Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Research of Additive Manufacturing Application for Complex Aircraft Components

Master's Final Degree Project

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Assoc. Prof. dr. Neringa Keršienė

Supervisor

Kaunas, 2021

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Aeronautical Engineering (6211EX024)

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Faculty of Mechanical Engineering and Design

Study programme: Aeronautical Engineering (6211EX024)

Task of the Master's Final Degree Project

Given to the student: Martynas Rutkauskas

1. Title of the Project:

Research of Additive Manufacturing Application for Complex Aircraft Components

Adityvinės gamybos pritaikymo sudėtingiems orlaivio komponentams tyrimas

2. Aim of the Project:

Offer approach of additive manufacturing for LAK glider‘s flap part

3. Tasks of the Project:

1. Carry out general analysis of 3D printing, applications in aviation and topological analysis approach; 2. Compile tests of additively manufactured specimens, calculate and check for the existance of isotropic properties; 3. Compose LAK glider‘s 3D drawing of a part, investigate the possibilities of topological optimization; 4. Complete a set of finite element analysis for both original and topologically optimized parts; 5. Manufacture chosen part, conduct prototype approval tests and offer final approach with suggestions and overview.

4. Structure of the Text Part:

Literature review; Research section; Final overview and conclusions.

5. Consultants of the Project:

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Supervisor of the Final Degree Project	Assoc. Prof. dr. Neringa Keršienė 2020-02-04
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Study field and area (study field group): Aeronautical Engineering (E14), Engineering Science.

Keywords: glider, additive manufacturing, aviation, topological optimization, isotropy.

Kaunas, 2021. 65 pages.

Summary

Final master‘s project presents the analysis done on additive manufacturing, isotropic properties and topology optimization while maintaining focus on LAK mini glider‘s flap part.

The purpose of final degree project: offer approach of additive manufacturing for LAK glider‘s flap part. Tasks set to achieve the goal of the work:

Carry out general analysis of 3D printing, applications in aviation and topological analysis approach; Compile tests of additively manufactured specimens, calculate and check for the existance of isotropic properties; Compose LAK glider‘s 3D drawing of a part, investigate the possibilities of topological optimization; Complete a set of finite element analysis for both original part and topologically optimized parts; Manufacture chosen part, conduct prototype approval tests and offer final approach with suggestions and overview.

Master‘s thesis consists of literature analysis and review, research section and final overview with conclusions.

Literature analysis part briefly discuss additive manufacturing as a whole, including environmental and economical impacts. Further on topological analysis is overviewed and application of additive maufacturing in aviation sector. Research section begins with explanation of what will be done and what part is on the focus. Tensile testing is conducted, results prove the existance of isotropy and fit standard requirements. Research section continues with multiple topological optimization alternatives and their finite element analyses. Results show that boundary conditions are preserved, moreover topology optimization with a factor of safety 2.5 is chosen for manufacturing. The section is finished with final topological optimization manufactured with additive manufacturing method as prototype and testing to approve the design. Prototype approval testing shows, that final part fits the requirements and could be used in real life application. Final overview and conclusion is given according to the whole project.

Rutkauskas, Martynas. Adityvinės gamybos pritaikymo sudėtingiems orlaivio komponentams tyrimas. Magistro baigiamasis projektas / vadovė doc. dr. Neringa Keršienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Aeronautikos inžinerija (E14), Inžinerijos mokslai.

Reikšminiai žodžiai: sklandytuvas, adityvinė gamyba, aviacija, topologinis optimizavimas, izotropija.

Kaunas, 2021. 65 p.

Santrauka

Baigiamajame magistro projekte pateikiama adityvinės gamybos metodo, izotropinių savybių bei topologijos optimizavimo analizė išlaikant pagrindinį dėmesį į LAK mini sklandytuvo vairų sistemos detalę.

Baigiamojo darbo tikslas: pasiūlyti LAK sklandytuvo vairų sistemos detalės gamybą pasitelkiant adityvinės gamybos metodą. Užduotys nustatytos darbo tikslui pasiekti:

Atlikti 3D spausdinimo, aviacijos ir topologijos optimizavimo bendrinę analizę; Sudaryti adityviškai pagamintų tempimo bandinių tyrimus, atlikti apskaičiavimus, ištriti izotropines savybes; Sukomponuoti LAK sklandytuvo 3D brėžinį, ištirti topologinio optimizavimo galimybes; Atlikti baigtinių elementų analizes originaliai ir topologiškai optimizuotom detalėm, išanalizuoti rezultatus; Pagaminti pasirinkto optimizavimo detalę, atlikti prototipo patvirtinimo bandymus, pateikti galutinę apžvalgą.

Magistro darbą sudaro literatūros analizė ir apžvalga, tyrimų skyrius ir galutinė apžvalga su išvadomis.

Literatūros analizės dalyje trumpai aptariama visa adityvinė gamyba taip pat apžvelgiant poveikį aplinkai ir ekonomikai. Toliau apžvelgiama topologinė analizė ir adityvinės gamybos pritaikymas aviacijos sektoriuje. Tyrimų skyrius pradedamas paaiškinimais apie tai kas bus padaryta ir kokia pasirinktos detalės paskirtis. Atliekami tempimo bandymai, nustatomas detalių izotropiškumas bei standartus tenkinantys stiprumai. Tyrimų skyrius toliau tęsiamas su keliomis topologinio optimizavimo alternatyvomis ir jų baigtinių elementų analizėmis. Gaunami rezultatai tenkina nustatytas topologinės optimizacijos ribas bei optimizacija su 2.5 saugumo faktoriumi parenkama gamybai. Skyrius baigiamas pasirinkto optimizavimo detalės gamyba pasitelkiant adityvinę gamybą ir prototipo patvirtinimo eksperimentais. Eksperimentuose gaunama išvada, kad detalė atitinka reikalavimus ir gali būti naudojama. Pateikiama galutinė apžvalga ir išvada atsižvelgiant į viso projekto užduotį.

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Abbreviations:

TO – topological optimization;

CAD – computer aided design;

AM – additive manufacturing;

SM – substractive manufacturing;

SI – systeme international;

FDM – fused deposition modeling;

SLS – slective laser sintering;

SLA – stereolithography;

DMLS – direct metal laser sintering;

SLM – selective laser melting;

HIP – hot isotactic pressing;

FEM / FEA – finite element method / finite element analysis;

OEM – original equipment manufacturer;

MRO – maintenance, repair and operations;

UTS – ultimate tensile strength;

YTS – yield tensile strength;

FOS – factor of safety;

SIMP – solid isotropic material with penalization method.

Introduction

Additive manufacturing is one of the easiest ways to rapidly produce new prototypes and parts. In the past it was called rapid prototyping, but more commonly it is named 3D printing. The term rapid prototyping lost its meaning because additive manufacturing is turning to manufacturing full detail, low-end to high-end final parts rather than sticking with constant prototype production. Furthermore, the term „additive“ is being used because a material is added rather than lessened [21]. This type of manufacturing is being used in many fields: automotive, medical, science, aeronautical and many more. 3D printing itself, as any other manufacturing type, has many advantages and disadvantages, therefore production should be chosen wisely and parts for 3D printing should be adapted for specific manufacturing type, in this case – additive manufacturing. To conclude, „Additive Manufacturing is defined by a range of technologies that are capable of translating virtual solid model data into physical models in a quick and easy process.“[1]

The aviation sector is the place, where additive manufacturing could probably change the whole industry. For general aviation, weight reduction always plays one of the most important parts, as less weight mean less fuel usage and further meaning increased profitability. For military aviation, additive manufacturing may help not only by weight reduction but by having the possibility to manufacture needed parts anywhere in the world and therefore increasing chance that once downed airplane could get back into fight. Moreover, all around aviation, quality control is very strict, and by reducing the number of parts or subassemblies by manufacturing these chosen parts with additive manufacturing the job is done easier and with more precision. Finally, with 3D printing, new huge possibilities of geometrical optimization come along. The biggest possible optimization for a part is topological optimization, where the whole topology of a part is changed. Topological optimization removes the material in a part, where it is unnecesary and leaves it where it is absolutely neccesary, therefore making natural looking geometry, that is nearly impossible to be manufactured in any other way than additive manufacturing. These reasons and many more make additive manufacturing a very viable choice for the manufacturing.

The purpose of final degree project: offer approach of additive manufacturing for LAK glider‘s flap part. Tasks set to achieve the goal of the work:

1. Carry out general analysis of 3D printing, applications in aviation and topological analysis approach;
2. Perform tests of additively manufactured specimens, calculate and check if printed specimens have isotropic properties;
3. Investigate given LAK glider‘s flap system‘s part, examine the possibilities of topological optimization;
4. Complete a set of finite element analysis for both original part and topologically optimized parts;
5. Manufacture topologically optimized part, conduct prototype approval tests and offer final approach with suggestions and overview.

1. Literature review

There are many different additive manufacturing processes to begin with. Each of these processes have differnet materials available and different working principles. For this work, only a couple of processes are chosen for in-depth analysis. The rest of the processes are going to be discussed briefly.

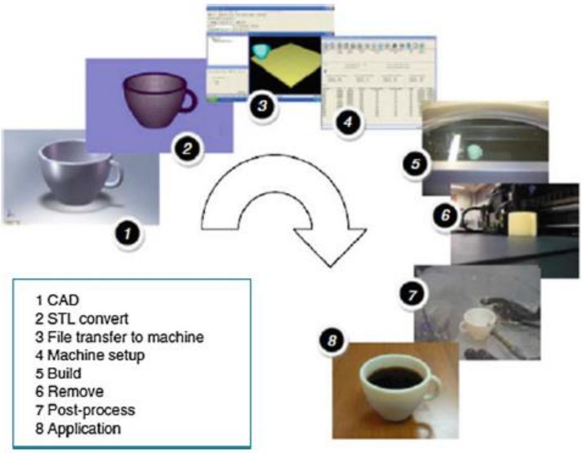


Fig. 1.1 Overall process flow of additive manufacturing [1]

Typically additive manufacturing process cycle is the same for each different principle [1]:

1. CAD creation: one of many softwares should be chosen to create a computer aided design model. The model should be created in accordance to specific printers‘ optimal dimensions and allowances;
2. Generating an STL file: additive manufacturing machines mainly use files with STL format. Such format is becoming a de facto standard for this manufacturing type. STL files show all surfaces, in a meshed triangle cloud;
3. File preparation in 3D printer: an STL file is exported to the printer and further manipulation happens in printers‘ software (orientation, position, sizing);
4. 3D printer setup: the machine should be set up before the beginning of actual manufacturing. Material addition, determining needed parameters for temperature, energy, timing, etc.;
5. Actual building: most of the time no human labour time is needed for this step, because the actual building is an automized process. Some monitoring may be needed to check if the material is being depleted or to fix other encountered problems;
6. Removal of the parts: when building process is finished, parts should be removed from the machine. This step is different for each unique machine;
7. Post-processing: during this step, parts are cleaned in any required way. For some processes it may be cleaning of supports, hardening, cleaning of materials, depowdering, etc.
8. Appliance: parts may be used for their actual purpose, or may be sent for the next step treatment, such as priming, painting or any other. All of other treatments are not a part of additive manufacturing process, therefore are not listed here.

All the steps are listed in Figure 1.1.

1.1. Different types of additive manufacturing

The overall additive manufacturing is divided into 7 different principles by ASTM F42 – Additive Manufacturing standard. Each different principle possess its own material, way to use said material, the specific work type and overall advantages and disadvantages. Considering all the differences, the principle which is the most beneficial for the specific aim should be chosen. The most common principles of additive manufacturing are listed in Figure 1.2.

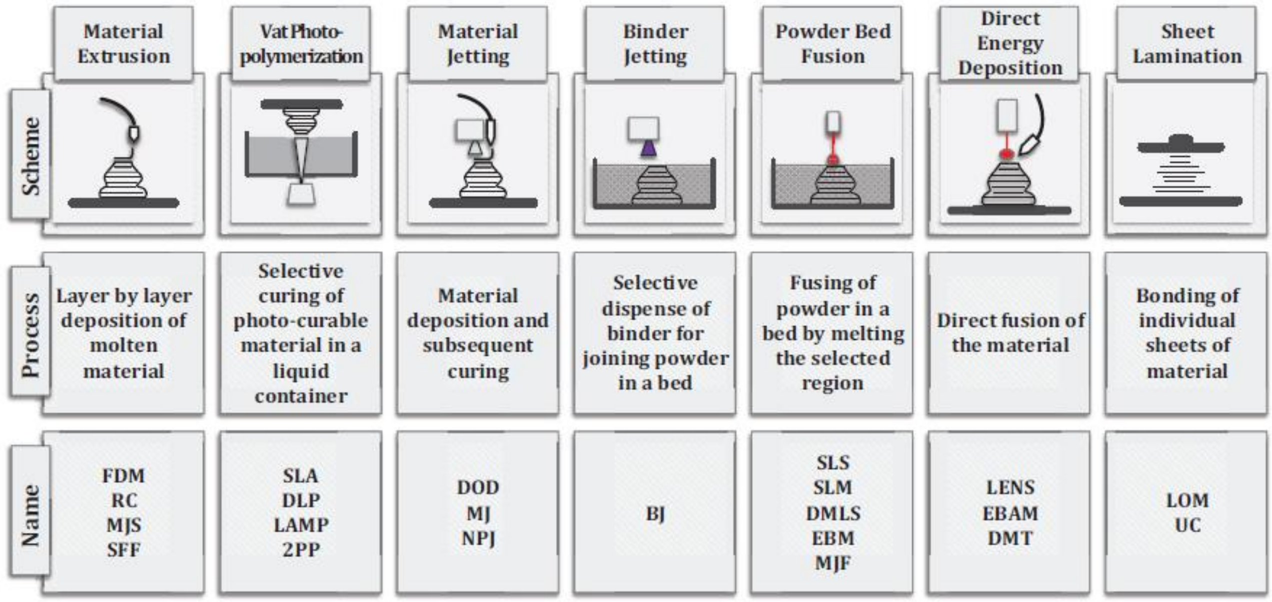


Fig. 1.2. 7 different additive manufacturing principles [35]

Nevertheless, not all the processes, that are listed in figure 1.2 are still being used, because there are many technologies that use similar principles, but have different process names and, therefore, are not on this list. The list of all different additive manufacturing processes that are still existing and being used would be exhausting and does not provide needed information to examine thesis further. There are many yearly exhibitions that gather engineers from all around the globe and new technologies are introduced rapidly – the future of additive manufacturing is constantly changing. The speed of new cutting edge design introductions is always increasing.

The popularity of different processes in the years 2017-2018 is shown in figure 1.3, the information is derived from the powerhouses such as Forbes and Sculpteo. As listed in the figure, FDM popularity is on the first place, mostly because of a low price for the machine itself. Moreover, most of the time the usage of FDM is uncomplicated and most of encountered errors may be fixed without external help [14]. SLS technology is on the second place because of the versatility of available material and because of high detail finished parts. SLA is on the third place. In the same sense as SLS, SLA has many different materials to choose from with highly different mechanical properties. This is highly appealing factor for the customers.

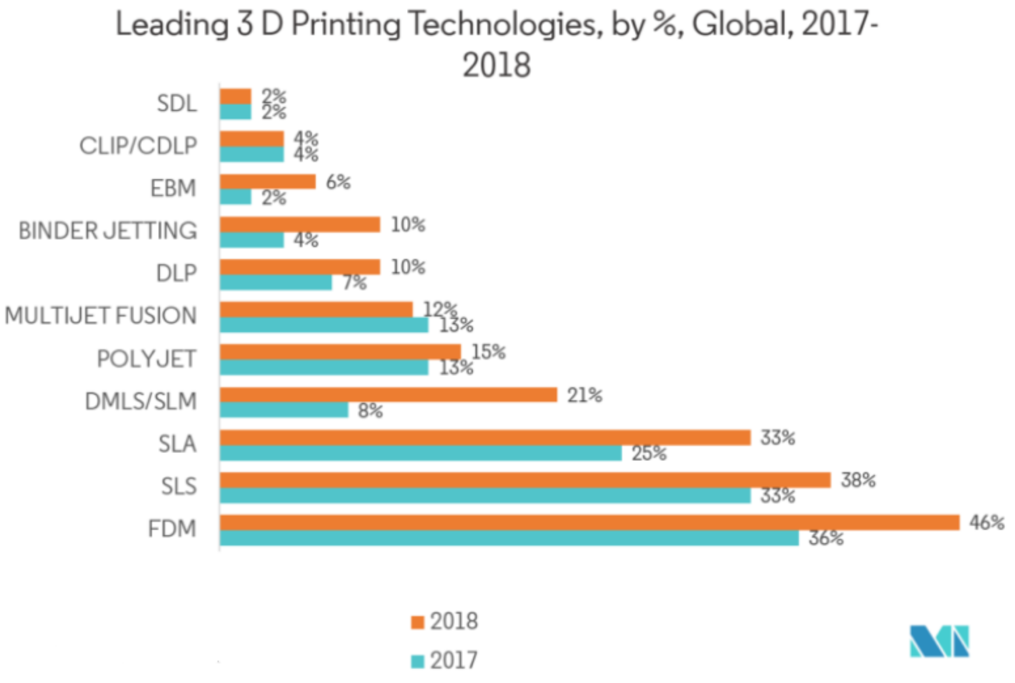


Fig. 1.3. 3D printing technologies popularity in the year 2017-2018 [37]

Because of the interest in high-detail and high-quality parts, only some metal additive manufacturing technologies, based on powder bed, are going to be discussed thoroughly. In addition to earlier statements, powder bed metal AM services are available in Lithuania and for further extent, test parts are wanted.

1.2. SLS (Selective Laser Sintering) or DMLS (Direct Metal Laser Sintering) technologies

As of current knowledge, only SLS/DMLS and SLM manufacturing is available as a service in Lithuania, therefore these technologies will be discussed further.

SLS and DMLS technologies are considered to be in the same technological field, as in different studies abbreviations are mixed. SLS and DMLS technologies refer to the same family tree of the manufacturer EOS GmbH [19]. The simplified working principle of these technologies is based on powder being sintered by laser [1, 2, 7, 13]. To discuss it in more depth, the process should be divided into multiple steps [1, 2, 20]:

1. A steel platform is pre-heated;
2. To provent oxidation, and remove excess air, chamber is filled with inert gas. Remaining oxygen is kept at 0.1%;
3. The desired material is layered on the top of the printing bed with coater;
4. Laser is sintering areas, where part should be located therefore creating actual volumetric part;
5. Building platform is lowered by one layer, and process repeats from 2nd step;
6. Once building is done, parts are cooled down and removed. The parts are ready for post-processing.

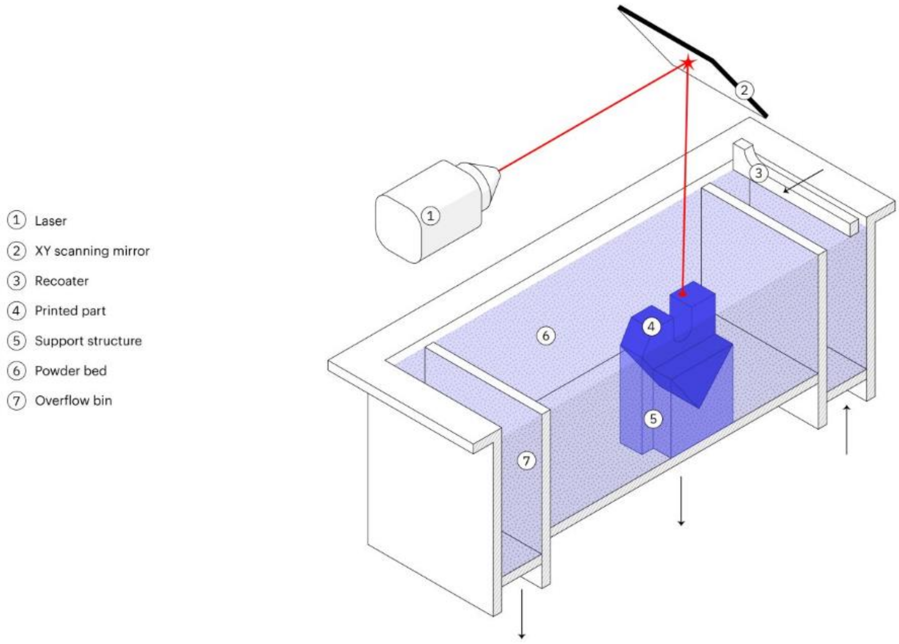


Fig. 1.4. DMLS printer overview [38]

The overview of SLS / DMLS printer machines is shown in figure 1.4, derived from 3D printing powerhouse – 3DHUBS. Regarding point 5 in figure 1.4, it is seen that DMLS requires full supporting structures, because overhang areas may curl [10, 21]. The curling, warping or any other unwanted effects happen because high-energy focused laser beam is used and such building process cause extreme temperature changes [21].

1.3. SLM (Selective Laser Melting) technology

As mentioned before, other technology of interest is SLM. The difference between earlier mentioned DMLS and SLM is quite small, as both technologies offer an almost identical process. One difference is the temperature at which the powder is melted: in SLM, powder is melted completely, therefore, the part is built by melting powder layer by layer; in DMLS however, powder is only melted partially, meaning that only the sides of the particles are welded together [13].

Furthermore, as SLM has same requirements as DMLS/SLS: heated building bed, chamber filled with inert gases, support structures, etc., there is no need to evaluate this technology furthermore [13, 23].

Materials of SLS / DMLS and SLM

The most common materials that are used in SLS / DMLS technologies [22]:

- Polymers;
- Ceramics;
- Metals;
- Composites.

The metal, that is going to be of interest for tests in further chapters is titanium alloy Ti-6Al-4V [7], therefore it is going to be inspected further here. The minimum tensile properties are listed in figure

1.5, in accordance to AMS 4999 (Titanium Alloy Laser Deposited Products, 6Al4V, Annealed) specification.

UTS, MPa *X*-direction	UTS, MPa *Y*- & *Z*-direction	YS, MPa *X*-direction	YS, MPa *Y*- & *Z*-direction	% Elongation
896	841	800	745	4

Fig. 1.5. Minimal tensile properties of Ti-6Al-4V [24]

Properties, reached after printing parts in EOS M280 machine are listed in figure 1.6.

	Typical wrought	M280, HIP + solution heat treat	
Orientation	n/a	*X-Y*	*Z*
YS, MPa	828	887	946
UTS, MPa	897	997	1010
Elongation	15%	11.4	13.9

Fig. 1.6. Properties of Ti-6Al-4V alloy reached by EOS M280 [7]

Values listed in figures 1.5 and 1.6 can only be reched by processing parts thermally. The HIP as stated in figure 1.6, is hot isotactic pressing, and may be revieved as the cycle with nominally 100 MPa and 926 °C for the duration of 2 to 4 hours, and after that, the part should be cooled in a furnace in the temperature below 427 °C. Other similar process is the thermal anneal treatment: the part should be annealed at 913 °C for the duration of 2 to 4 hours, after that part should be cooled in the same way as for the HIP cycle [7, 11]. These post-processes change microstructural features of the produced parts in such manner, that residual stresses are relieved and defects are minimalized. Nonetheless, the way that part was oriented in building platform, has an impact on the final result [11].

The most commonly used material for SLM is metal. As the process is very similar to DMLS, there is no need to evaluate this further. According to many different studies, the properties of Ti6Al4V, manufactured by SLM machine are comparably the same to the ones given in figure 1.6 [25]. Post-processing of these different technologies once again is the same [13].

1.4. Additive manufacturing in real world

The additive manufacturing has a huge impact on many fields as it is highly automized technology. The way that this modern technology is used and integrated most recently justifies the reason behind additive manufacturing being a big part of latest industrial revolution, called Industry 4.0 [17, 35].

Furthermore, additive manufacturing offers many benefits over the conventional manufacturing:

- **Efficiency.** 3D printing allows ordinary customers to fix print their own parts and fix any household item [17].
- **Resource and material efficiency.** Additive manufacturing does not require additional resources, as cooling, jigs and so on. Also, the additive way of manufacturing parts results in little loss of material when compared to substractive manufacturing [5].

- **Flexibility.** Complex parts are able to be made out of one piece, improving the level of complexity. Also, small batch production is cheap and therefore does not require huge setups [5, 6, 8, 12].

Further list of advantages over traditional manufacturing can be seen in figure 1.7.

Areas of Application	Advantages
Rapid Prototyping	Reduce time to market by accelerating prototyping Reduce the cost involved in product development Making companies more efficient and competitive at innovation
Production of Spare Parts	Reduce repair times Reduce labor cost Avoid costly warehousing
Small Volume Manufacturing	Small batches can be produced cost-efficiently Eliminate the investment in tooling
Customized Unique Items	Enable mass customization at low cost Quick production of exact and customized replacement parts on site Eliminate penalty for redesign
Very Complex Work Pieces	Produce very complex work pieces at low cost
Machine Tool Manufacturing	Reduce labor cost Avoid costly warehousing Enables mass customization at low cost
Rapid Manufacturing	Directly manufacturing finished components Relatively inexpensive production of small numbers of parts
Component Manufacturing	Enable mass customization at low cost Improve quality Shorten supply chain Reduce the cost involved in development Help eliminate excess parts
On Site and On-Demand Manufacturing of Customized Replacement Parts	Eliminate storage and transportation costs Save money by preventing downtimes Reduces repair costs considerably Shorten supply chain The need for large inventory is reduced Allow product lifecycle leverage
Rapid Repair	Significant reduction in repair time Opportunity to modify repaired components to the latest design

Fig. 1.7. Additive manufacturing advantages in reference to conventional manufacturing [17]

Of course, with advantages there are always some sort of disadvantages. The main drawbacks are in case of mass production, because [5, 6]:

- **Surface.** As listed in section before, parts manufactured by AM, have rather rougher surface than of those, manufactured conventionally;
- **Price.** Currently the price of AM machines is rather big and has comparably big influence on the Industry 4.0 revolution;
- **Limitations of size.** Large sized objects are not available for production with AM, because of lack of build batch size and because of degradation of material strength.

According to scientists and manufacturers, AM may never fully change the conventional manufacturing [17].

1.5. Economical, environmental and social effects

Furhter development of additive manufacturing machines rapidly changes the way the parts are being produced. The environmental influence is felt from the aspects, such as material [8]. As it is known, parts production with additive manufacturing leads to less material wasted and used by the production process [5, 8]. Furthermore, high recycle rates lead to further positive environmental side [31, 32]. In some cases, some AM technologies have proven to be more environmentally friendly by 70% than conventional manufacturing [5, 8]. Nevertheless, even though AM has clear advantage over other manufacturing types in the field of environmental impact, the need of energy is rather shocking [5], as seen in figure 1.8.

Process	Energy use (kg CO_2 per component)	Water usage (kg per component)	Landfill waste (kg)	Virgin material use (kg per component)	Hazardous waste (kg per component)
Casting	1.9	0	N/A	2	N/A
Flexline machining	2.4	0.08	1.512 (waste can be recycled)	2 (from casting)	0.0064ii
Clean machining	N/a	0.15	N/A	N/A	N/A
AM	13.15	0	0	0.65	0

Fig. 1.8. Environmental impact of different manufacturing types [5]

The field of energy consumption might be the only factor in the means of environment, where conventional manufacturing has a considerably better outcome. As found out in the studies, most energy is consumed during heat-up and cooldown phases of AM building, and the production phase itself was not energy thirsty phase at all, therefore further studies should be done [5].

The social effect, that AM has, can be examined in the simpliest aspect, as when in every industrial revolution many jobs were lost, because of high automatization. In regard to Industry 4.0, the AM may not be preffered choice for mass productions, therefore the massive loss of jobs may be reverted. In more direct stage of diversification, the labor force may be changed to white collar jobs rather than blue collar jobs. Finally, students of any sort may start maker movements to start manufacturing for themselves, as additive manufacturing is highly approachable [35]. Furthermore, as mentioned before, new technologies require new researchers and new manufacturers, therefore new jobs would be introduced [3]. The price of part production with labor cost in mind can be seen in figure 1.9.

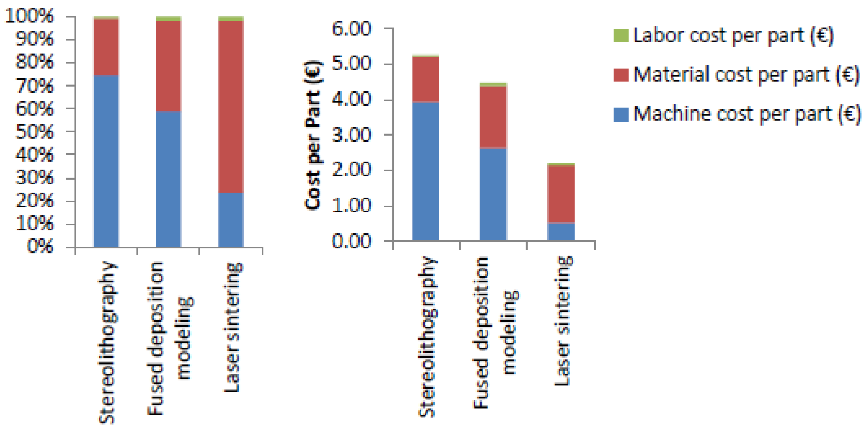


Fig. 1.9. The cost of specific part [4]

One of conomical sides of additive manufacturing may be explained through the understanding of supply chain. The overall supply chain is the complete process, starting from material distributor, to the shelves of the store. In case of additive manufacturing supply chain, there are couple of possibilities [5]:

1. The redesign of a product to reach a reduction of different components;
2. The distributed manufacturing (products are manufactured near the customer).

These possibilities completely reduce the need of transportation, warehousing, etc. Thus meaning massive improvement in economical aspect [5, 15]. The supply chain differences between conventional and additive manufacturing may be seen in figure 1.10.

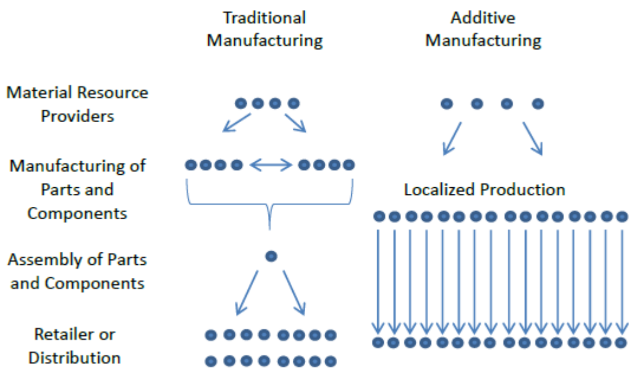


Fig. 1.10. Supply chain differences between traditional and additive manufacturing [4]

Moreover, the highly dependant factor on the price of the part is complexity. Additive manufacturing allows easy production of complex and joined parts, therefore the cost reduction is justified [3, 15, 16, 17, 35]. There are studies for overall diversification of part complexity, customization and mass production in additive manufacturing [16], therefore to understand it more clearly, figure 1.11 shows the relevance between complexity and cost of a part.

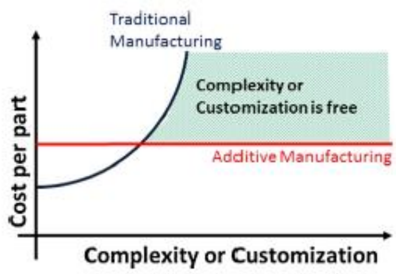


Fig. 1.11. Cost of part in relevance to complexity. Complexity and/or customization is free with AM [16]

The economical side of additive manufacturing may be discussed in very broad sense, and many studies have been done over this field, therefore in this work only abstract information is given. For general understanding, the part has to be optimized for additive manufacturing to reach cost efficient design and therefore to lower overall price of manufacturing for AM [4, 9].

1.6. Reliability of additive manufacturing

As with any other system, the reliability of manufacturing principle or system is very important and has high impact to the designer, as higher reliability factor is always wanted. Furthermore, as with other manufacturing systems, the reliability may only be calculated with serial system instead of parallel system and that may result in very low level reliability level, as each additional factor reduces final result [69]. Additive manufacturing contains a lot of different factors, such as the lifetime of the laser or other inner systems of 3D printer, material quality, printer software settings, human error, possible support structures, slicing software settings, post processing, etc. If all of these factors had a reliability of 99%, the final resulting reliability could be approximatelly 90%, but if factors had a reliability of 95%, then the final reliability could be 60% or even less and this is highly unwanted. Formulas for serial calculation (1) of reliability and parallel calculation (2) of failure are given:

$$R = R_1 \cdot R_2 \cdot R_3 \cdot \ldots \cdot R_n = \prod R_j \quad (1)$$

$$F(t) = F_1(t) \cdot F_2(t) \cdot F_3(t) \cdot \ldots \cdot F_n(t) = \prod F_j(t) \quad (2)$$

If: R – reliability factor;

F – failure factor.

The final reliability could be greatly increased if some factors were considered from different point of view, such as instead of reusing old material, new material would always be used, or software and hardware reliability could be increased by having constant and periodic maintenances of manufacturing machine and etc. This shows that different systems have different reliabilities and furthermore different manufacturers have different inner politics of maintaining needed level of reliability.

As for DMLS printing, some studies are done and they cover small area of interest therefore to understand the reliability up to wanted level, testing should be conducted primarily for research of reliability factors and as this would be out of scope of this paperwork, only literature is analyzed. Different studies have different outcomes and therefore resulting reliabilities may seem different. Furthermore, it is studied that different mechanical properties of manufactured part have different reliability factors and these may vary up to 12% from theoretical calculations and between each manufacturing iteration [70]. Also, overall process of DMLS additive manufacturing is tested in studies using compressive specimens and compressive data and it is found out that DMLS has a reliability of 90% [71]. Moreover, when reliabilty is compared between the part that was manufactured using AM and the part that was manufactured by using weldment joint it was found out that welded part has higher reliability in higher number of cycles, while AM part had higher reliability in lower number of cycles [72]. This means that full inspections of a part should be taken on earlier notice, but as it is unknown if specimen had any post-processing to smoothen the surface, the results of the study could be different. Finally, other studies show even higher reliability of metal additive manufacturing and even higher chance of reproductability [73], the final resulting reliability should be tested before constituting any facts.

1.7. Application of and optimization for additive manufacturing

The overall application of additive manufacturing is completely dependant on the field of need and on the design of the part itself. Currently there are many industries that benefit from additive manufacturing, main factors being easy prototyping, weight reduction, complex component manufacturing, unique designs that are only able to be produced by additive manufacturing [12, 15, 17, 18]. Even application of AM in space is a matter of discussion, as printing out of moondust is researched to build colonies in space, and transportation needs from earth would be reduced [35]. Many industries, as mentioned before, consist of such fields as food and fashion, as edible filaments are being studied and flexible garments are also of discussion matter [17, 35]. The wide possible applications of additive manufacturing are unimaginable.

There are some applications, that require higher level of detail or need to accelerate production process, thus leading to introduction of hybrid manufacturing. Hybrid manufacturing is the combined process of additive manufacturing and substractive manufacturing (usually milling). There are some researches over the implementation of AM and SM into one station, to reduce the overall machinery and increase work space. Usually, hybrid manufacturing is used for the need of high-grade parts, e.g. low surface roughness is needed without impacting morphology. This whole hybrid manufacturing process is still under development, but there are some examples that are continuosly used, in such fields as medical or aeronautical [35].

Furthermore, additive manufacturing allows high topological optimization of the parts. The topology optimization is the determination of material distribution throughout the part. This optimization leads to less material usage and reduced final weight of the part while maintaining same needed properties. Usually topological optimization is determined through the use of CAD softwares, that allow for finite element method (FEM) simulations [10]. The complete scheme of topological optimization can be seen in figure 1.12.

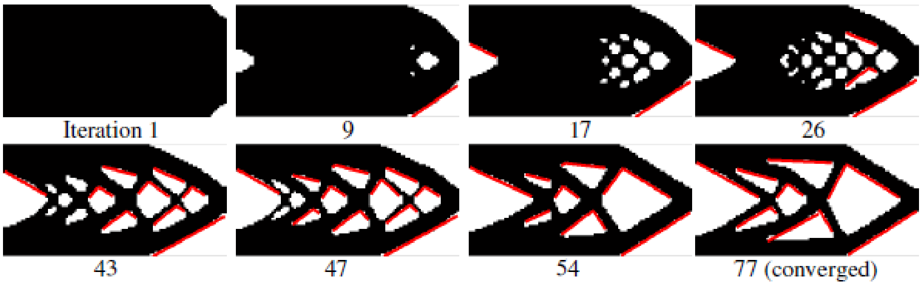


Fig. 1.12. Topological part optimization after 77 iterations [10]

The topological optimization is only available by additive manufacturing, because parts are built layer by layer, therefore inner constructions are built altogether. This is highly appealing factor for the growth of additive manufacturing as a whole. The most difficult aspect of topological optimization is the correct usage of CAD softwares, therefore experienced user must be in mind [10]. Topological optimization is researched deeper in further chapter.

1.8. Topological optimization

As it is already known, additive manufacturing works by building layer by layer, therefore in such way, creating a part. Whilist using this unique method, every single complex part, as mentioned before, is easy to manufacture, therefore different optimizations to a part are logical. The topological optimization is a process of distributing the material across desired part in a best way while following specific contsraints [26]. Overall, such optimization usually results in a part, that is nearly impossible to manufacture in any other way, furthermore increasing the potential between engineering, part design and manufacturing. Part optimization may be categorized in three different sections [27]:

1. Parametric shape optimization – parts shape may be optimized by different parameters, such as thickness, dimensions, etc. This category does not change shape of the part, as it only finds out what basic parameters would fit the best to existing shapes. Usually it works well only with shapes that are able to be parameterized, since free-formed shapes would be too dificult to calculate with this method.
2. Geometric shape optimization – this category may be introduced as the upper level of optimization, as it not only optimizes parameters, but also changes the geometrical shape of the part. Nevertheless, boundaries are set, therefore the topology of part itself is not changed.

3. Topological shape optimization – this category offers highest level of optimization, as it may change the part in any way. The topological optimization offers solutions, which may be uncomfortable for engineers themselves, as these solutions may be free-formed shapes.

The example of topological optimization is given in Figure 1.13.

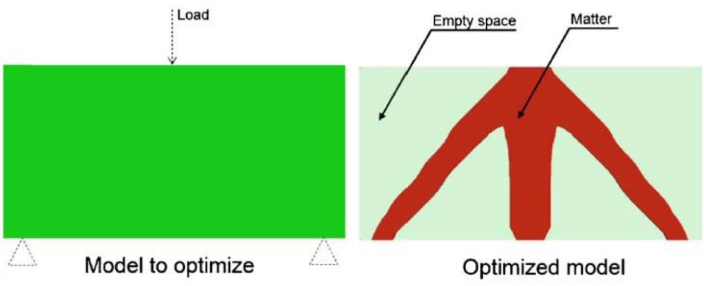


Fig. 1.13. Topological optimization example [28]

The overall workflow of topological optimization may be understood by introducing purely mathematical model. The main objective is to optimize the layout of material in given design space Ω. The idea is given in figure 1.14.

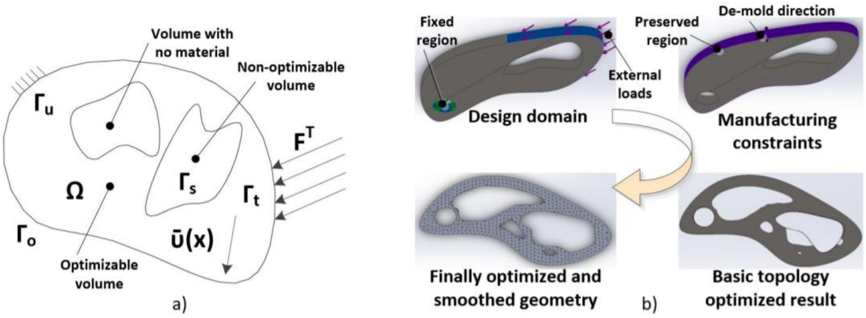


Fig. 1.14. a) General topological optimization problem; b) TO steps [48]

Generally, the problem consists of design area Ω, loads F^T and boundary Γ conditions. Boundary conditions further are composed of different parts, Γ_t, Γ_u, Γ_s, Γ_o, and other possible constraints. Forces on the surface are introduced in area Γ_t; Γ_u show support conditions; non-optimizable areas are shown by Γ_s and boundaries of the geometry are shown by Γ_o. For further layout of material, many different methods may be used, but one of the main problems is the distribution of volume by minimizing specific criterion. Most common criterion is compliance C, where density values x (that are dispersed in Ω) are used for the control of material distribution in Ω. These values x are shown in small range of 0-1, where 0 means the absence of material [48, 49]. Finally, TO can be written as Formulas (3):

$$\begin{cases} C(x) = F^T \cdot \bar{u}(x) \\ \begin{cases} \frac{V(x)}{V_0} = f \\ F = K(x) \cdot \bar{u}(x) \\ 0 \le x_{min} \le x \le 1 \end{cases} \end{cases} \quad (3)$$

If: C(*x*) – structure's compliance;

F^T – force vectors that are applied upon structure;

$\bar{u}(x)$ – global displacement vector;

K(x) – global stiffness matrix.

The second part of the Formula (3) indicate the volume constraint, as the *f* mean fractions of the volume of Ω, where optimized part should be laid out. Third part of Formula (3) is the equilibrium equation. Last part introduces the density value set. As seen from 1.14 b), TO consists of multiple stages, where first stage is the set up of geometry, constraints and outer forces. Further on, TO constraints are introduced where manufacturing options are set, so the part would be possible to manufacture after optimization with desired manufacturing technique [48, 49].

Furthermore, most common variation of topological optimization is the solid isotropic material with penalization method or SIMP method. SIMP method Formula (4) is given:

$$K_{SIMP(\rho)}=\sum_{e=1}^{N}[\rho_{min}+(1-\rho_{min})\cdot\rho_e^p]\cdot K_e \quad (4)$$

If: K_e – the element stiffness matrix;

P_{min} – the minimum relative density;

P_e – the element relative density;

p – the penalty factor;

N – the number of elements in the design domain.

SIMP method does work similarly to the overall topological optimization method as given in Formula (3). First difference is that the SIMP method is directly connected to the materials young’s modulus and density. Second difference, is that the penalization factor is implemented, which steers the result of one point either to being void or filled with material, so there would not be a chance for the probability of an intermediate result. Finally the result is given and works only for parts that contain isotropic material properties [67]. This method is used by many main softwares, such as Ansys or SolidWorks.

1.9. CAD preparation for AM

As the scope of this work is oriented to overall part preparation and optimization for additive manufacturing, the main principles behind designining and applying the said design for AM must be discussed firstly, before going in depth in wide possibilities of topological optimization. If part is not too difficult, there may not be too many differences between designing for conventional manufacturing or designing for additive manufacturing, but as every single manufacturing type has its own limitations, they should be known prior to designing. It is known, that design for conventional manufacturing may rely on many different aspects, therefore different and in some cases contraversial criterias are set. Whereas design for additive manufacturing mainly relies on manufacturing duration, raw material usage, overall cost and electricity consumption. Furthermore, all of these criterias are linked to volume, therefore while optimizing part for AM, minimization of volume is of the biggest interest [29].

There are couple speceficities, where additive manufacturing excells, they are [30, 33]:

– Complex and hierarchic parts;

– Non removable assemblies;
– Material complexity.

It has already been discussed, that every single imaginable and unimaginable object may be made by AM, therefore complexity shows how powerfull AM may be under use of experienced engineer. Wide possibilities of creating hollow, monolithic or different in any other way part while maintaining same or even increased high mechanical performances and at most times reducing the weight further proves this point [26, 34]. Non removable assemblies are also of high importance, as not only complex parts, but complex assemblies are a possibility with AM. Nonetheless, non removable assemblies require higher level of post-processing, but different processes may even print completed final part [30, 33]. In regard of material complexity – it completely depends on process, because some processes allow for varied material properties through part‘s volume, while other processes only allow for single material with full homogeneity [30].

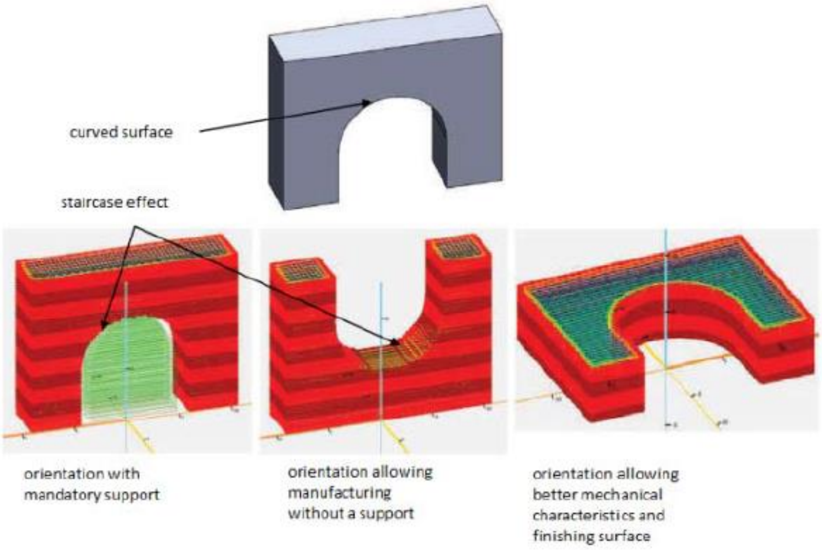


Fig. 1.15. Staircase effect [33]

As every other process, AM has it‘s own limitations, some of these, that should be taken into account before designing are [33]:

– If part is hollow and closed, material that is not sintered inside, is stuck, therefore draining holes or cleaning channels must be implemented;
– The temperature of process must be carefully managed, as every material has it‘s own fusion temperature. This is even more difficult with multi-materials;
– There are material limitations, as glass or wood can not be implemented in AM process;
– Crystal fusion of material must be taken into account, as small change in building temperature may change whole plasticity;
– If assembly with multi materials is of interest, further studies must be taken for post-processing, as for example heat treatment may be different for each of the material;
– Orientation and design of the part must be carefully examined, as the staircase effect and support structures are highly dependant on the experience of engineer;
– If part is hollow, or curved shapes are designed, support structures must be implemented, thus post-processing (support removal) must be taken into account.

Staricase effect is shown in Figure 1.15.

1.10. Topological optimization possibilities

There is estimation, that less than 20% of dimensions of the part or assembly are not critical or of utmost importance, therefore the rest is only left to connect functional surfaces. This means, that the design of the part has many different variations and „connect-the-dots“ problem can fully be solved by AM, since as mentioned before – possibilities are endless [30, 33]. This is the perfect assumption, how topological optimization may save weight.

In regard of topological optimization, further aspects will be discussed :

1. Support structure design;
2. Porous infill design;
3. Material features.

1.10.1. Support structure and porous infill design

Many AM processes require support structures to make sure that overhang areas will be printed with no problems. There is estimation, that 40% - 70% of total part cost, manufactured by AM, could be reduced by removing support structures [36]. Support structures, that are unable to be removed, add unnecessary weight and this is highly unwanted. There is solution to use other, dissolvable, material for support, but it is not available for every process, therefore such processes may require topological optimization to completely eliminate the urgency of supports or to design slimmed support structures.

As support structure design is very wide, only cellular structures are briefly overviewed, as they are designated for DMLS or SLM machines (shown in Figure 1.16). Such supports are used, when very stiff support is needed, therefore they are mainly designed for metal AM. Overall, typical support design for metal AM is a straight wall, once again, for stiffness reason. Cellular structures do not change the support drastically, but rather lightens it up by introducing holes and other gaps in the support itself. It was researched, that with this specific support structure method it is possible to save approximately 40% of the material that would have been lost instead [40, 41].

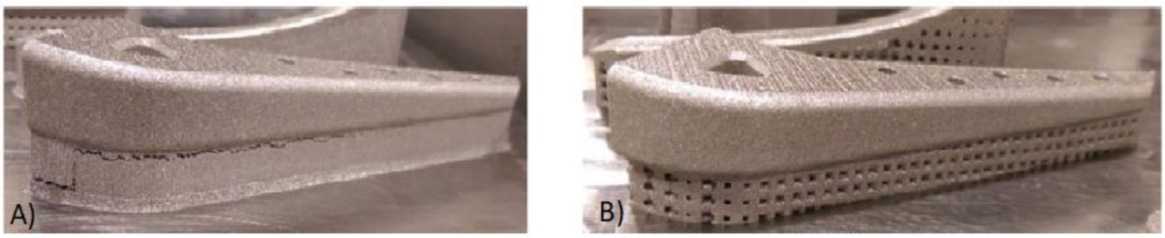


Fig. 1.16. Cellular structures. A) shows the automatic support design; B) shows the cellular support design [36]

Furthermore, regarding support structures, it is known, that different orientations result in different outcomes. With different part orientation settings inside the printer building zone, there is a possibility to achieve both higher printability chance, different mechanical properties, reduced material usage and reduced building time. Furthermore differently bent parts have further different structures, therefore if there is ability to bend the part in needed direction (topologically optimize the part), it is highly advised.

As the additive manufacturing is based on layering one layer of material on top of the other layer, this means that there are many possibilities to create different infills rather than sticking with monolithic part. As number of such infills is very big, only couple will be inspected, that have direct applicability with metal AM, they are:

– Voxel based optimization (shown in figure 1.17). This topological infill optimization is inspired by natural bone structure. The result of this technique is lightweight, resistant, succeptable to damage infill. Furthermore, such infill completely fits to technologies, that are powder or liquid based, as there is possibility to optimize the part in such way, that inside channels may be cleaned, and all powder may be gathered. This may be one of the most difficult optimizations yet, but at the same time it offers one of the best results [50].

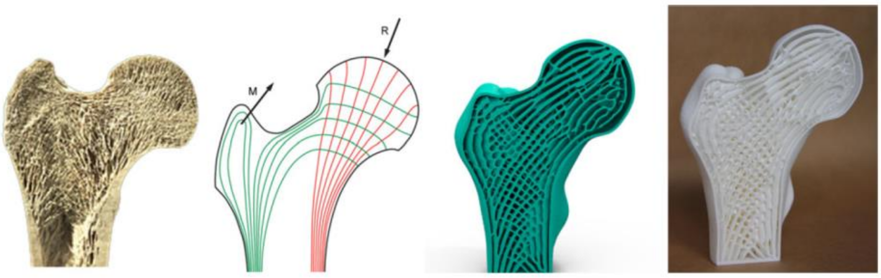


Fig. 1.17. The study and initialization of voxel based optimization (left to right) [50]

– Variable density lattice infill (shown in figure 1.18). This optimization technique may seem similar to voxel based optimization, but it has some differences. The main difference is that lattice structure is typically hexagonal structure, therefore having different approaches to mechanical loads. The optimization is oriented towards having different densities of lattice form, where the load is the highest, as with all other optimizational techniques [51, 52].

Fig. 1.18. Variable density lattice infill [36]

– Complete lattice infill (shown in figure 1.19). Such infill has same density across the whole part, while maintaining the same lattice strucural design. According to studies, complete lattice infill saves a lot of material, while maintaining optimal mechanical properties [53]. It has been researched, that variable density lattice infill is rather more popular, because of multiple reasons, such as easier computation, less organic shapes, which are difficult to accept even novadays and more, nonetheless, the material savings in some cases might be the needed point [36].

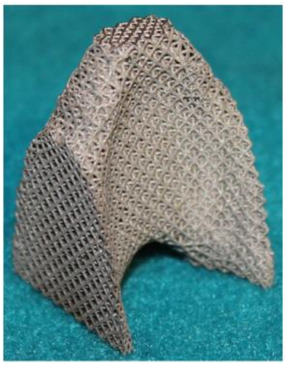


Fig. 1.19. Complete lattice infill [53]

The lattice infill design and overall, latice structures should be studied more in further studies, and as it is very wide topic. There are many different lattice shapes, that are being implemented in the topological optimization, as each of them has specific properties of their own. It is probably one of the most important studies regarding additive manufacturing topological optimization. Even though, it is known that lattice structures are succesful in most places, there still are some downsides, such as part‘s performance reduction. According to studies, performance may be reduced by approximatelly 50% when comparing to solid infill [36].

Even though, the topics of infill and spport structures are very interesting and very wide, sadly they will not be implemented in current work‘s practice, because there are not many actual CAD softwares, that are capable of producing such infills or support structures, and furthermore – high computer power is needed for optimal results [36, 44]. Finally, the manufacturer is completely responsible for support structures.

1.10.2. Material features

The most widely known material feature in regard to additive manufacturing is the lack of the isotropy. Most usually, engineer must keep in mind the anisotrpoy, when designing a part for additive manufacturing. There is a study, that researches the topological optimization anisotropy with different techniques and different stress criterions. The studie‘s main goal was to test the difference in optimization, comparing Von Misses and Tsai-Wu stress criterions. According to study, the Tsai-Wu stress criterion offers greater optimization, when it comes to additive manufacturing, as it outperforms Von Misses by 65% (as seen in figure 1.20) [54].

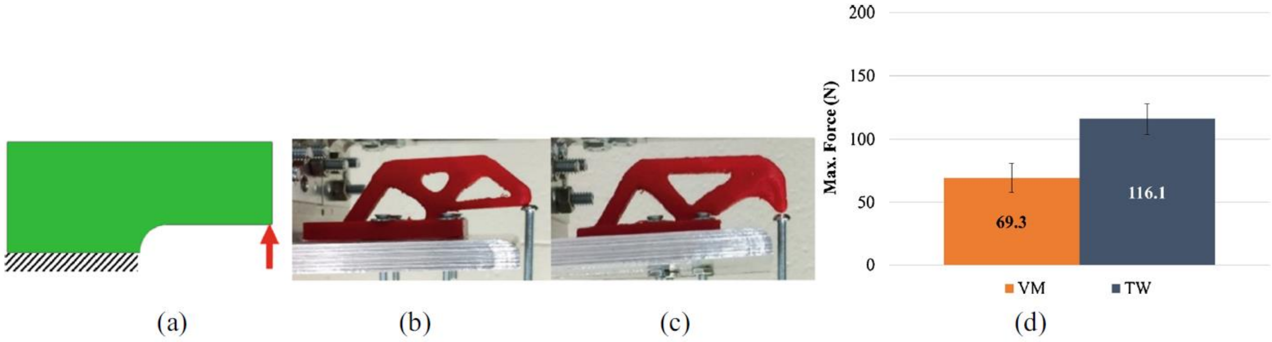


Fig. 1.20. A problem (a), topologically optimized by Von Misses criterion (b) and Tsai-Wu criterion (c). The difference in performance may be seen in (d), as how Tsai-Wu outperforms Von Misses [36, 54]

Furthermore, the anisotropy may be dealt by changing part orientation in build to more favourable one, so the build direction would be manipulated [36, 56].

Although, different studies show that in some cases, additive manufacturing is able to produce fully isotropic parts [55]. Because of this specific reason and contradictory researches, there will be isotropy testing and validation of additive manufacturing further in this work.

1.11. Different CAD softwares, steps, examples

Different CAD softwares offer different topological optimization techniques, that are somewhat simplified. As mentioned before, typical CAD softwares do not offer support structure optimization or infill optimization. As the topological optimization is difficult technique to master, different approaches are justified. Different approaches depend on the required and wanted outcome, therefore standart CAD features offer mostly needed and mediocre quality outcome, which for most parts works well. When high quality optimization is needed, specific softwares must be used with specific tools, so the surface would be treated with highest precision. If high quality is of demand, then topological optimization is usually done within multiple softwares, as in multiple steps of optimization must be taken [26]. Different approaches, their quality and time taken can be seen in table 1.1.

Table 1.1. 5 different topological optimization approaches [26]

Criteria	CATIA (standart features)	Evolve 2015 (standart features)	Magic‘s software (high-quality result)	MeshLab (high-quality result)	CATIA (extra add-ons)
Execution time (in hours)	1.5 to 5	1.5	1.5	2.5	2
Sensitivity on the execution time (in hours)	+/- 5	+/- 3	+/- 1	+/- 1	+/- 1
Time control	++	++	-	-	-
Resulting shape quality	++	++	--	-	+
Repeatability of the result	--	--	+	++	++
Capability to create complex surfaces easily	-	+	++	++	++
Capability to create basic surfaces (plane, cylinder)	++	+	--	--	--
Capability to be accurate in the part dimensions	++	-	--	--	--
Capability to integrate client requirements easily	++	+	--	--	--
Capability to integrate manufacturing constraints	++	-	--	--	--
Number of needed softwares	1	1	2	3	2
Number of elementary surfaces created	795	520	6900	7200	6200
File size in Mb	3	8	64	66	70

There is no specific right way to do topological optimization, since every different software has different capabilities and therefore different steps are taken, but most usually, topological optimization follows steps shown in figure 1.21.

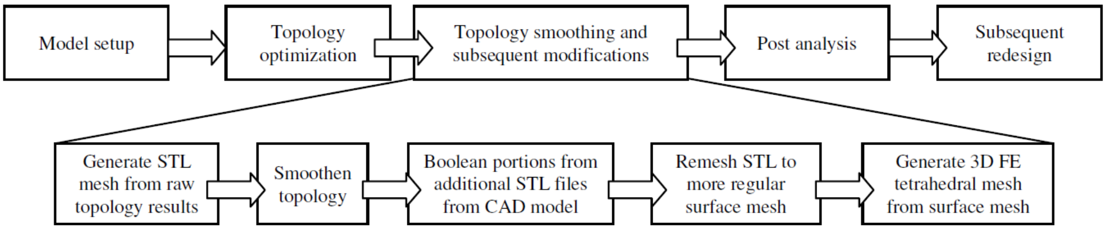
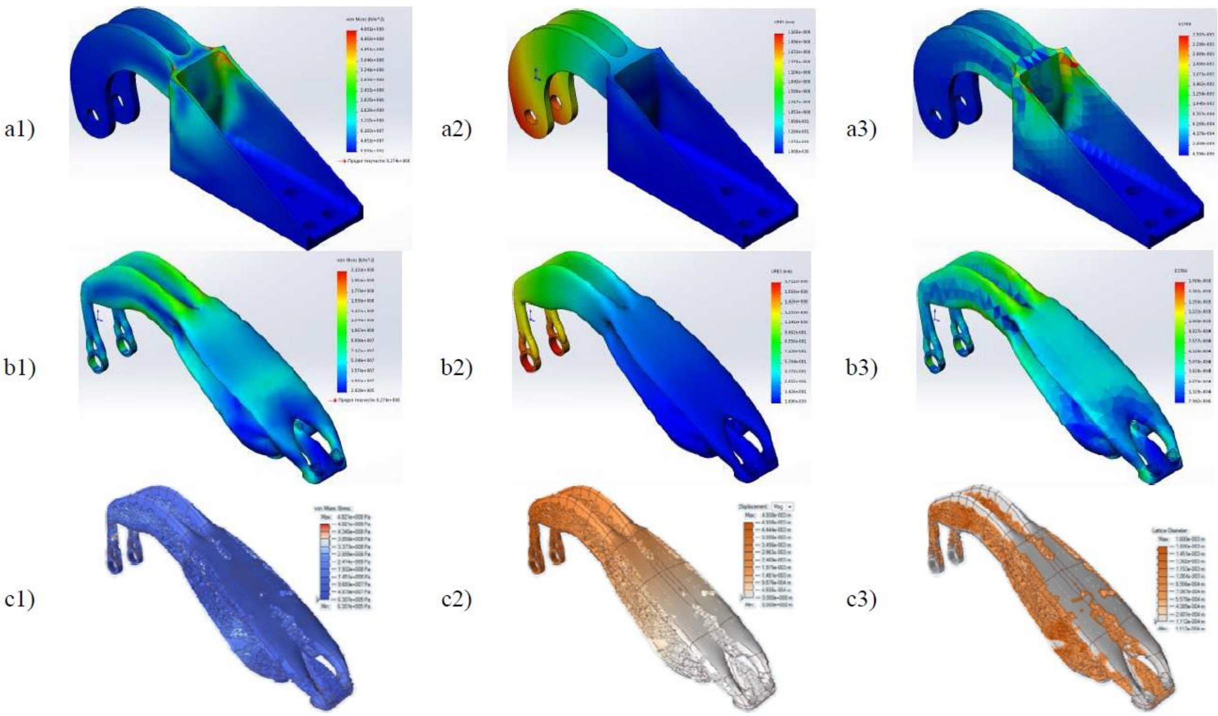


Fig. 1.21. Most common topological optimization steps [57]

Many real life applications of topological optimization have already been researched in many studies, therefore it would be too wide to list them all. One of more interesting topological optimization applications – diesel engine support [59].

Moreover, as mentioned before, topological optimization is different with every single software, and the end result after optimization may be completely different from the one, that started as original part. Mounting bracket topological optimization was studied completely with both geometrical change and infill variation and can be seen in figure 1.22, with study in the difference of mechanical properties.



The load of 5000 N in the vertical direction	Stress, MPa	Displacement, mm	Strain, 10-3	Volume/mass, cm^3/g
A source model	486.1	3.16	2.507	877.84 / 3887.78
The model after topological optimization	213.1	1.711	1.508	746.85 / 3307.63
The model with a cellular structure	482.1	4.938	∅ rods of 0.5-1.6 mm	364.3 / 1613.85

Fig. 1.22. Topologically optimized mounting bracket. a) – source model; b) – model after topological optimization; c) – model after changing infill to light weight structure. 1 – Stress according to Von Misses; 2 – displacement; 3 – strain. Further on a table of mechanical properties is given [58]

Most often, topological optimization offers designs that are completely unique, therefore it may be difficult to control optimization process, as it is completely automatic (one has only to set a number of constraints) [30, 33]. The process completely differs by what specific engineer selects and what are the needs of the part. There is number of different researches done, that prove the significant importance of need for further topology optimization studies and further innovations regrding this subject. Furthermore, number of studies prove the real life applications that are being used already [28, 59]. As adressed before, certain problems will keep most of topological optimization techniques out of the question mostly because of the lack of easily, publicly accessible or free softwares. Other question at hand – available computer power, that is the needed computer power for topological optimization is rather higher than accessible now.

1.12. Review of Aeronautical Field

As this work is oriented towards the aeronautics, literature research of current, past or upcoming articles in respected fields must be done. There are many studies that cover the wide possibilities, different variations and real life examples of additive manufacturing and topological optimization in aeronautical field [60, 62].

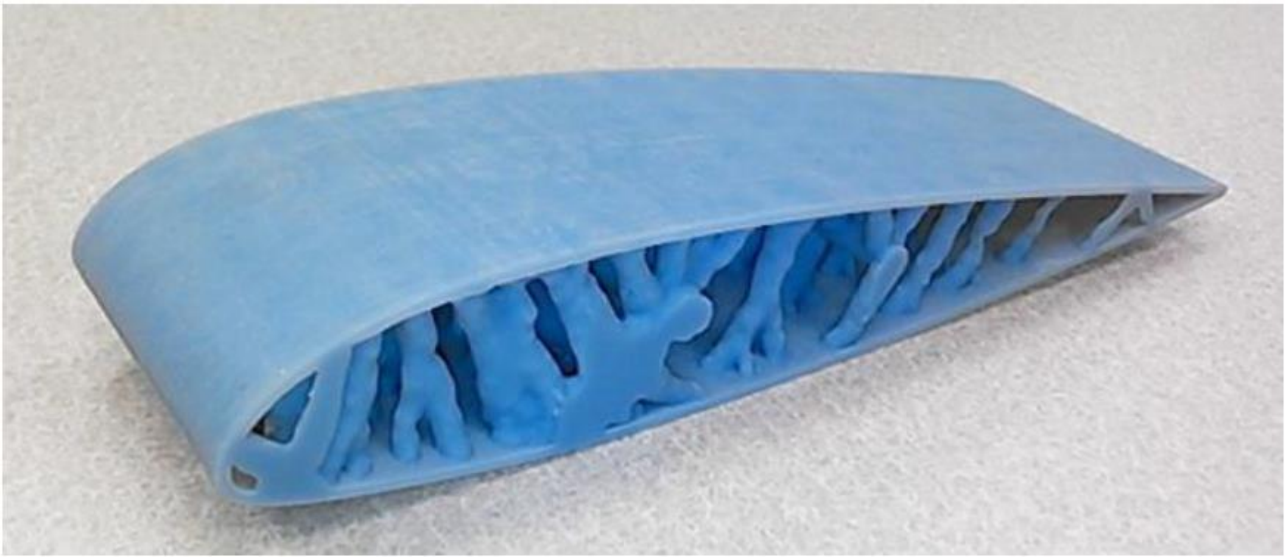


Fig. 1.23. Topologically optimized and manufactured wing structure [47]

The topological optimization of many different aspects in aeronautics has been addressed multiple times. For the sake of this work, only one example will be examined, as it is not the main point. It is widely known fact, that aviation is controlled by special reglaments and specific requirements are needed to be met for part. These requirements range from structural to aerodynamical field and many more. Moreover, these requirements show the need for multi-level optimizations, where different disciplines are joined together to optimize single part. Such example was studied with Airbus pylons [61]. The main idea behind this optimization was to optimize weight and strength of the pylon while respecting the area of aerodynamics and other structural requirements, such as stiffness. The optimization can be seen in figure 1.24.

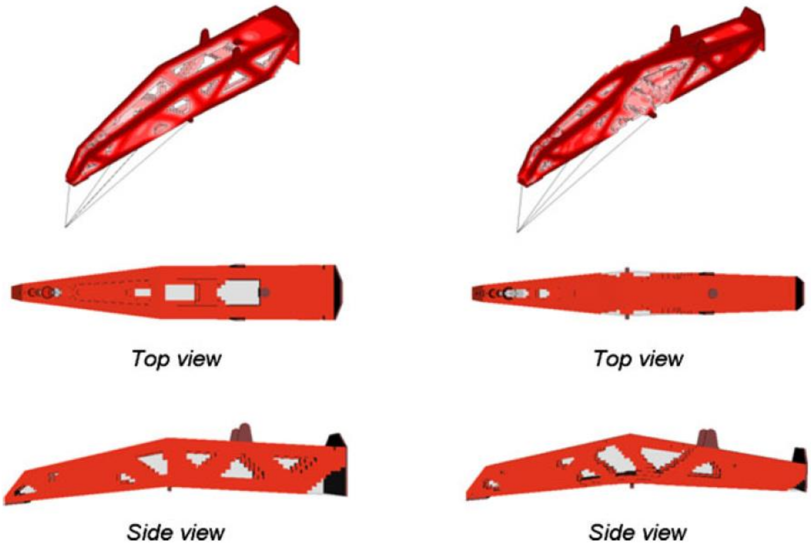


Fig. 1.24. Topological optimization of Airbus pylon. Left – initial design, right – optimized design [61]

As it can be seen in the picture, the overall shape remains the same, but at the same time, new holes and cut outs are introduced. As the optimized outcome is more difficult to manufacture than initial design, this leads to further tests and studies, therefore currently, mainly smaller parts are highly viable for topological optimization (bigger parts, such as pylon, are viable as well for topological optimization, but this should be addressed in different studies).

As it has already been asserted multiple times – almost anything is possible with additive manufacturing. From the simpliest parts in aeronautical field, such as gears, that may be used in more difficult assemblies, such as transmissions [19], to strange appliances, such as landing gear [6] to the most difficult ones, such as fuel injector nozzles [18].

Even if the gear itself is simple part, it is almost always a part of a difficult assembly, in this case – transmission. Study shows the optimization of tolerances and support structures, and post-processing applied in real life [19]. As the quality is one of the prior concerns regarding additive manufacturing, geometrical quality control in study shows the deviation analysis map. This proves, that currently for completely high-end parts, extra machining would be needed, but for medium to high-end quality parts, no extra machining is needed (shown in figure 1.25).

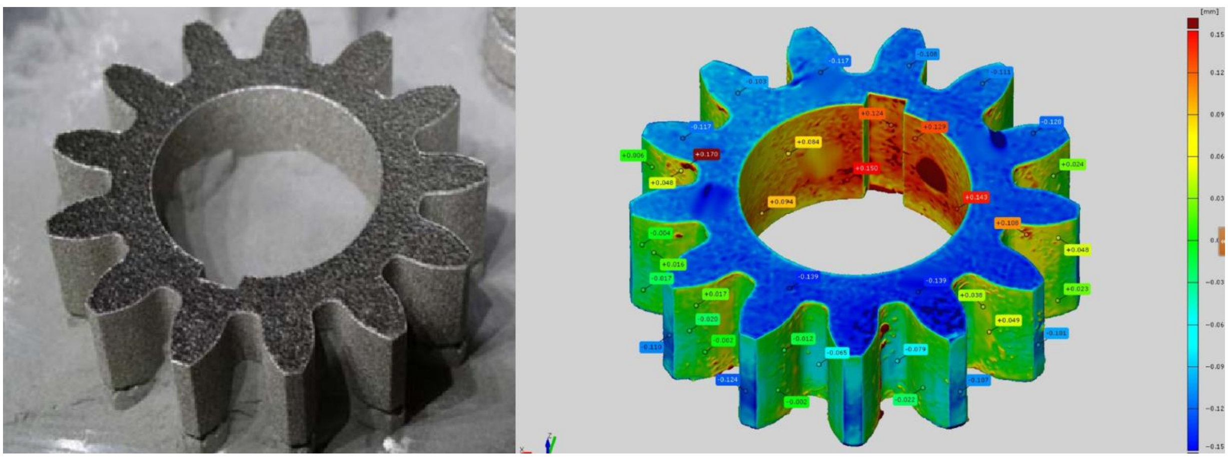


Fig. 1.25. 3D printed gear with DMLS (left) and deviation analysis map (right)

Different studies show, how additive manufacturing may be applied for more difficult fields in aviation. One study researched, that if the component of main landing gear in Piaggio 180 Avant II would be manufactured by additive manufacturing, without any major changes in the part itself, the price of the component would be cheaper for small to medium batches. For that specific study, it was calculated, that after 42 pieces, the conventional manufacturing would be cheaper option for a batch. The study was done without any major changes to the geometry of the part, therefore meaning not all of the AM possibilities were exploited, further meaning that there are many further possibilities in respected study [6].

When topological optimization is applied in aeronautics, with addition of additive manufacturing, spectacular outcomes may be obtained, such as in study of Airbus 320 nacelle hinge bracket optimization [63]. The study completely shows all the points of optimization, from loading cases to final design. Figure 1.26 shows the initial design and optimized design for part. The optimized part in this study is 64% lighter, than original part, as optimized part weighs 326 grams, while original part weighs 918 grams.

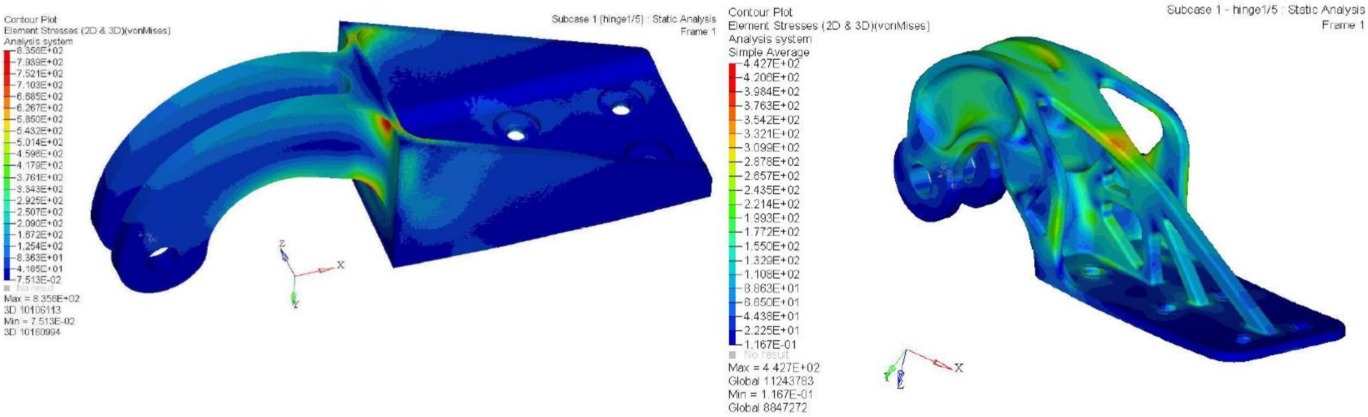


Fig. 1.26. Airbus 320 nacelle hinge bracket original part (left) and optimized (right) with interest in loading [63]

According to publically available sources and studies, aviation companies, such as Boeing, are using additive manufacturing in many different parts and levels of complexity for quite some time. As studies show, Boeing has redesigned more than 300 parts to apply them specifically for additive manufacturing. Furthermore, these redesigned parts are being used on more than 10 different planes (commercial and military use). At the same time, General Electric Company has redesigned fuel injector nozzles, so the conventionally manufactured nozzle would be changed to additively manufactured nozzle. This saves a lot of weight (25% lighter) and introduces more features to make new nozzles more energy efficient. Conventionally manufactured nozzles were made out of 18 parts, while with AM, it can be manufactured as one part, further reducing the price in assembly, complexity and increasing lifetime of the part [18].

Many different factors may summarize the way and the time for AM to be fully adopted by aviation [15]:

– Experience – when industrial knowledge in AM will increase, the overall cost of AM will drop and the speed of manufacturing will increase as well. This would be more viable for high volume parts or for big quantities;

- Stability of technology – AM machines and technology must be stable, because current changes of machines or technologies are bad for manufacturers;
- New generations of aviation – with new aircraft being designed, newer and more innovative ideas are beign introduced, further adding more parts manufactured by AM;
- Bussiness questions – questions, regarding bussines are not fully addressed yet, such as costs, volumes, transportation, etc. This is also a question of stability of technology, as frequent technological changes, change the questions in business;
- AM selection – as number of technologies increases, identification of needed technology mostly suitable for needed part must be more accessible easier;
- Aircraft Original Equipment Manufacturers – once OEM’s will start to lead the adoption of AM into aeronautical field, MRO’s will start to follow, further increasing number of AM in aviation.

Positive change in these and many more factors would lead to increased usage of additive manufacturing in aeronautics, further increasing the researches in topological optimizations and overall technological capabilities.

2. Research section

As it was mentioned in the introduction, the main purpose of this work is to propose better design for LAK mini glider‘s (glider can be seen in figure 2.2) control system part using advanced additive manufacturing and topology optimization. The part itself is a flap system‘s bellcrank, therefore the purpose of the part is to assist in moving of the flap with transfering force from the control stick. The location of the part can be seen in figure 2.1 and is numbered in 16th position.

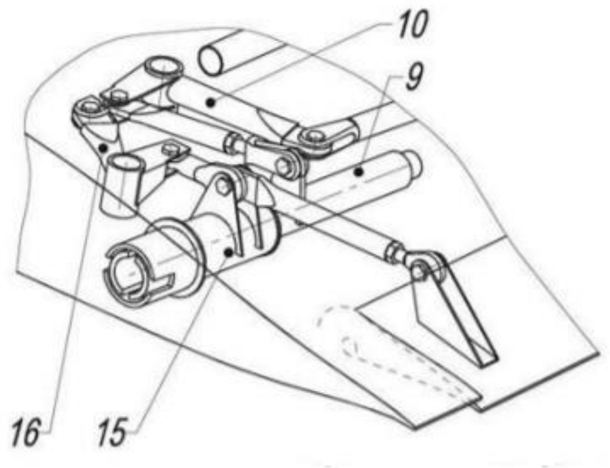


Fig. 2.1. LAK mini control system. Part under interest is numbered in 16th position [46]

The part is originally manufactured from 30ChGSA steel, and different components of the part carry different GOST standards. The manufacturing process of the part itself is rather difficult and require many different techniques – laser cutting, welding, pressing. Such manufacturing is not only difficult in the sense of time spent, but keeping with so many different techniques lead to other problems, such as more difficult logistics, and quality and tollerance reassurement. The problem with quality reassurement is that the part includes a lot of non-parametrical geometry and therefore it is difficult to obtain same part with same quality every single time.

Fig. 2.2. LAK mini glider [42]

As the scope of this master‘s thesis is very wide, only some aspects were chosen to be studied in deeper sense therefore consisting of real life and computer based experiments. Because of greater power to weight ratio and other mechanical properties than 30ChGSA, such as tensile, compressive, yield or other strength properties, the chosen material of interest is Ti6Al4V titanium alloy. Same as for the manufacturing process, the chosen is direct metal laser sintering. Reasons being :

- Only DMLS and SLM machines are available in Lithuania;
- Titanium is chosen for its high strength to weight ratio;
- According to manufacturer given information, DMLS offers full isotropy. As controversial studies were researched before, specimens will be tested out and compared to have further understanding of actual material properties given by chosen manufacturer.

Regarding application of AM to aeronautical field, it was chosen to contact one of more widely known Lithuanian aviation manufacturers - JSC „Sportine Aviacija ir Ko“. The company was kind to give drawings of specific part, used in LAK 17B FES mini flap system. This part is studied in further chapters.

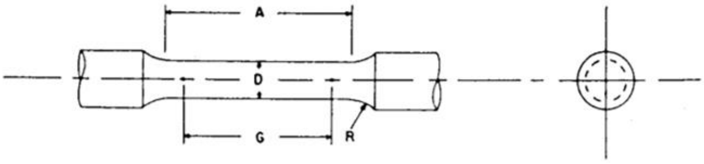
All real life experiments are done in KTU laboratories and computer based simulations are completed using SolidWorks software. To have more in-depth results, Femap NASTRAN and Ansys softwares were used to simulate same problems and results are compared to SolidWorks.

Experimental phase consists of multiple parts :

1. Tensile research with specimens for analysis of isotropy;
2. Multiple computer based simulations of given glider‘s flap system‘s part for topological optimization;
3. Additively manufactured part‘s concept approval test.

2.1. Research of isotropic properties

Many different studies have different opinions regarding the isotropic properties of 3D printed parts. While some studies determine the isotropic or anisotropic properties by simply completing the tensile tests of specimens and comparing the results [7], other studies complete the study by involving many different optimizations of printer itself, different heat treatment itterations, etc. [55]. It is proven, not only by manufacturer, but by studies as well, that additively manufactured parts out of Ti6Al4V are possible to obtain isotropic properties, but specific measures have to be taken, such as keeping exact screening speed of the laser, having parts heat treated at specific temperature and for set amount of time [55]. Because of these reasons, specimens must be tested before finalizing with prototype part, as the manufacturer may not provide completely isotropic parts. This would mean that prototype part must be optimized for anisotropic manufacturing. This furthermore would mean, that different layouts would have to be tried out and final build orientation would have to be deeply thought of, as because of anisotropy, the part would not have same mechanical strength across the whole surface. Finally, as the manufacturer for final part is decided, it is needed to test if proposed 3D printer is capable of producing parts that are completely isotropic. Isotropy may depend on the setting that the printer has, but it is not sure if every manufacturer is using same preferences.



Dimensions, mm [in.] For Test Specimens with Gage Length Four times the Diameter [E8]					
	Standard Specimen	Small-Size Specimens Proportional to Standard			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gage length	50.0 ± 0.1 [2.000 ± 0.005]	36.0 ± 0.1 [1.400 ± 0.005]	24.0 ± 0.1 [1.000 ± 0.005]	16.0 ± 0.1 [0.640 ± 0.005]	10.0 ±0.1 [0.450 ± 0.005]
D—Diameter (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]	9.0 ±0.1 [0.350 ± 0.007]	6.0 ± 0.1 [0.250 ± 0.005]	4.0 ± 0.1 [0.160 ± 0.003]	2.5 ± 0.1 [0.113 ± 0.002]
R—Radius of fillet, min	10 [0.375]	8 [0.25]	6 [0.188]	4 [0.156]	2 [0.094]
A—Length of reduced section, min (Note 2)	56 [2.25]	45 [1.75]	30 [1.25]	20 [0.75]	16 [0.625]

Fig. 2.3. Specimen dimensions according to ASTM E8/E8M

Because the parts are manufactured with 3D printing, and are made out of metal, tensile tests must comply with LST EN ISO 17296:2017 [64] for overall testing of additive manufacturing parts, LST EN ISO 6892-1:2016 [65] or ASTM E8/E8M [45] for geometry of specimens and testing procedure, results, and finally with AMS 4999 [24] for the mechanical properties of Ti6Al4V.

Specimen was chosen according to ASTM E8/E8M. Figure 2.3 shows the possible specimen sizes. As for additive manufacturing parts should not be too big, the specimen 3 sizing was chosen.

All of the specimens were manufactured by Lithuanian company UAB „SmartFactory“ with EOS DMLS M280 3D printer while maintaining software optimization by EOS itself, therefore laser screening speed, power is unknown. Parts were manufactured with Ti6Al4V material, made by same exact manufacturer – EOS. Furthermore, parts were heat treated at 850 ^{0}C for approximately 2 hours. The layout and orientation of parts in a build are shown in figure 2.4, and as it can be seen, orientations are set to 3 variants – 0 degree, 45 degree and 90 degree angle according to build plate. If the chosen manufacturer would produce parts with anisotropic features, every different orientation might have different strength and different tensile properties. This orientation differentiation is the easiest way to test the parts for their homogeneity of strength.

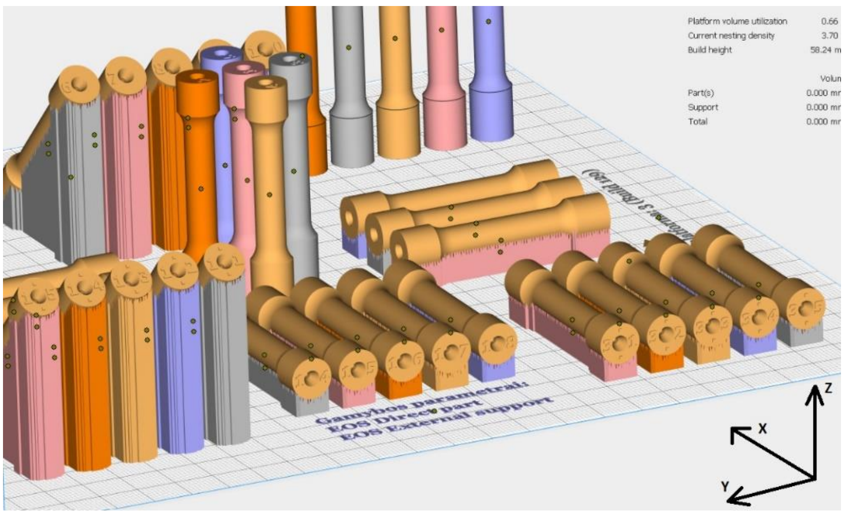


Fig. 2.4. Layout of tensile specimens prepared for manufacturing in M280 machine

The testing phase was divided into two sections – first section was done with universal electromechanical 50kN tensile and compressive testing machine, which is located in the faculty of Mechanical Engineering and Design. Results were derived with HBM measuring unit and later on processed with Microsoft Office Excel software. Second section was done with 2054 P-5 testing equipment which is as well located in the faculty of Mechanical Engineering and Design. Results were processed with Microsoft Office Excel software. Sadly it was impossible to fit special equipment for deformation calculations, as specimens were too small.

First tensile testing section - specimens had a problem of constantly slipping out of claws of the tensile testing machine, because the strength was very big while the specimen had small area for anchoring, therefore the yield strength point is nearly impossible to point out. Because of the same problem, Young‘s modulus is impossible to determine.

Second tensile testing section - specimens, that were tested with different machine had rather more succesfull results, as there was less slippage. Nonetheless, it was impossible to obtain accurate strain results, because during the testing phase, specimen holding claws had deformed the anchoring area, therefore introducing tangential deformation into that specific area. This tangential deformation had summed up with total deformation and therefore final value of strain is incorrect.

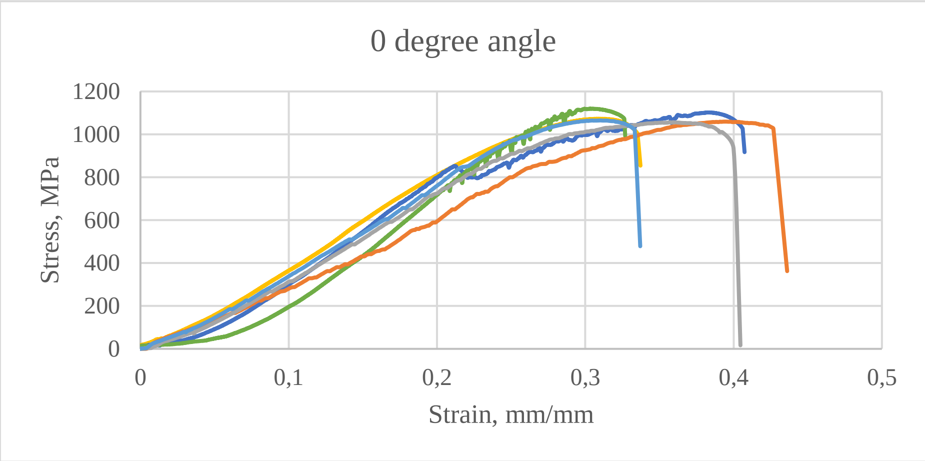


Fig. 2.5. Strength values of specimens, manufactured in 0 degree angle in accordance to build plate

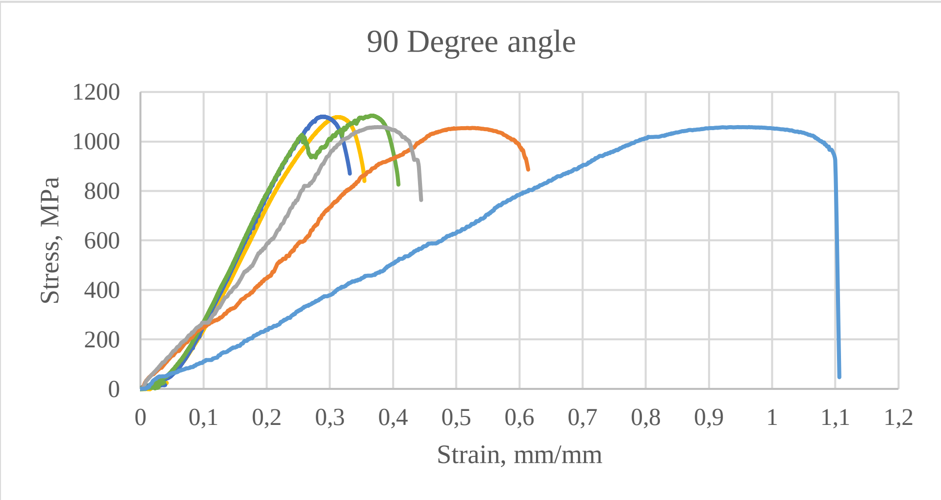


Fig. 2.6. Strength values of specimens, manufactured in 90 degree angle in accordance to build plate

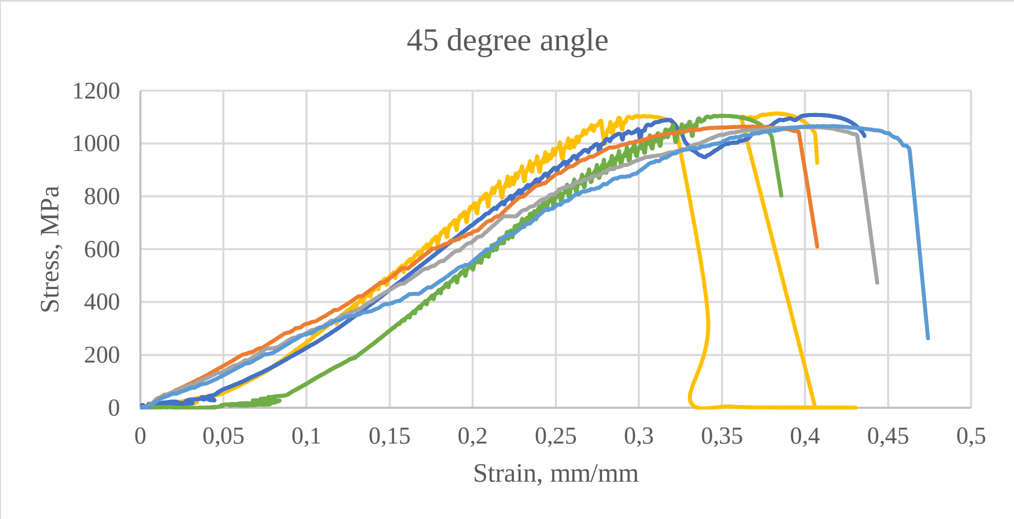


Fig. 2.7. Strength values of specimens, manufactured in 45 degree angle in accordance to build plate

Table 2.1. Tensile strength results of specimens

		1st tensile test			2nd tensile test		
	Specimen N°.	1.	2.	3.	4.	5.	6.
0 Degree angle build orientation	Ultimate Tensile Strength, MPa	1072.102	1101.723	1119.507	1058.921	1056.250	1064.604
	Strength at break, MPa	853.941	916.859	916.859	1025.852	931.853	1021.128
90 Degree angle build orientation	Ultimate Tensile Strength, MPa	1098.808	1100.429	1104.703	1054.994	1058.441	1058.372
	Strenght at break, MPa	840.169	870.234	825.727	886.363	922.241	763.315
45 Degree angle build orientation	Ultimate tensile strength, MPa	1113.731	1108.367	1105.177	1064.371	1062.572	1066.309
	Strenght at break, MPa	926.853	1028.193	802.605	1043.124	1028.659	974.883

To prove the result, theoretical calculations are provided further according to Formula (5). The ultimate tensile strength value chosen is given by material manufacturer EOS, and in regard to Ti6Al4V it is equal to 1050±20 MPa.

$$F = \sigma \cdot A, \tag{5}$$

If: σ – stress;

F – force;

A – cross sectional area.

Then: $F = 1050\ MPa\ \cdot 28.26\ \text{mm}^2 = 29673\ \text{N}$

Because there is difference between theoretical calculations and actual results from experiment, further calculations are needed to find result deviations. Calculation method is taken from [66].

Table 2.2. Calculations of measurement inaccuracies, here Student's t-criterion t_p is 2.447 with reliability of β=0.95.

	Arithmetic mean, (N)	Standard deviation, (N)	Random inaccuracy of measurement result, (N)	Random inaccuracy of measurement result in sense of stress, (MPa)	Relative inaccuracy, %
0 Degree angle build orientation	30487.96	729.631	728.890	25.792	2.39
90 Degree angle build orientation	30711.75	696.580	695.872	24.624	2.27
45 Degree angle build orientation	30503.93	688.196	687.497	24.328	2.25

As it can be seen from the table, the difference between results of the same build orientation do not reach 2.5%. To check if these results are correct, arithmetic mean will be checked together with theoretical calculations (results given in table 2.3) calculated with Formula (11).

Table 2.3 Possible error calculations between theoretical and experimental values

	0 Degree angle build orientation	90 Degree angle build orientation	45 Degree angle build orientation
Possible error, %	2.75	3.50	2.80

As the calculations in table 2.3 are provided without relative inaccuracy in mind, values are higher than expected. Nonetheless, if relative inaccuracy was introduced together with ±20MPa value of material, the difference between theoretical calculations and experimental values would drop down quite a lot. Lastly, same calculation of possible error is calculated to understand the isotropic properties. This time, relative inaccuracy is introduced, therefore values are adapted for more precise calculations and results.

$$\text{Possible error} = \frac{|1054.994\ \text{MPa} + 2.27\% - 1119.507\ \text{MPa} - 2.39\%|}{|1119.507\ \text{MPa} - 2.39\%|} \cdot 100 = 0.95\% \quad (6)$$

If : 1054.994 MPa - lowest stress value of tensile testing;

1119.507 MPa - highest stress value of tensile testing;

2.27% - relative inaccuracy of 90 degree angle build orientation results;

2.39% - relative inaccuracy of 0 degree angle build orientation results.

The calculation, given in Formula (6) prove, that results indeed show high level of isotropy in regard of UTS, because the difference between highest and lowest values, taken from experiment, is less than 1% (that is if relative inaccuracy is introduced). As tensile, shear or other properties are not tested, complete isotropy is unknown. Formulae for all deviation calculations can be seen further:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (7)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (8)$$

$$\mu_{st} = t_p \cdot \frac{\sigma}{\sqrt{n}} \quad (9)$$

$$\delta = \frac{\mu_{st}}{\bar{x}} \quad (10)$$

$$\%\text{Error} = \frac{|Experimental - Theoretical|}{|Theoretical|} \quad (11)$$

If : $\bar{x}$ – arithmetic mean;

x_i – results;

n – number of measurements;

σ – standard deviation;

μ_{st} – random inaccuracy of measurement result;

t_p – Student's t-criterion according to chosen reliability;

δ – relative inaccuracy;

Experimental – values from experiment;

Theoretical – values from theoretical calculations.

Results from these tests satisfy the requirements of Ti6Al4V strength, mentioned in AMS 4999. Although, the difference between the strength at break point is a bit bigger than it would be expected, but this may be because of the constant slipping and therefore not correct values are given by the measuring machines. The strain values are not given in table 2.1, because specimens were constantly slipping out of the claws and therefore results are violated.

Fig. 2.8. Specimen fitted in the 2054 P-5 testing machine

To sum up the results, second tensile test gave more uniform results, than the first one, but it is disregarded, because total deviations between results of one building orientation did not reach 2.5%. This shows that results of each orientation are valid, as there is no deviation that would seem too big from mean. Furthermore, once checked with theoretical calculations, experimental values were proven correct, as highest percent of error was 3.5%, but as this value was calculated without taking account of any deviations, calculated beforehand or given by manufacturer, it may be concluded, that experimental values show high similarities to theoretical calculations. Lastly, once biggest difference between values was checked (with result deviations taken into account), it was found out, that it is less than 1% and therefore it shows high level of UTS isotropy.

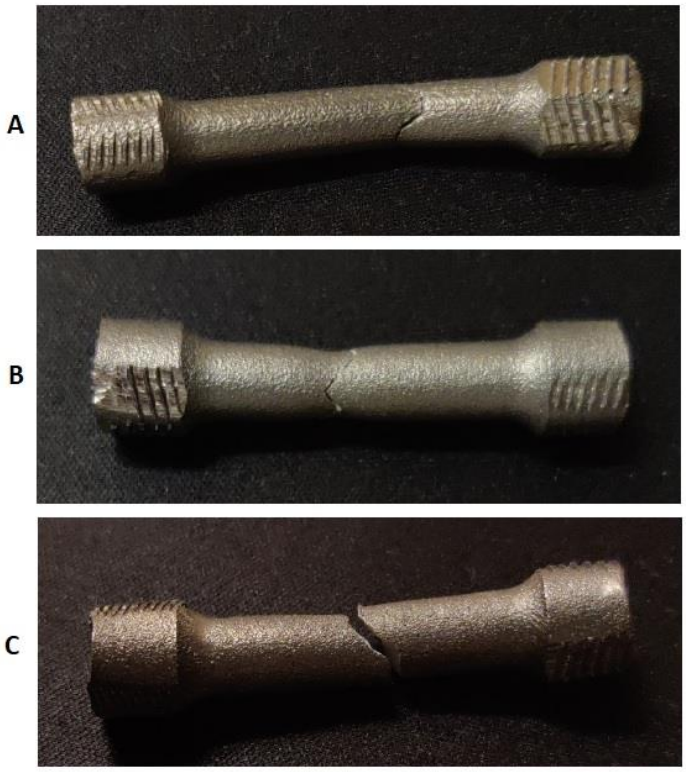


Fig. 2.9. Broken tensile specimens. A) 0 degree angle; B) 90 degree angle; C) 45 degree angle

Regarding specimens, as it can be seen from the figure 2.9, ones with the manufacturing angle of 90 degree had the most visible neck that has formed at the break point. Meanwhile specimens that were manufactured with an angle of 0 or 45 degrees do have more visible crack and neck did not form at all. This should be investigated further in different studies, as the difference in the way that specimens broke may lead to isotropical anomalies or other abnormalities and therefore lead to uneven breakdowns of final parts or different deformations. As this would be too wide for the master's thesis, because of uniform values that were received from tensile tests it is considered that Ti6Al4V manufactured by EOS has isotropical properties, needed for further designing and manufacturing of a prototype part. Moreover, received values prove, that UTS, given by EOS itself are correct and further proves the point, that EOS as a manufacturer provides correct mechanical properties of the material and the isotropy is proven. Finally, AMS 4999 (Titanium Alloy Laser Deposited Products, 6Al4V, Annealed) requirements are satisfied.

2.2. Topological optimization

As the main purpose of this work is to optimize single part for additive manufacturing, this section is probably the most important. Topological optimization was done with couple of different softwares and results were compared between each other in the sense of finite element analyses. Further on, FEA's were completed with three different softwares, to have understanding how different softwares may show different results.

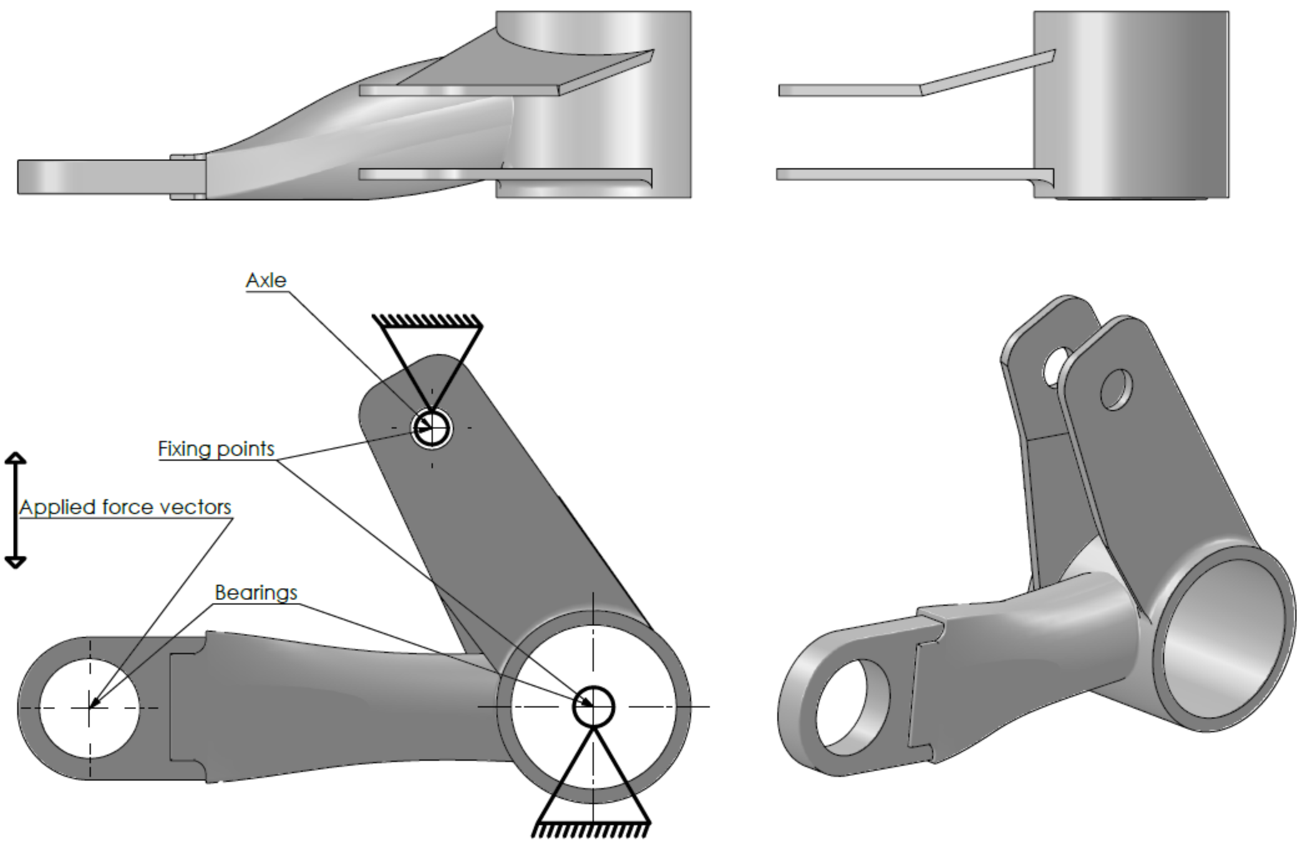


Fig. 2.10. LAK mini flap system's bellcrank, drawn in SolidWorks. In lower left corner, the loading conditions can be seen

The drawings of the part are given by the manufacturer, therefore the part itself must firstly be drawn in 3D CAD system. For this purpose, SolidWorks software was chosen. The 3D drawing of a part can be seen in figure 2.10. As it can be seen from the position of bearings, fixation points and vectors of applied forces, the part spins around bearing that should be installed in the biggest cylinder. By doing this motion, the force from leftmost cylinder (given as application force vectors) is translated to an axle, which in reality should move the flap. In most simple terms, the force is applied on first bearing, the bellcrank rotates through second bearing making the flap move. The flap is connected with bellcrank through axle. Originally, part is manufactured out of 5-6 different subparts.

As the material for this part is known, full weight is also known to be ~83-85 grams. The weight here does not include welding spots or any other connections that would increase final weight, therefore complete weight of the part that would be used in real life is only estimated. The estimation is done, that final part without bearings should not weigh more than 90 grams. Furthermore, according to drawings and to GOST standard specifications, the yield strength of 30ChGSA is 700MPa [39].

To determine the original strength of the part, 1N force must be applied to the part (loading scheme given in figure 2.10). From the resulting stress values, and known material properties the maximum loading force can be obtained. The yield strength of the part is divided from the highest stress value, therefore obtaining complete strength of the original part. Final result of simulation is given in figure 2.11.

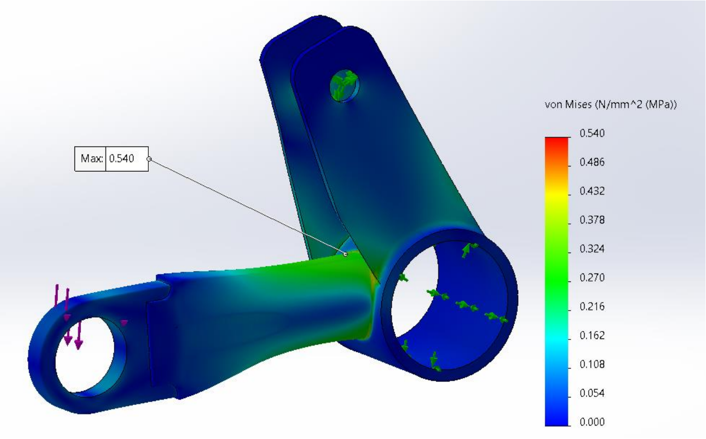


Fig. 2.11. Von Mises stress results of 1 Newton of force applied to the original part

As all values are known, the maximum force that may be applied to original part can be calculated:

$$x = \frac{1\text{N}\cdot 700\text{MPa}}{0.540\text{Mpa}}; x \approx 1300 \text{ N}. \quad (12)$$

The value here, 1300 N, is supposed to be the force, that the part should be able to withstand, without applied factor of safety. Since the FOS value for aviation is typically 1.5, the maximum force that should be applied on the part with safety taken account for, is equal to ~867 N.

Further on, as the material properties (UTS) are tested, and the maximum applicable force is known, the topological optimization may be done further. These were done in couple different steps while maintaining strength characteristics and having manufacturability in mind. All of further optimized options are completely manufacturable.

First topological optimization simulation was done with SolidWorks software, the result is given in figure 2.12. The constraints, that were applied, were maximum possible mass reduction and minimum possible factor of safety should be equal to 1. This is because 1300N is the original applicable force, and the factor of safety was already applied to the original part, making any simulation with applied force of 1300N to have factor of safety already de facto applied. This would mean that the part would reduce its weight until it reaches the phase, where a force of 1300N combined with topologically optimized geometry would reach a stress of 1000MPa. Once such point is found, optimization is finished, and final solution is given.

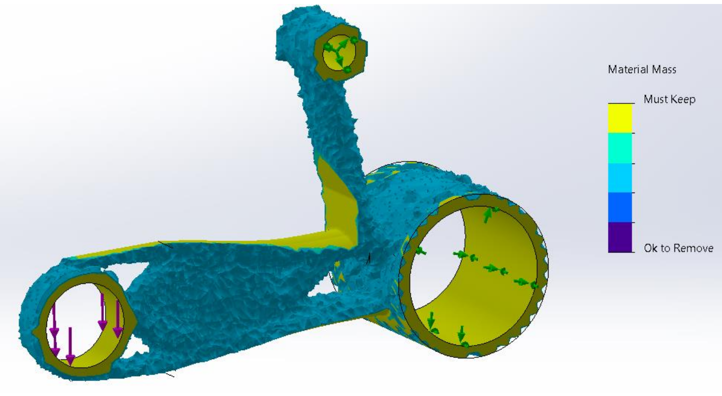


Fig. 2.12. Topologically optimized part by SolidWorks software (yellow colour shows the material that must be kept, cyan colour shows the material that is not that important, but should be kept)

The next topological optimization was done with Ansys software. One of the problems that were faced with Ansys software were the lack of elements and nodes in the meshing phase, as the maximum allowable number of elements or nodes in Ansys software for students is 32 000. This was not a problem for topological optimization, as the original part does have smooth surface as well as many parametric shapes. But once a part is topologically optimized, the number of parametric shapes increase by a lot and the surface looses its all smoothness, therefore a number of 32 000 nodes or elements was too little. As for now, the topological optimization was done with the original shape and there were enough elements to conduct reliable TO. Result of Ansys TO can be seen in figure 2.13. The constraints that were set in Ansys simulation, were similar to the ones, set in SolidWorks TO. One constraint was again maximum possible mass reduction, and second one, instead of factor of safety, maximum allowable stress was set to 1000MPa. Once again this would mean, that once construction reaches the stress of 1000MPa, it would stop and show the result that was calculated.

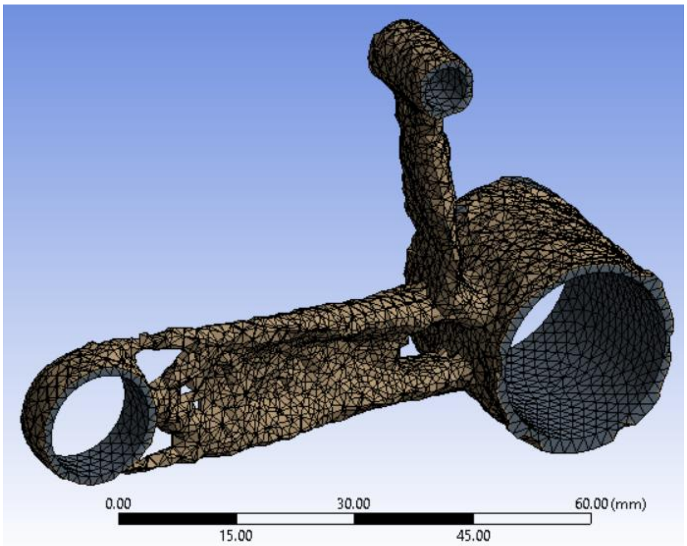


Fig. 2.13. Topologically optimized part by Ansys

The third software, Femap NASTRAN, does not offer topological optimization simulations for students and therefore it must be bought to be used. This sadly means that only SolidWorks and Ansys TO results will be of discussion and Femap NASTRAN will only be used for FEA. As it can be seen from the figures 2.12 and 2.13, the results look very similar to each other and therefore to conclude which of these alternatives is the better one, static and buckling studies will be examined. Results of static loading (of 1300N) on a part that was topologically optimized by SolidWorks are seen in figures 2.14, 2.15 and 2.16.

Moreover, as results of these different softwares must be comparible, similar or same conditions must be set before calculations. Also, to as more accurate results are wanted, higher quality mesh was applied in every situation. The conditions that were set in FEA's:

- Mesh size – 1.1-1.3 mm;
- Constraints – radial growth and axial constraints on fixed cylinders, while leaving tangential movement free to simulate bearings and movement conditions;
- Force – 1300N on the surface of frontal cylinder.

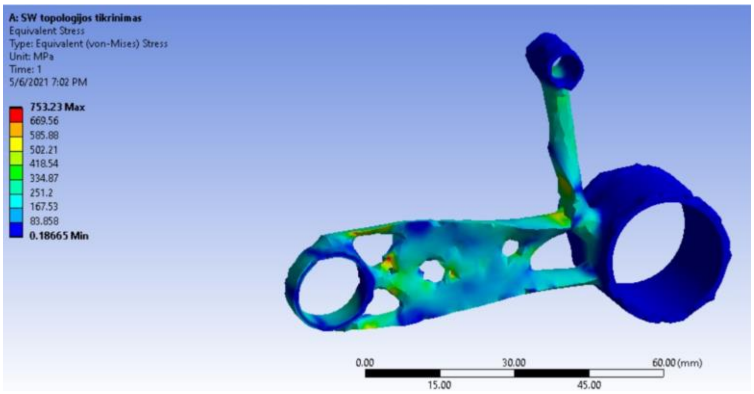


Fig. 2.14. Part optimized with SolidWorks topological optimization. Von Mises stress results from Ansys software

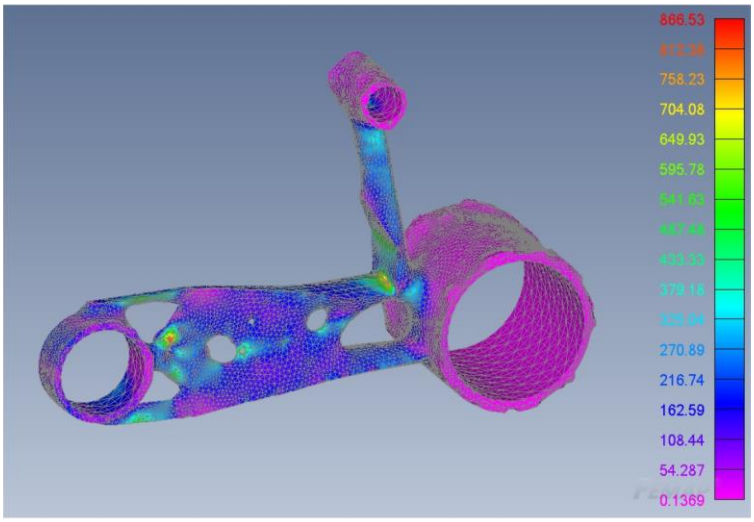


Fig. 2.15. Part optimized with SolidWorks topological optimization. Von Mises stress results from Femap NASTRAN software

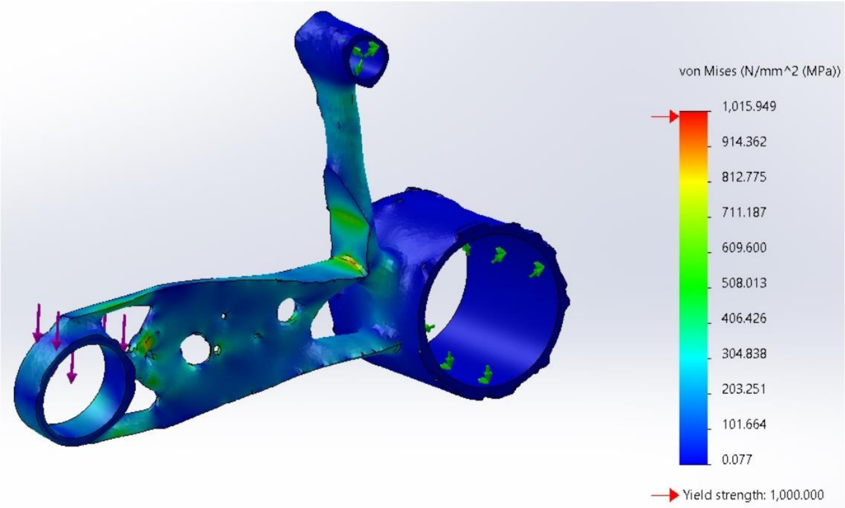


Fig. 2.16. Part optimized with SolidWorks topological optimization. Von Mises stress results from SolidWorks software

It can be seen, that only SolidWorks software does show the resulting 1000MPa, and in Ansys or Femap softwares, maximum stress does not reach 900MPa. The reason, why Ansys does not reach such high stress, is because of the lack of the elements and nodes. As mentioned before, topological optimization does not have smooth surface, therefore meaning that each of the triangle elements, that are gained through optimization should be transformed into continuous mesh, but as the number is limited, aggressive reduction of geometry takes place and therefore some elements are removed at all and some elements become smaller than they should be. Furthermore, because there is lack of elements in the stress accumulated areas, the maximum results are not completely correct. Nonetheless, the average stress points do show correct values. As for Femap NASTRAN – the software is capable of very high level meshing and solving stress accumulations, therefore result is once again different, but as it may be seen, the other areas show similar or same results and color schemes, therefore the difference between these softwares in this case lies in the stress accumulated area. The static results of topologically optimized part by Ansys software are given in figure 2.17, 2.18 and 2.19.

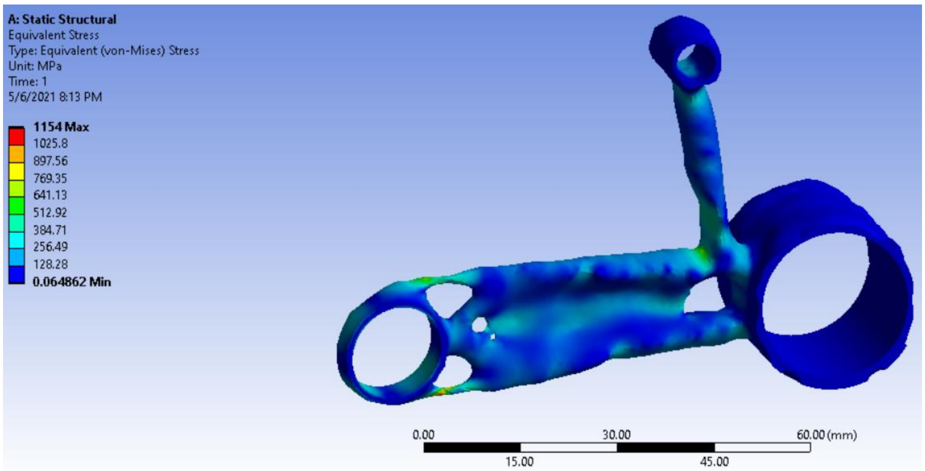


Fig. 2.17. Part optimized with Ansys topological optimization. Von Mises stress results from Ansys software

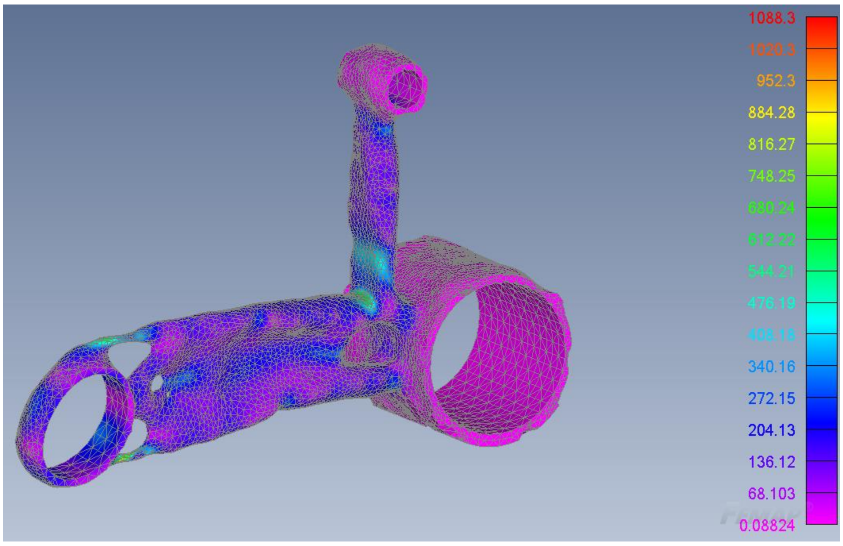


Fig. 2.18. Part optimized with Ansys topological optimization. Von Mises stress results from Femap NASTRAN software

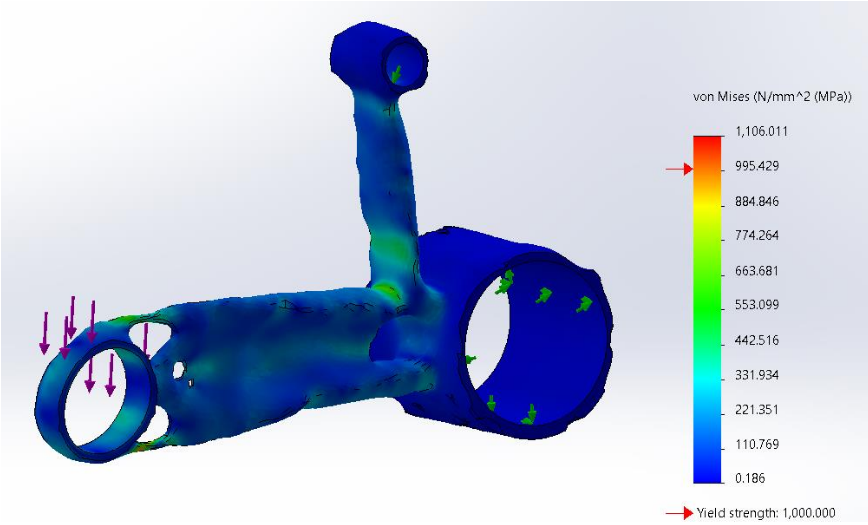


Fig. 2.19. Part optimized with Ansys topological optimization. Von Mises stress results from SolidWorks software

As seen from figures, the difference between results is quite small and maximum stress is almost the same, through all simulations. This could be the reason that Ansys software does export better meshed topologically optimization files. The mesh smoothing difference between SolidWorks TO and Ansys TO is very big, as SolidWorks only optimizes some areas and the smoothing of the mesh does not seem to be highly dominant on sharp edges, while on the other hand Ansys does optimize every single detail around the part and smoothing of the mesh is done more aggressively, therefore the final file is more applicable in different softwares or higher quality 3D printing. Complete results of different studies are given in the table 2.4.

Table 2.4. Finite element analysis results of different topological optimizations

	FEA software	Von Mises maximum stress, MPa	Total deformation, mm	Maximum strain, mm/mm	Buckling factor of safety
Topological optimization by SolidWorks	Ansys	753.23	1.186	0.0069	4.455
	Femap NASTRAN	868.53	1.149	0.0065	4.607
	SolidWorks	1015.95	1.153	0.0061	4.415
Topological optimization by Ansys	Ansys	1154.00	0.954	0.0099	7.895
	Femap NASTRAN	1088.30	0.943	0.0080	7.879
	SolidWorks	1106.01	0.951	0.0071	7.872

As it can be seen, all results of one TO are almost the same, only in the SolidWorks TO there is bigger difference in stress value. As mentioned before, this is highly because of the meshing in different softwares, and how different softwares cope with very difficult geometries. Furthermore, it is impossible to obtain same results, because Ansys does limit the number of nodes for simulations and studies. Finally, the mass values that were received by these topological optimizations were:

- SolidWorks topologically optimized part – 32.06 grams;
- Ansys topologically optizimed part – 36.83 grams.

Fig. 2.20. Final iteration of topological optimization by Ansys software. This iteration is chosen for manufacturing

As these two topologically optimized options are too risky for manufacturing, the third one should be introduced. Even though the first parts are completely manufacturable, there is high risk of having prototypes manufactured with big deformations, having the prototype not manufactured at all or broken while cleaning from support structures, therefore safer route for this thesis is chosen. It is known, that prototyping phase is quite long and requires specific amount of money, the constant communication with manufacturer must take place and many different iterations should be 3D printed before obtaining final part that is manufacturable with 100 percent repetition of the same quality. Because of all of these reasons, final part is chosen to be manufactured with ~2.5 factor of safety from original part. Because from earlier topological optimizations Ansys showed rather better results for both, overall strength and file meshing control, it was chosen for optimization of final part that would be manufactured. Although the method of Ansys showed to be safer, as it reduced less weight, the bigger value in this sense is complete, easy and deformationless manufacturing, therefore the difference of weight result is disregarded at this point.

As it can be seen in figure 2.20, the final part does have extra geometrical features when compared to first TO's, when it comes to the tension and compression. Furthermore, overall visual of the part is the same. The part has to be tested, therefore same studies will be done using three different softwares. The results furthermore will be compared to the ones that are of original part.

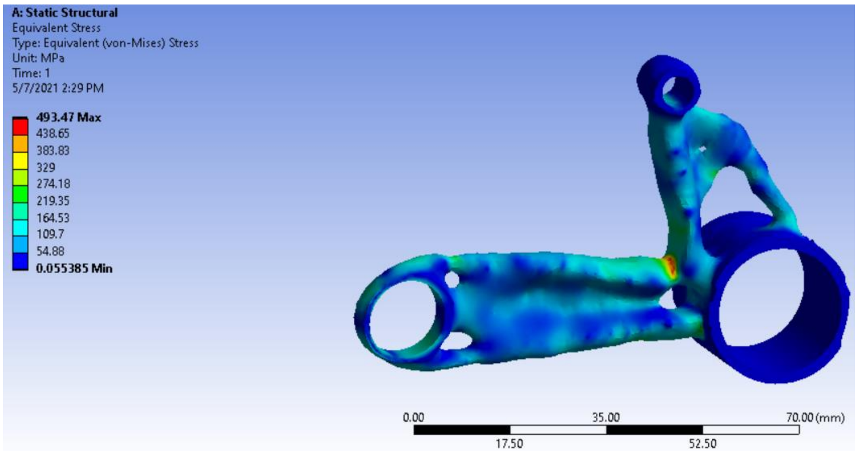


Fig. 2.21. Final part optimization with Ansys topological optimization. Von Mises stress results from Ansys software

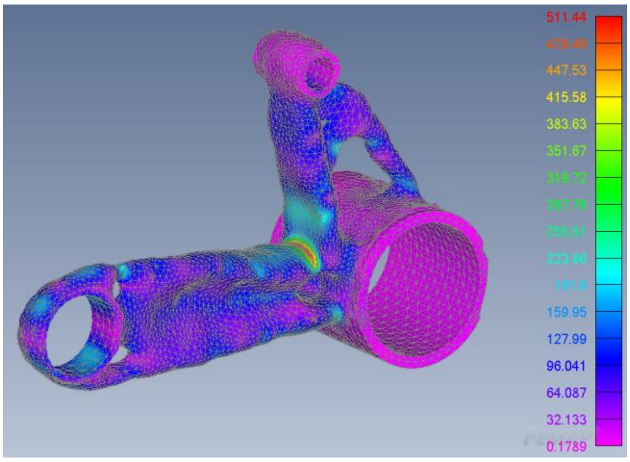


Fig. 2.22. Final part optimization with Ansys topological optimization. Von Mises stress results from Femap NASTRAN software

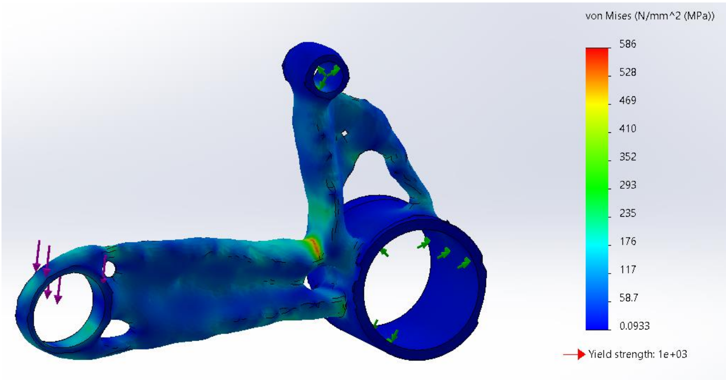


Fig. 2.23. Final part optimization with Ansys topological optimization. Von Mises stress results from SolidWorks software

As it can be seen from the images, the results are more or less similar to each other. SolidWorks software gives out the most different result, but as it was for the last time, only in stress accumulated area. As it can be seen from colour scheme, other areas are calculated to have almost the same or the same values as calculations with other softwares. Furthermore, as it was mentioned before, since Ansys software offer very high detail mesh smoothing, once the topological optimization is done, the files are easier to work with, easier to be meshed and therefore results show more uniform.

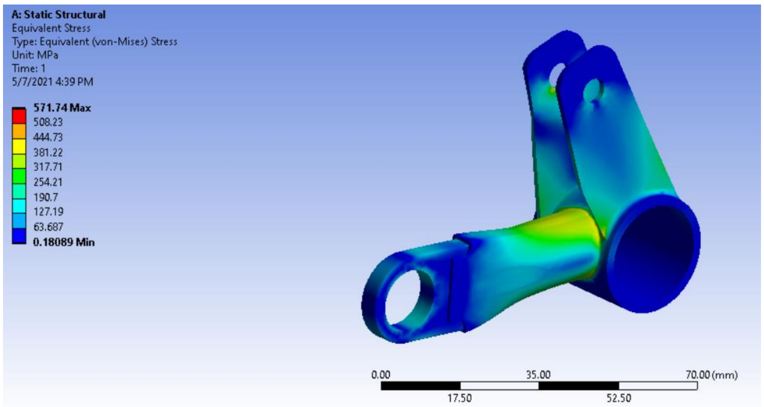


Fig. 2.24. Von Mises stress results of original part from Ansys software

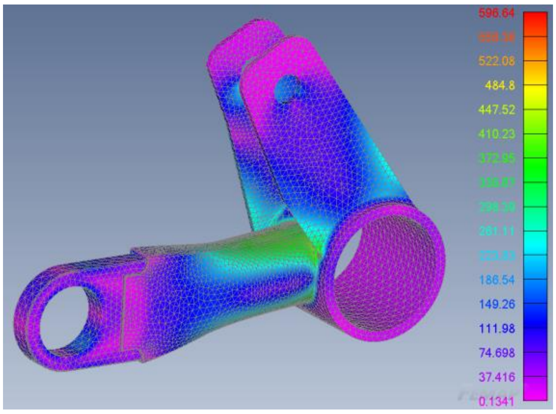


Fig. 2.25. Von Mises stress results of original part from Femap NASTRAN software

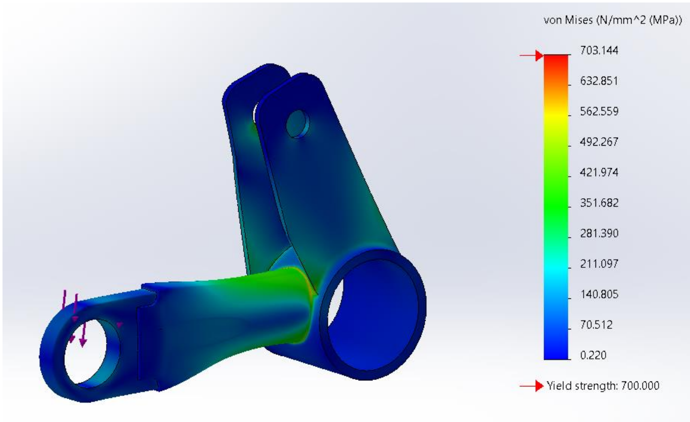


Fig. 2.26. Von Mises stress results of original part from SolidWorks software

Figures 2.24, 2.25 and 2.26 show the original part's stress values with 30ChGSA material applied. As it can be seen, the SolidWorks software does come out with the most different value out of all three softwares. This, as it was for all of the previous studies, is only in the stress accumulated areas. To have more clear understanding of what the final values are, table 2.5 is composed.

Table 2.5. Finite element analysis of final TO compared to original part

	Material	FEA Software	Von Mises maximum stress, MPa	Total deformation, mm	Maximum strain, mm/mm	Buckling factor of safety
Topologically optimized part for manufacturing	Ti6Al4V by EOS	Ansys	493.47	0.591	0.0043	28.854
		Femap NASTRAN	511.44	0.589	0.0039	28.095
		SolidWorks	586.00	0.591	0.0035	29.213
Original part	30ChGSA	Ansys	571.74	0.729	0.0030	18.15
		Femap NASTRAN	596.64	0.730	0.0027	17.86
		SolidWorks	703.14	0.732	0.0026	17.91

As it is shown in the table, topologically optimized part does not only show better values, but also reduced amount of stress. This means that changed geometry does not have such spots, where stress could easily accumulate. Furthermore, factor of safety in case of buckling is increased greatly, this is because geometry changes that were applied, increased bulky areas where it was needed, therefore risk of buckling decreased by a lot. The weights are as follows:

- Topologically optimized part for manufacturing – 54 grams;
- Original part – 83-85 grams.

According to the weights, the reduction of weight in topologically optimized part would be ~35%. Moreover, while weight was reduced, the strength of the part was increased, deformation values and risk of buckling decreased. This shows that every single feature was improved with the choice of additive manufacturing with Ti6Al4V over conventional manufacturing. As the studies have shown, riskier options with more weight reduction are possible, but because of the reasons mentioned before, the latest TO will be the choice for AM. Lastly, the maximum strength of the final TO was checked, using the same method as with the Formula (9) and 1N force. Maximum force that should be applied to the part is as follows:

- Ansys software – 2542N;
- Femap NASTRAN software – 2217N;
- SolidWorks software – 2634N.

As the maximum force for original part was chosen 1300N, it can be seen, that final factor of safety of the part is 2.5. This not only leads to safe choice for use but also show how topological optimization may greatly improve every single aspect of the part.

Finally, the fatigue of the final toplogical optimization should be discussed, therefore according to S-N curve [68], the lifetime of a part is calculated using Ansys software. Results are given in figure 2.28.

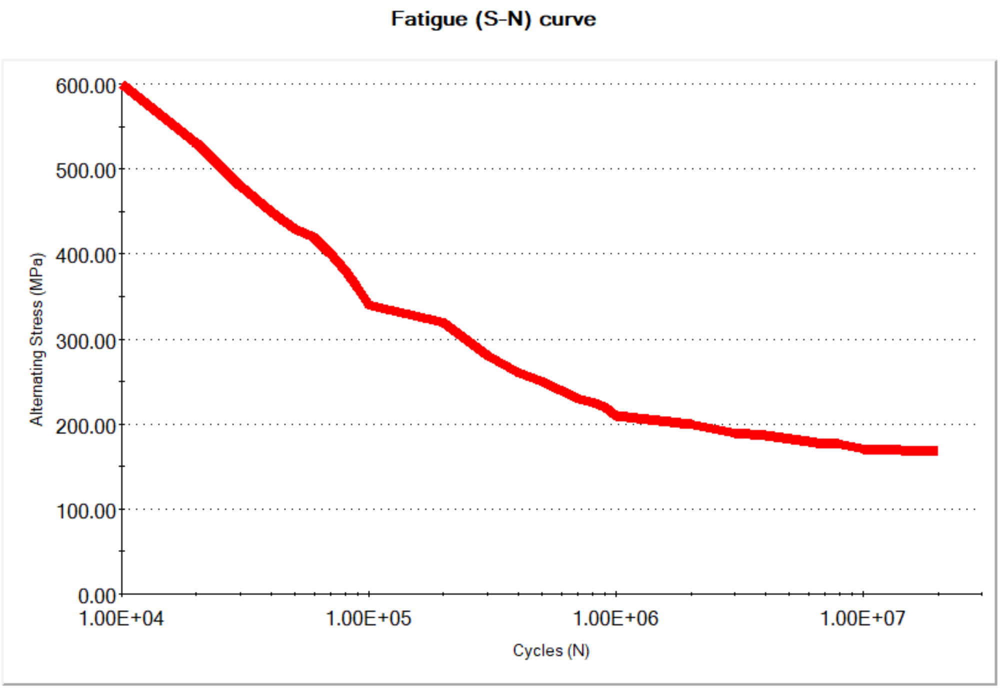


Fig. 2.27. S-N curve of Ti6Al4V + HIP treatment as printed [68]

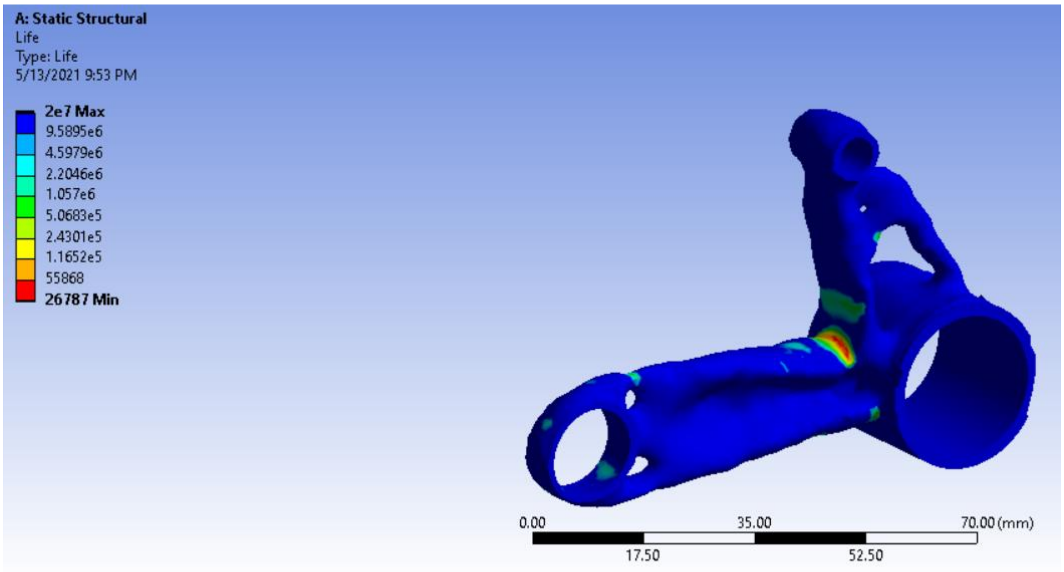


Fig. 2.28. Sensitivity of a part according to fatigue calculated using Ansys software

As it can be seen from figure 2.28, the maximum number of cycles this part could withstand with maximum loading is approximately 27 000. One of the reasons behind this is that there is no further information of cyclic loading and fatigue under higher stress than 600 MPa. According to studies, if the part is post-processed using any kind of sanding or machining, so the surface would be smooth, the available life would increase drastically, but this needs further research and is out of scope of this paperwork. The fatigue is not calculated using other softwares, as the S-N curve is always going to be the same.

Furthermore, according to sailplane's maintenance manual, the lifetime is 6000 hours [46], therefore the lifetime of this part could be calculated approximately. As there is not actual statistic loading data available, the cycles and overall loading principle should be approximated. It can be easily calculated, that the part is capable of maximum loading once every 13.3 minutes in the full lifetime, and it is known that typically sailpane's do not fly in difficult and high loading conditions or it happens very rarely. Fatigue calulcations would be a lot more precise if actual data of loading was known and fatigue of material was tested.

2.3. Geometry of additively manufactured part

As it was mentioned, the part that was chosen to be manufactured, was the one that had increased safety factor and was over all a bit bulkier. It took over a month for a single part to be manufactured. It took this long, only because a single part need to be put up together with full batch of other parts into single build, so it would be profitable for manufacturing company. If the part was ready for batch production, the manufacturing time would drop down to less than a week (discussed with manufacturers).

Fig. 2.29. Manufactured part; a) upskin, with visible layer lines; b) downskin with visible support area

The manufacturer of this part have told the orientation in which the part was built. It can be seen in the figure 2.29 a) the layer lines are fully visible, therefore it is concluded that this side was upskin and therefore it was left completely untouched as it did not need any kind of post-processing. In the lower part of the figure 2.29 b) it can be seen that this part was the downskin and therefore all supports were added to this area. Furthermore it can be seen, that this area is post-processed by removing support structures. Close up of layers is given in figure 2.30, with added axes to understand layers.

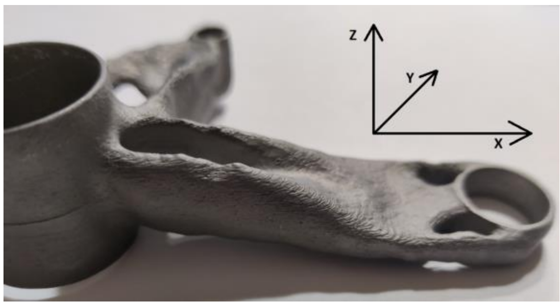


Fig. 2.30. Visible layering and orientation of manufactured part

Nonetheless, as the part arrived, there were some defects that were easily noticeable. Defects can be seen in figure 2.31. The a part shows how one one cylinder is not round at all, and rather resembles ellipitical shape. This deformation could be because of couple of reasons – the printer was not set up correctly, lack of support structures made the part deform and lastly the part could have been deformed during post-processing due to human error of too aggressive support cleaning. The b part shows the same cylinder but with focus on the inside, as some layers have moved a bit to the side and therefore visible geometrical deviation can be seen. This could have happened only because of wrong printer set up, as the deformation is in the middle of the part. There is slight chance, that deformations correlate together and lack of support structures in beginning of the print made sure that further deformations happened. The deviation of cylinder geometry to the side further on returns back to original position. This could have also been impacted by human, as it is possible to stop manufacturing in the middle of action, adjusting laser of build platform axes and to continue further on, but as it is unknown, it may only be guessed. Further on, as b picture is taken from the other side (upskin side), it can be seen that cylinder in this side is completely correct. Lastly as seen in photo c, the same deformation as in b happens on the outside of the cylinder. Furthermore in c it is visible, that the upskin of the part (left side of the photo) is perpendicular to z axis, while the downskin (right side of the photo) does not have such feature, even though it was designed so. This deformation could happen because of the same reasons as deformation in a, because it was once again, the beginning of the part. These deformations should be considered as critical, as it is nearly impossible to find right center axis for big cylinder. On top of that, the insertion of the bearings or any other kind of material that would be a fit for testing phase is going to be more difficult, as the whole cylinder is warped inside out.

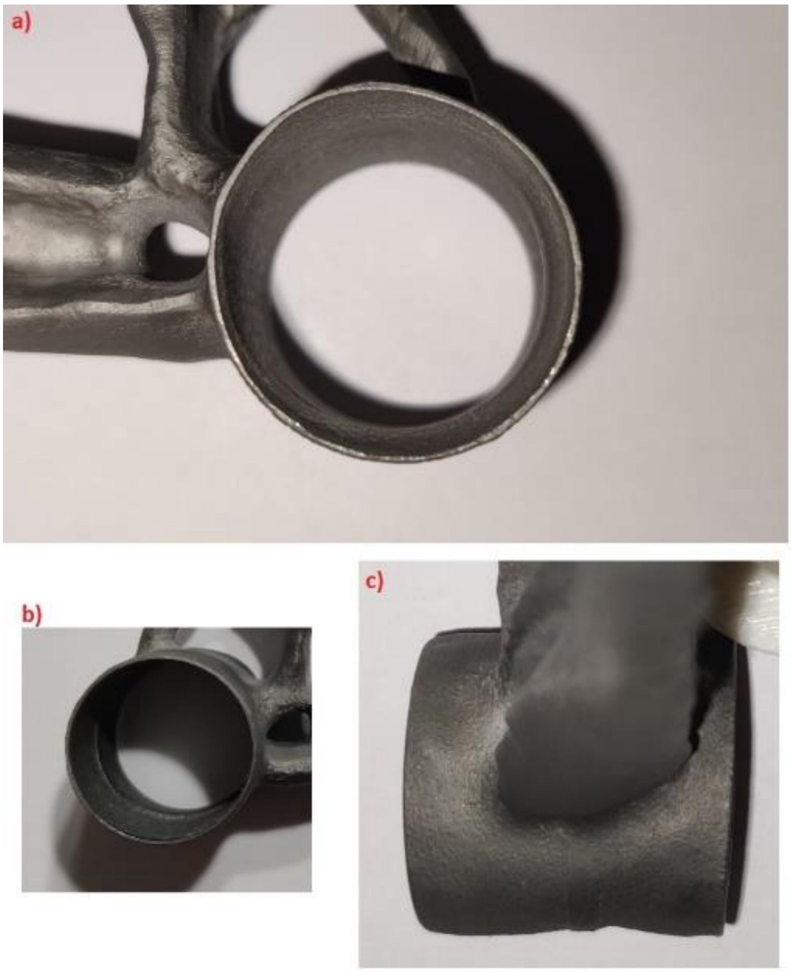


Fig. 2.31. Deformations of manufactured part; a) cylinder deformation to elliptical shape; b) geometrical deviation inside of the cylinder; c) loss of perpendicularity and geometrical deviation outside of the cylinder

The deformations show that it was necessary to choose bulkier and more secure topological optimization, since riskier TO’s are hard to manufacture. The deformations of slimmer parts compared to the one that is manufactured can only be estimated, as support removal procedure is a lot more difficult and overall support positioning should be though of very thoroughly while constant communication between customer and manufacturer must be established. The full process of part's complete optimization for AM may reach from months to years, completely depending on funding and deadlines (information from manufacturer). Final deviations are given in figure 2.32. It can be seen, that nominal dimensions (a) in most cases are a bit bigger. Dimensions of actual part (b) show, that smallest deviations are of the circular areas in cylinders. Nonetheless, deformations that were given in figure 2.31 can be seen where dimension is given with dash. In figure 2.32, dash shows dimensions of both sides, therefore the deformation could be understood in the sense of millimeters.

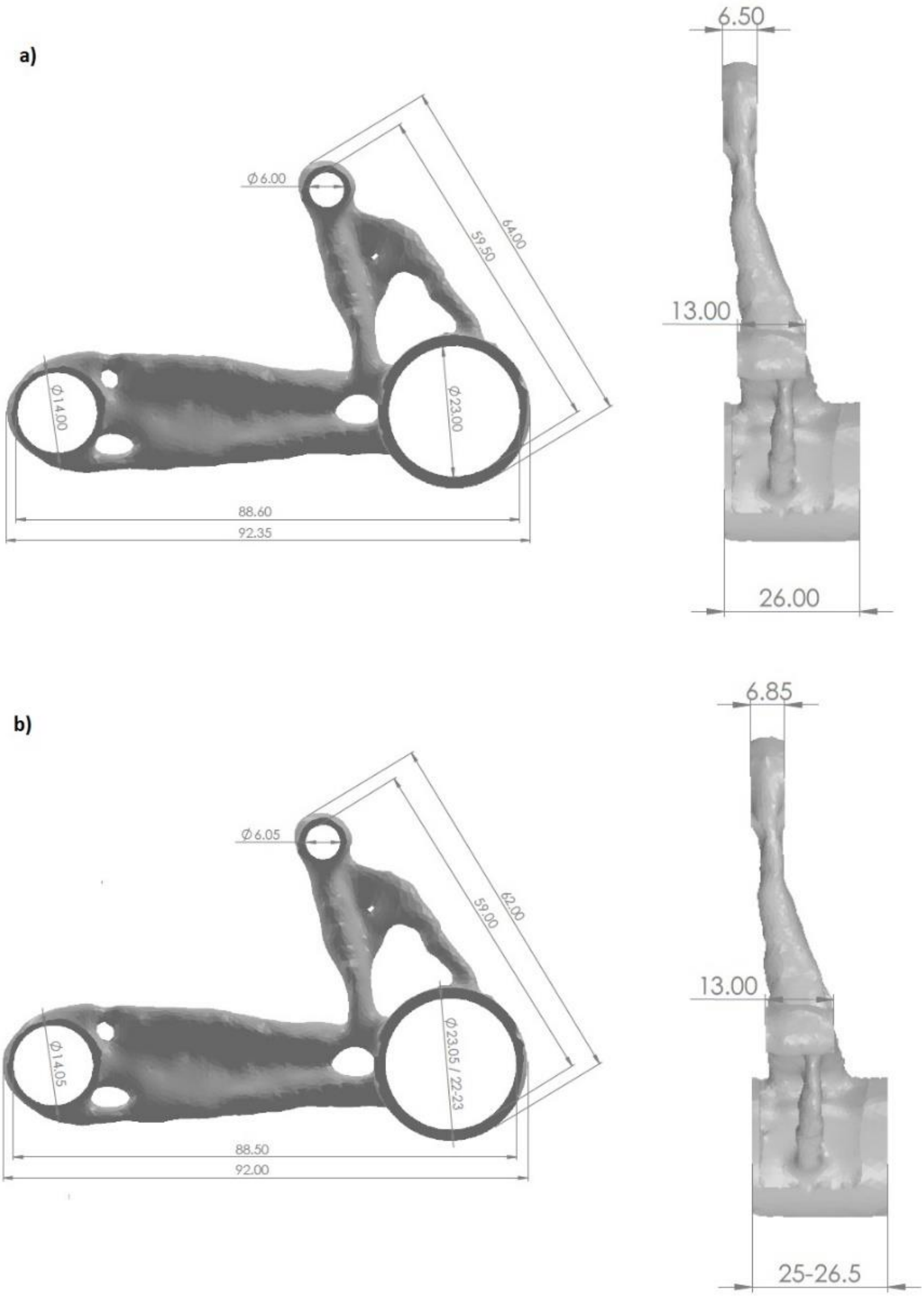


Fig. 2.32. Geometrical deviation of manufactured part; a) nominal dimensions; b) actual dimensions

2.4. Concept approval testing

Lastly, as the manufactured part had to be tested out for concept approval, it had to be fully assembled and testing mount had to be built. For this specific reason, bearings that fit the bigger cylinder were glued into position. Furthermore, individual bushing was turned for the cylinder in the front (where forces should be applied) and same as with bearings, was glued in position. Lastly, rod for tension was attached to the bushing. Fully assembled part can be seen in figure 2.33. Once the part was fully assembled, the mount was built and the part was attached with spacers to have every single connector in line with force vector.

Fig. 2.33. Completed part with bearings and tension rod

The testing of the part was done with Tinius Olsen h10kt machine that is as well as other machines, located in the faculty of Mechanical Engineering and Design. The machine is capable of forces up to 10kN. The testing speed was chosen to be 2mm/min. Lastly, the actual testing phase was divided into 3 sections:

1. Tension and compression up to 867N (force of original part with 1.5 factor of safety applied);
2. Tension and compression up to 1300N (force of original part's failure point – without factor of safety applied);
3. Tension OR compression up to breaking point (which according to simulations should be approximately ~2500N).

The specimen with a mount attached to testing machine can be seen in figure 2.34. As it can be seen, the mount was built so compression of the part could be tested by turning the whole assembly around and reattaching the fixing plate to different holes.

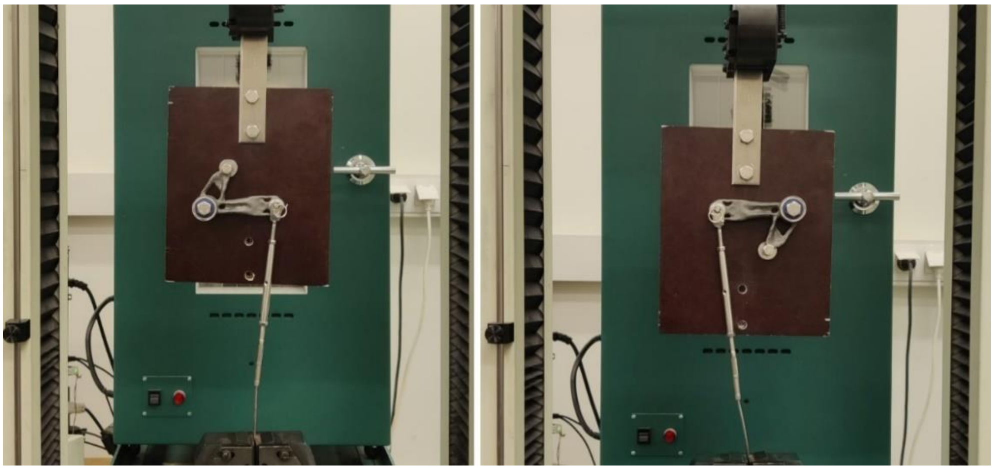


Fig. 2.34. Tension (left) and compression (right) of manufactured part

With this mount the first and second parts of testing phase were completed successfully, and as it was known, the part withheld all of the forces, without any deformations whatsoever. As the mounting bracket was not strong enough for forces that would have broken the part, new mounting bracket must be built or the last one reinforced.

As the test's main purpose was to test if the part is capable of withstanding nominal forces and is designed and manufactured in the manner that was desired. Such testing did not provide stress values. Moreover, the strain results do not show correct information, as the whole mount was not stiff enough and all deformations were put up together. One of the parts, that was constantly moving and deforming – tension rod. Secondly – some of the bolts did move as well, therefore the deformation was accumulated with all of these factors and in some cases amounted to ~20mm.

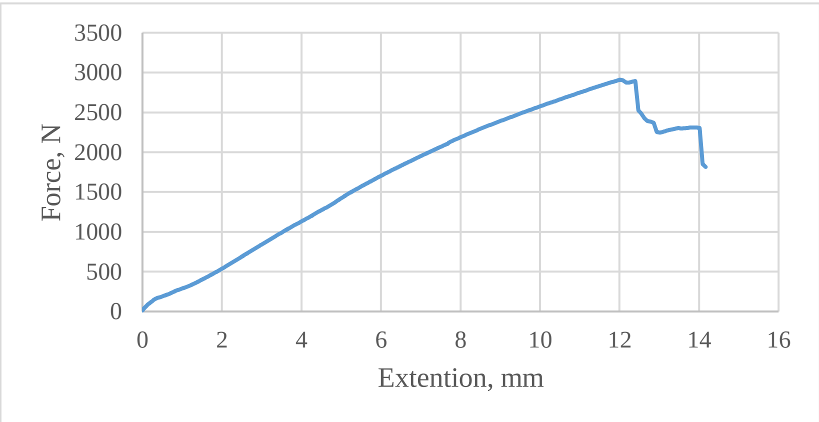


Fig. 2.35. Results of additively manufactured part's testing until breakdown. Part broke at 2900N

The figure 2.35 shows curve of force needed until part broke apart. Extention is inaccurate in this graph. As it can be seen, the maximum force that was needed to break this part was aproximatelly 2900N and this resulting force is only about 10% higher than it was calculated with FEA. Also, to have more accurate results more iterations of testing should be conducted, but that requires more specimens.

As it can be seen, the part did actually withstand all of the original forces that were the nominal factor. This means that this part could easily be tested real life applications and furthermore means that every other similar part that is manufactured in conventional way, could be adapted for AM with big increase in technical and mechanical properties.

2.5. Final overview

From economical point of view, the part's cost with AM is noticeably higher, as when tested in price optimal price calculator [43], price of one part is approximately 240 EUR+VAT. But if bigger batches would be ordered, for example a batch of 50 pieces, the price would drop down to approximately 170 EUR+VAT / pcs. If manufacturing was done with local manufacturer, with help of contracts, there would be possibility of further price reduction. Furthermore, as original part is constructed of 5-6 different subparts, it needs assembly, welding and quality control. This means that it requires a lot of human working hours for a single part, high level of welding (as the part is very small), constant ordering and logistics management of different materials. All of these procedures combined show how complicated conventional manufacturing is, and how much time could be saved if turned to AM.

As it was mentioned in literature review, different machines or materials may not have isotropic properties, therefore this must be kept in mind before designing a part. The customer should order specimens for different tests and should test if chosen manufacturer is capable of manufacturing parts with isotropic properties. Furthermore, different tests should be conducted, as for example shear forces in this thesis are not tested, because of lack of capabilities. The specimens for tensile testing should have longer arms, so the probability of slipping should not occur and therefore not only UTS would be tested, but also plastic and elastic properties would be known.

As for topological optimization and FEA, the software of choice should be carefully examined. Even though the results of FEA are similar (only stress accumulated areas show different results), the results of topological optimization are a bit more different. The Ansys software does a better job at smoothing the whole part, but at the same time is a bit more "careful" than SolidWorks. SolidWorks software does optimize part with more aggressive approach, therefore calculations must be performed to know if final part is strong enough to withstand needed forces.

Regarding the manufacturability, the part must be manufactured in multiple iterations, so the printer's setting would be optimal for such part. Furthermore, different support settings must be thought over, so the risk of breaking part while removing support structures would be narrowed down. Same goes for quality control, as if parts were ordered in bigger batches, the manufacturer would hold the responsibility for any kind of deformations, making sure that finally received parts are always of the highest condition.

The proposed part should be tested as installed into full assembly to understand if it fits correctly. Furthermore, there is huge possibility, that better geometry is possible and even lighter part could be offered, but as the actual free space is unknown, it could be investigated furthermore.The final geometry, designed by original glider's manufacturer could look completely different than it looks now and therefore it opens a wide array of possibilities.

Finally, the thesis proves, how additive manufacturing could be integrated in aviation and how difficult and complex assemblies could be changed to easily maintainable and lighter parts. As mentioned couple times in the work – the possibilities are limitless, as any kind of geometry is possible to be manufactured.

Conclusions

1. With analysis of 3D printing and application to aviation conducted it was found out, that additive manufacturing brings not only huge possibilities, but also is greatly environmentaly friendly, as it reduces waste, need for logistics and other aspects. Also it was found out, that additive manufacturing is starting to be greatly tested and used for aviation, meaning that the innovative design optimizations and overall quality of additive manufacturing will increase greatly. Finally, with topology optimization analyzed, it is seen that to get the most out of the part, topological optimization must be conducted with great interest in boundary conditions. If the level of topological optimization should be increased, extra programming or specific softwares should be used for the design of infill, support or anisotropical part optimizations.
2. Tensile tests were conducted of different orientations specimens to check if manufacturer is capable to produce parts with isotropic properties. It was found out, that specimens are capable of withstanding forces of: 30 487.96N ± 2.39% in 0 degree; 30 711.75 ± 2.27% in 90 degree and 30 503.93 ± 2.25% in 45 degree orientations with accordance to the build plate. The ultimate tensile stress across all specimens was approximately 1100MPa and difference between strongest and weakest specimen's value of ultimate tensile strength with possible error in mind was less than 1%, therefore meaning that these specimens do have full isotropic properties.
3. Sailplane's part was composed in SolidWorks computer aided design software and tested using same software's finite element analysis tool. It was found out, that original part with 30ChGSA steel is capable of withstanding approximately 1300N. Further on multiple topological optimizations were conducted, but as higher chance of easy manufacturability was desired, the part for manufacturing had to be chosen with extra factor of safety. That is because if a part is slim, or has small features, that are in fact still manufacturable, it could be easily deformed with wrong printer settings or non-careful support structure removal procedure. This would increase the final value of the part and manufacturing time.
4. With multiple sets of finite element analyses conducted, it was noticed that different softwares do have different outcomes with calculation of stress accumulated areas. Moreover, it was found out that topological optimizations that were done to parts with factor of safety 1 (that would break on 1300N force) had mechanical properties that would satisfy needed strength requirements. This furthermore shows how strong topological optimization tool could be if every boundary condition and every aspect about the part were known. Nonetheless, because of manufacturability, the final topological optimization with factor of safety 2.5 was conducted and the part not only showed better mechanical properties with decrease of stress and deformation values and increase of buckling and static factor of safety, but also reduced the weigh by 35%. As more than one topological optimization was done, it is known that further weight reduction could be implemented further increasing the percentage of reduced weight up to 60% or even more with additional constraints and iterations.
5. As the part was manufactured and received, after inspection, huge defects were noticed. Once part was fully assembled with bearings and other subparts the prototype approval tensile tests were conducted. With testing finished, it was found out that the part is capable of withstanding forces that were an original factor of design (1300N). Furthermore, the part withstand the force of 2900N, therefore the maximum force is 10% higher than it was calculated using FEA software. The difference is very small and might be resulting error because of numerical or meshing, possible manufacturing or experimental errors. As every testing section was done and results were correct, it can be stated that part is ready for testing in real life applications and situations.

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