of recyclable materials, or by using less energy consuming methods. If generative design could give the environmental cost of manufacturing the part according to the manufacturing method, the material used, ..., it would be an additional positive point for these methods.

It seems quite natural that we are moving towards the automation of this kind of processes, especially if they allow us to obtain better results more quickly.

In a way, this fits in with the logic of Industry 4.0 as we understand it today, according to which all means of production will be optimally connected, and where machines will work in collaboration with humans.

However, all these remarks and comments reflect my vision of things through my perception as a young engineer just finishing my studies. The only experience I have of mechanical design in industry is the one I have been told in my courses and in various discussions. My vision misses some essential elements in the industrial world, but I have not yet been sensitized to them. However, this work will have allowed me to start thinking about the way mechanical design is organized in general, and this will bring me a greater open-mindedness on this domain in my future professional life.

To conclude, I would like to specify that all these remarks and comments reflect my own vision of things, through my perception of a young engineer just finishing his university studies. The only experience I have of mechanical design in the industry is the one I have been told in my courses and in various discussions. My vision will then surely miss elements that are essential in the industrial world, but to which I have not yet been made aware. However, this work will have allowed me to start thinking about the way mechanical design is organized in general, and it has definitely brought me a greater open-mindedness on this professional field.

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UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**