Implementing 3D printers to produce airworthy aircraft cabin parts.

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Summary

The entire project is based on investigating the implementation of 3D printers to produce air-worthy aircraft cabin parts. The project consists of 3 phases : research phase, design phase and final phase where the design is finalized and validated.

The research phase
The research phase starts with an extensive literature study. To this end, a research question was drawn up, which reads as follows: What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?

The most interesting findings from this literature study are as follows. The 3 most frequently mentioned benefits that AM offers the aviation industry is the ability to produce complex geometry, lightweight part production and reduce material waste. Moreover, each conserved kg saves US$3000 on an annual basis in fuel. Designated certification standards or criteria applicable for AM parts do not exist yet. Besides, material plays an overwhelming role in the selection of an AM machine. The current use in the studied literature were mainly certified metal AM parts, all were critical components from the engine or wing. Last, the production of plastic tooling is low-hanging fruit, which means that all the benefits that AM offers can also be used here and no certification is required.

The result from the literature study was very educational and broad. However, not all found can be used immediately for KLM's purpose. As a result, in the continuation of the project are some topics which were not applicable, re-examined and elaborated for KLM's use.

This involved firstly investigating the European regulatory bodies, EASA. Indeed, there are no standards or regulations for the use of AM in aviation yet. However, we know that 3D printed and certified exists. EASA explains the importance of repeatability of the production process and traceability of the material quality is the most important in general for production in the aviation. When we talk about producing and certifying parts, the certificates DOA and POA of EASA are of importance. With a DOA, an organization is allowed to design new parts within a specific category. While a POA allows an organization to produce new parts within a specific category. KLM holds of a DOA in aircraft cabin parts, but doesn't hold a POA yet.

Next are the applicable benefits AM offer applicable for KLM researched. This resulted in the top 5 of faster lead time, integrating assemblies, reducing weight, customization and reducing purchase costs. In the same way is the current use of AM by direct competitors of KLM investigated. Interesting to see that all these parts were plastic while most examples in the literature were about metal parts. With this outcome and the area in which KLM is allowed to design with its DOA is the cabin. An investigation has been done into which plastic printers may actually be used in the aviation industry to produce certified parts, due to the fact the cabin mainly consists of plastic parts. The result was only SLS and FDM. Because these 2 processes only have material that meets the general cabin material requirements applicable in the aviation.

Thereafter, a list of suitable components for AM was drawn up at 3 different times with different techniques executed during these moments.
In addition is a very elaborated trade-off table constructed to select part with the largest potential for each of the prior found top 5 benefits AM offers KLM. The list of criteria of the

trade-off table is based on previous AM benefit consequence relations found. All criteria are rated by 8 KLM experts to provide objective weights. This resulted into the selection of 5 products for each benefit.

The design phase

When entering the design phase with the 5 selected products, it was realized that some of the selected were categories instead of specific products. A new route has been created for this to easily find partner numbers for each category and compile real parts.

AM benefit = Selected component
Faster lead time = Zodiac seat armrest
Integrating assemblies* = Toilet paper holder*
Reduce weight = Recaro bi-fold seat tables
Customization = Boeing window shades
Reduce purchase costs = Zodiac business class cabin bumpers

Next is a standard template created which serves during the redesign process of each part and ensures structure but also that every concept is equally worked out. The template consists determining 4 comparison aspects, mind mapping, inspiration collage, idea sketching, CAD modeling, strength analysis and test on printability. The 4 comparison aspects create an overview on purchase price, lead time, weight and amount of parts between the original and redesigned parts. This overview easily displays whether an improvement or deterioration has been achieved with the redesign. The purchase price and weight are determined with a constructed formula. These formulas have been drawn up based on the ratio method. The lead time with an assumption, while the amount of parts can easily be counted in the CAD model. After this step is every redesign tested for strength with FEM analysis. This is done based on specific maximum use scenarios created for each component. The forces in these scenarios are determined by DINED, anthropometric database created by TU Delft. The strength analysis is highly important to validate and accept the determined comparison aspects for the redesigned parts. It can be shared that all components have passed the strength analysis. Similarly is testing on printability of a part very important. Even though all parts will be redesigned for AM, there may still be reasons why a component is not suitable for printing. It is best to remove these parts as quickly as possible. A method has been devised for this. Printability is related to 2 conditions, the function requi¬rements of the component and printer specifi¬cations. A list of function requirements are set up and linked to printer specifications of both FDM and SLS. When selecting the function requirements for the part, the limitations of the AM process will immediately be discovered which will serve to decide whether the part fits for AM or not.

All 5 parts have been developed into concepts where according to determinations very large improvements have been made compared to the original part. The main target during development of the 5 concepts was the AM benefit this part was selected for. While other advantages of AM are side concerns. One thing is certain, there can be lots gained even with the side issues.

Using the elaborate trade-off table constructed previously for selecting the most pro¬missing part to further develop. This resulted in the selection of the Zodiac seat armrest.

The final phase

During the final phase is the seat armrest redesigned concept further optimized. A specific list of requirements has been constructed and fined tuned by KLM experts specialized in airworthiness and seats. Consequently is the AM process and material selected, with which the strength analysis of the optimized component has been carried out. The process is SLS and material is PA2241FR. The maximum usage scenario has been changed to an extreme scenario whe-re the size of the prior force exerted on the component in the concept phase is doubled for the final phase. The optimized component even passed this analysis. After this the printa-bility test was performed for SLS and are the 4 comparison aspects determined.

Next is the component is checked on its preci-sion of dimensions and real fit on the assembly by producing tangible prototypes. Iterating the design in the real world and real use of context resulted into finalizing the CAD model.

With the final redesigned armrest being produ-ced in the eventual real specifications, could this SLS printed part be used to validate the previ-ously determined comparison aspects with the eventual real aspects. This results in 97% reduc-tion in lead time, 37% reduction in purchase costs and 58% in weight reduction when com-pared with the original part. This shows that the main benefit, lead time, the armrest is selected for is achieved. Besides, in case all current arm-rest will be replaced on the 777 and 787 fleet by the final seat armrest redesign, will result in a potential fuel cost reduction of $4.665.000 on an annual base.

After all the previous steps in design, test and maturation in the process, we have now fully completed the development of the new part and printability has been proven. The last final step is making a statement on meeting pre-viously set require¬ments and whether this part has a chance of obtaining a certification. This certification should declare the part being airworthy and therefore authorized to fly. To be able to make a substantiated statement, 7 experts actively on this topic were consulted. All have been shown the list of requirements and has the issue whether or not having a chance of success at KLM and obtaining certification for this redesign has been asked. We can conclude from the conversations and discussions held. That the results together prove the armrest meet previously set requirements and provide enough confidence to conclude that the new armrest will get certified and thus succeeded. The most important thing is that the operator (KLM) accepts the new part and expiry of the ETSO certificate. And the com¬ponent must be proven for flammability and the moment of breaking will have sharp edges. We know that this has happened before, which generates sufficient confidence.

All in all, the results from the discussions held with 7 experts together with the real compari-son aspects of the SLS printed part shows that the project has led to an amazing and suc-ces¬sful result.

1. Introduction

Air travel is something many of us take for granted. We don't stop to think about the millions of people traveling up in the sky at any moment. To continue to do this safely, these aircrafts often have to pass the garage to get maintained. The role of these garages are to keep aircrafts technically fit to fly, the condition it remains airworthy.

Every detailed maintenance record is retained for several years to enable to demonstrate it's being done in accordance with all requirements and by an appropriately approved certifying engineer. This has been imposed and is being monitored by the regulatory body, European Aviation Safety Agency (EASA). Its mission is to promote the highest common standards and environmental protection in civil aviation where safety is being the driving factor.

KLM Royal Dutch Airlines is the flag carrier airline of the Netherlands. The KLM Group consists of KLM and several daughter companies. They fly passengers and cargo from a to b and hereafter maintain their aircrafts. This last business domain is the called KLM Engineering & Maintenance (KLM E&M) and is unknown by the general audience. Important to know is that not many airlines in the world operate in the aforementioned 3 businesses.

The aerospace industry is constantly striving and demanding for lighter, better and cheaper aircraft components without compromising on safety and reliability requirements. The never ending thirst is keeping the search alive to continue optimizing strength-to-weight ratio to improve fuel efficiency and reduce emissions. (Braga D., et al., 2014). This thirst ensures aerospace designers to strive in minimizing the amount of material used in every component, which results in increased design complexity with respect to the structure, function, and property. (Gibson I., et al., 2014).

The traditional manufacturing methods already reached the limits in achieving weight reductions. (Simgamneni S., et al., 2019). Additive manufacturing (AM), generally known as 3D printing, has been around for decades, but the developments in materials and reliability of the printing process have found their way into aviation. AM allows the fabrication of parts with virtually any shape (Gibson, et al., 2014). This development and interest of various companies in the aviation industry for this technology has not gone unnoticed by KLM. To understand the opportunities and get acquainted with this technology and its process, KLM started using FDM printers of Ultimaker one year ago. Uncertified tooling and equipment for own use such as jigs, fixtures, etc. are being produced on these printers to make the job easier, faster, cheaper and safer for maintenance engineers.

The next step for KLM is, manufacturing own certified and airworthy aircraft parts with 3D printers. But how?

2. Problem Definition

Exactly at the point where developments in Additive Manufacturing (AM) took place enabling its use in aviation, sees KLM the opportunity of implementing AM to locally manufacture spare parts in their E&M department.

KLM is especially interested in clarifying the pros and cons AM could offer KLM and the aviation industry. They do not want to lag behind in terms of technology and are curious about what kind of advantages KLM can acquire from AM. Besides, the additional and required frameworks by means of legislations developed by regulatory bodies such as EASA and FAA regarding the use of this new technology should be determined. Additionally, the current permissions of KLM and restraints to overcome should be well defined.

The goal and interest of KLM are rather clear. However, even when the exact capabilities of the 3D printing technology would be known, and the certification to produce is received by KLM would the research not be successful. It is unknown which components could provide new opportunities when printed, how they would need to be (re)designed and made suitable for 3D printing.

All result in the formation of the following main research question: "What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?".

This project will function as a first step in the direction of the future for KLM in AM. The objective in this early stage of innovation is only to focus on the non-critical parts of airplanes. Which embraces everything that has neither influence on the safety nor the control of the aircraft. This in connection with the known strict regulations of the sector and raising the odds of getting certifications on the design and production of these parts.


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3. Literature Review
additive manufacturing for aviation

The objective of this first chapter, the literature review, is to find answers to the main and sub-research questions as on an academically based manner. While the study is mainly done to find answers to the main question of the project, it could possibly provide advice on the next steps in the process of this project. The method of Dr. J.R. Ortt (2017) has been used to select the most suitable articles in a substantiated manner.

Chapter structure

The method that will be used is elaborated in §3.1. The results of the literature study for each sub-question are being treated in §3.2, together with the conclusions for each sub-question. The general conclusion of the whole literature study is explained in §3.3. At last is the literature gap described in §3.4.

3.1 Method

The main research question of this project:
What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?

The main question can actually be divided in three parts:
1. What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production?
2. In what way can suitable parts be selected for airworthy AM parts?
3. In what way can suitable parts be redesigned for airworthy AM parts?

We will try to answer the first and second part of the main research question by literature. For this reason are these parts of the main question enriched with sub-questions. These sub-questions serve in searching by a more focused and framed way, this may possibly lead faster to better results.

Sub-question 1: Which factors affect using AM to produce airworthy parts?
Sub-question 2: Which AM techniques are applicable in aviation?
Sub-question 3: What are the criteria to measure usability of AM techniques in aviation?
Sub-question 4: How should AM need to mature for aviation use?
Sub-question 5: For which applications is AM currently used in aviation?

The search engines Scopus, Science Direct and Google Scholar have been used to track articles with relevance to the sub-questions. To work in a structured and efficient way, the selection method of Dr. J.R. Ortt (2017) has been used to reduce the number of articles which are fully read and analyzed. This selection method is illustrated in Figure 1.

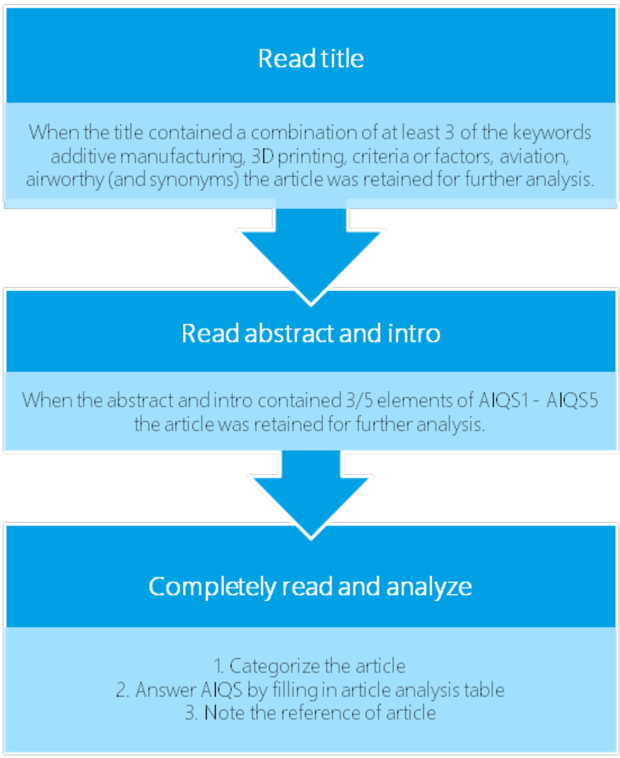


Figure 1. Article selection process

When the title of the article contained a combination of at least 3 of the keywords additive manufacturing, 3D printing, criteria or factors, aviation, and airworthy the article was retained for further analysis. As Cummins (2018) explains, is flying the safest way of transportation. This is achieved thanks to strict rules and standards of operation in the aviation industry, constructed and maintained by institutions whom focus is retaining flight safety. Dozens of flights are being cancelled for safety inspections (Cummins E., 2018). For these reasons it is not allowed to simply implement AM. This difficulty level in the industry is also one of the reasons why KLM found it necessary to start this project. It is important to investigate whether it is possible to use this technology and how this is possible. For this reason, it seems sensible to narrow the search field to articles that are specific about the industry combined with AM. This approach has been implemented to reach usable information faster.

The sub-questions have been formed into Abstract and Introduction Questions (AIQs). These AIQs are used to assess whether an article needs to be read fully or not. When the abstract and introduction contained the 3 out of 5 of the following elements the article was completely read and analyzed.

AIQS1: Benefits AM offer aviation
AIQS2: Differences and types of AM techniques in aviation
AIQS3: Criteria to asses different AM techniques on usability in aviation
AIQS4: Future potential, gaps and needs of AM in aviation
AIQS5: Current use of AM in aviation

This complete selection process, analysis of the selected articles and total results as bar charts are displayed elaborately in Appendix A.

3.2 Results

In total of 48 relevant articles are found about this research topic, 47 are collected with the preset constraints of the method explained in the previous paragraph. One article is subtracted from the reference list. During the analysis, several similarities were concluded between articles in their way of presenting information and method. These resemblances are used to cluster the articles on which resulted in the following 5 clusters. This clustering method is developed to create an overview and because the similarities between articles was noticed.

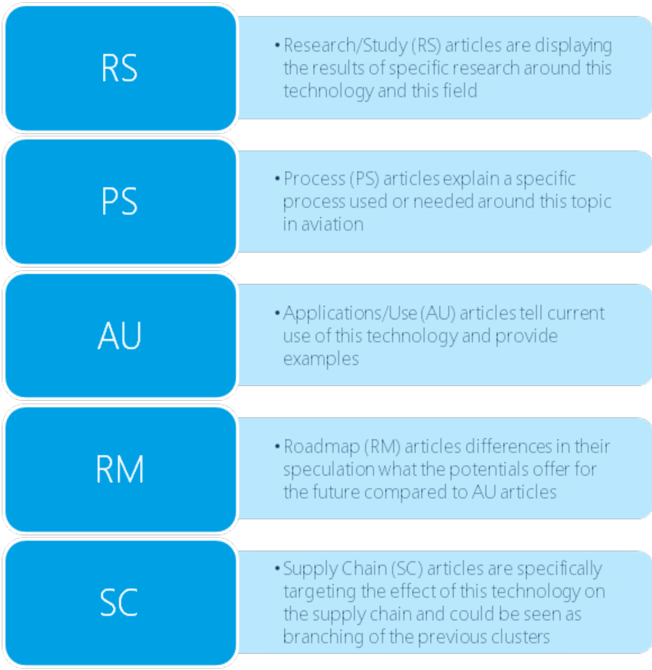


Figure 2. Clustering articles method

After the selection process used to filter out read worthy article with the use of AIQs, 17 articles are left over. The following paragraphs will narrate the in-depth results for each AIQ and visualize these graphical when possible.

3.2.1 AIQS1 Results: Benefits AM offer aviation

With the first question we tried to get the following question answered, AIQS1: Benefits AM offer aviation.

The mostly mentioned keywords and terms answering the benefits in the 17 analyzed articles are cited in Appendix B. These citations are clustered and significant resemblances could be derived from the articles, figure 3 shows exactly which benefits were the mostly mentioned. This could mean that the more often something returns, the more important it is.

Additive Manufacturing (AM) has be defined according to ASTM International (2012) as the process of joining materials to make objects from three-dimensional model data, usually layer upon layer.

Complex geometries

76% of the articles agrees AMs ability to produce complex geometries thanks to its use of layer upon layer construction technique as an important benefit for aviation. AM can manufacture novel geometries that would be difficult or impossible to achieve using Conventional Manufacturing (CM), which can improve a components engineering performance (Horn et al., 2012; Tuck et al, 2008). Aerospace components often have complex geometries because aerospace applications usually require components with integrated functions, such as airfoils with an embedded cooling channel (Liu R. et al, 2017).

Design freedom

This benefit provides design engineers unparalleled freedom in component design and fabrication as compared to CM (Atzeni E. et al, 2012). In the era of CM processes, the designer used a term called design for manufacturing (DFM), which was essentially a constraint against design options since more intricate designs were extremely costly to produce. AM changes this paradigm into "if you can design, AM can produce it" (Schiller G.J., 2015). Unlike DFM which has to contend with production constraints, does AM enable to design focused on the function of the part. Which actually means that AM enables truly optimization of parts to make it more efficient and reliable, by not having these production constraints. This makes it possible to design a system directly according to end-user requirements, while not necessary compromising due to manufacturing infeasibility (Han P. 2017).

Lightweight design

The advantage of AM over CM is its capability to handle very complex shapes, and particularly internal shapes (Han P., 2017). This way, AM can more easily produce different honeycomb structures and shapes that ensure weight reduction. So does 65% of the articles mention the ability for lightweight design and reducing weight as an benefit. Lighter weight aircrafts are a critical strategy for reducing societal energy use and emissions (Immarigeon et al, 1995). Aviation is currently the second largest consumer of transport fuels globally (IEA, 2010). AM has the potential to drastically reduce resources, energy requirement, and process-related CO_2 emissions per unit of GDP (Petrovic V. et al, 2011; Baumers M. et al, 2011; Baumers M., 2012; Campbell T., et al, 2011; Kreiger M. et al, 2013). Every kilogram is pretty important in aviation industry, each saved kilogram reduces the annual fuel expenses by US$3000 (Reeves P., 2012). The most attractive benefit for this industry is the potential for fuel savings due to more lighter parts (Sunil C., 2015).

Reduce material waste

The so called "buy-to-fly ratio", which is the total of raw material needed per unit mass of the finished components. AM significantly reduces this ratio to (almost) 1:1 while CM process this ratio ranges from 12:1 to 25:1 (Oak Ridge

National Laboratory, 2010; Dornfeld, 2011). These high buy-to-fly ratios result in massive amounts of waste of materials, which leads to unnecessary high manufacturing costs, large energy and environmental emissions footprint (Dornfeld, 2010). Machining of aircraft structural components can waste even up to 90% of the raw material (Hodonou C. 2019). The environmental footprint of component manufacturing is reduced through avoidance of tools, dies and materials scrap associated with CM processes (Morrow et al, 2017; Serres et al, 2011). The majority of the energy savings will come from a reduction in airplane fuel consumption due to the lighter weight of the AM parts (Huang R., 2016).

No tooling or multi channel processing ensure faster lead time and enables customization

AM doesn't require any traditional tools, jigs or even multi-channel processing to manufacture parts (Wohlers Report, 2013). These characteristics of the AM production process greatly reduces the processing process and shorten the processing cycle (Lu B. et al, 2013). The cost and time advantages for AM parts are considered to be one of the best solutions to handle the upcoming mass customization trend (Zhang X. et al, 2019).

In contrast to CM, does AM enable to completely revision of design without additional extra costs due to no tooling being used. Which prevents project delays, huge cost overruns due to modification and increased lead times. Besides, AMs cubic workspace allows multiple different shaped parts to be printed all in the same production run saving valuable machine an printer time (Rehmanjan U.H. 2015).

Reduced inventory and quick production

AM manufacturing process being automated drastically reduced the amount of supply chain management (Berman B., 2012). Whereas the requirements for inventory and stock can be reduced (Sutherland W.J. et al. 2013; Khajavi S.H. et al., 2014). According to Airbus, the turnaround for test or replacement parts can now be as short as 2 weeks (Smar Tech, 2014).

Integrate assemblies and reduce (labor) costs

As complexity increases, traditional manufacturing costs increase simultaneously. Complex

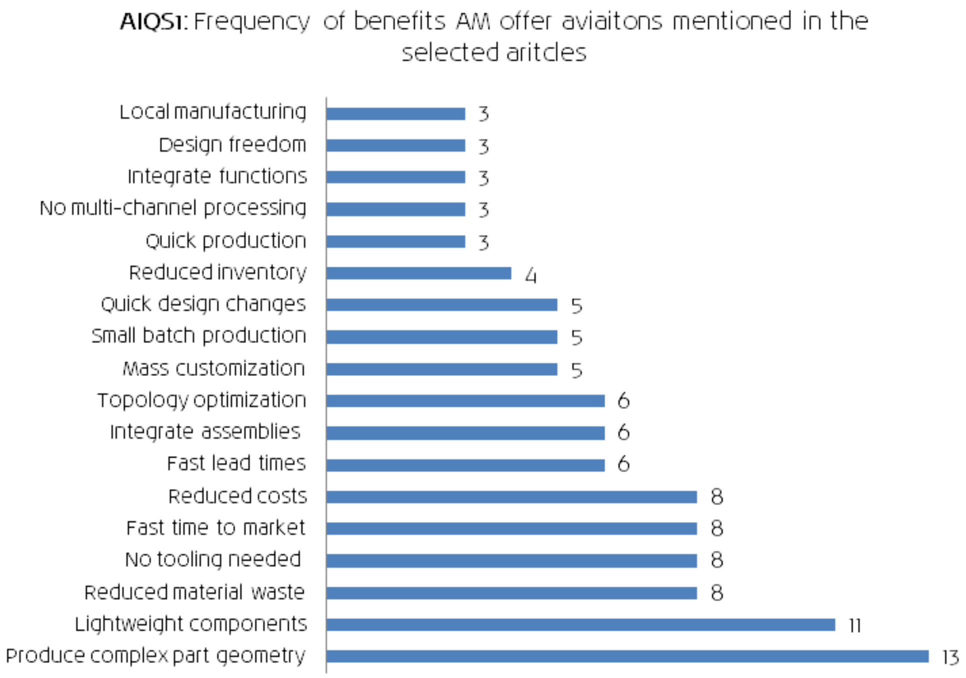


Figure 3. Results of AIQS1 Frequency of mentioned benefits.

parts require multitudes if individual parts that must be fastened together with nuts, bolts, welds or brazed. Each of these connections reduces the reliability of the component which leads to increased inspection requirements (Schiller G.J., 2015). All of these require extra human labor which result in even more increase in costs. AM makes multi-channel processing where fabricated parts are getting assembled in multiple steps unnecessary by printing the whole assembly as one part (Sunil C. 2015), which logically ensure cost reduction in labor.

Cost savings with tooling

At last, if aerospace companies are only looking at flight applications, they are missing a significant opportunity for cost savings in their tooling departments. This is the low hanging fruit, many of the same advantages are exemplified such as faster turn times and dramatically lower costs (Schiller G.J., 2015).

3.2.2 Conclusion AIQS1: Benefits AM offer aviation

It can be concluded that AM processes offer many advantages to the aviation industry. The 3 most frequently mentioned advantages that AM offers according to the researched articles are: complex geometry production, lightweight production and material waste reduction. This popularity in the aforementioned benefits for AM only applies to the researched list of articles for this project. The popularity could possibly change when another list of articles would be read.

AM offers design freedom thanks to its ability to build components layer by layer the possibility of producing complex geometries resulting in reducing weight. Which is really important in the aviation, each conserved kg saves US$3000 on an annual basis in fuel and the additional CO_2 reduction.

Material waste reduction is quite important for this industry, because in aviation are often expensive metals used. Traditional techniques remove material from the whole, this causes a great deal of waste and the additional costs required for the material, while AM produces by adding material and thereby (almost) only uses what's needed.

Another outstanding benefit AM offer in contrast to traditional manufacturing is the ability to produce parts without tools. This mean that various objects can be implemented simultaneously in each production which additionally offer enormous freedom in customization and small series production.

3.2.3 AIQS2 Results: Differences and types of AM techniques in aviation

The second question which is analyzed is AIQS2: Differences and types of AM techniques in aviation.

Mentioned keywords and terms answering AIQS2 are listed in Appendix B. The researched articles contain many different examples in printing techniques to start with. However, not all mentioned techniques are currently used in the aviation industry, which means that used ones are already explored and tried out within this industry. While there exists a chance of these not used (yet), do not fit into this industry at all. This is due to the reason of insufficient knowledge, research or information about some techniques, which makes it impossible to make a statement about it. Nevertheless, all remarkable findings about the different techniques are included in this section. If nothing is told about a technique in an article, then this will not be reported here either.

A significant resemblances could be derived, figure 4 displays the exact results in the number of times a type of print techniques occurred in the total of 17 examined articles. Except for the techniques, SLA and FDM are all use metal as its material during manufacturing. This means that 80% of the techniques used in figure 4 are metal printers while the remaining 20% use plastic.

All various AM processes are clustered according to the ASTM F2792 standards AM process categorization and color coded to easily find in the tables.

Powder Bed Fusion	Directed Energy Deposition	VAT Photopolymerization	Binder Jetting	Material Extrusion	Hybrid
SLS	LENS	SLA	BJ	FDM	
SLM	LMD		3DP	RDP	
EBM				WAAM	
DMLS				LC	

Figure 5. AM processes clusterd according to ASTM standards.

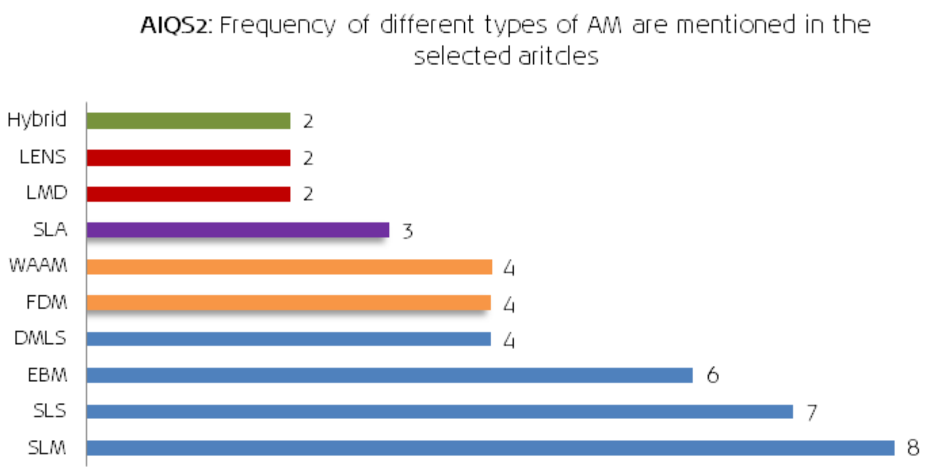


Figure 4. Results of AIQS2 frequency of mentioned AM processes.

Since metals like aluminum or titanium are major components for most aircraft models, metal Additive Manufacturing are more important for the aircraft. This has ensured that a lot of research have been made on popular metal AM like Selected Laser Melting (SLM), also named as Directly Metal Laser Sinter (DMLS), Electron Beam Melting (EBM) and Wire-Arcing Additive Manufacturing (WAAM) as well as commercially produced for the aviation sector (Zhang X. et al. 2019). That's how Uriondo likewise tells us SLM, EBM, LMD, WAAM are seen as the 4 most applicable AM processes to the aerospace industry due to the fact they produce almost fully dense components without any post-processes with mechanical and electrochemical properties compared to other traditional methods (Uriondo A. et al., 2015).

Figure 6 shows all types of AM techniques which occur in AIQS5: Current use of AM in aviation. This means that these types are already being used or tried out in the field of aviation. Some are more popular than others and can be selected for different purposes and applications. More about this is described in AIQS5.

Each of the various AM techniques have their own strength and weaknesses. Both metallic and nonmetallic parts fabricated by AM technology have potential applications in the aerospace industry (Liu R. et al., 2017). Figure 7. contain all processes found in the articles and are classified in two categories described by Sunil (2015) , according to the physical state of the raw material (liquid, solid, powder) and by the manner in which the material is fused (laser, wire, beam, ultraviolet).

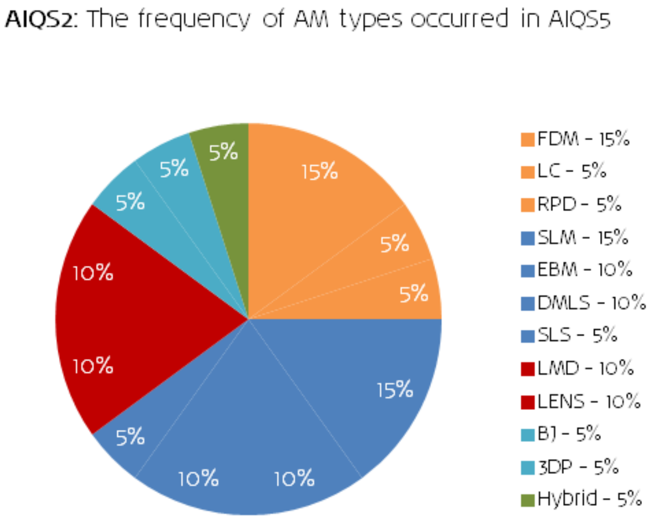


Figure 6. Results of AM process in AIQS5.

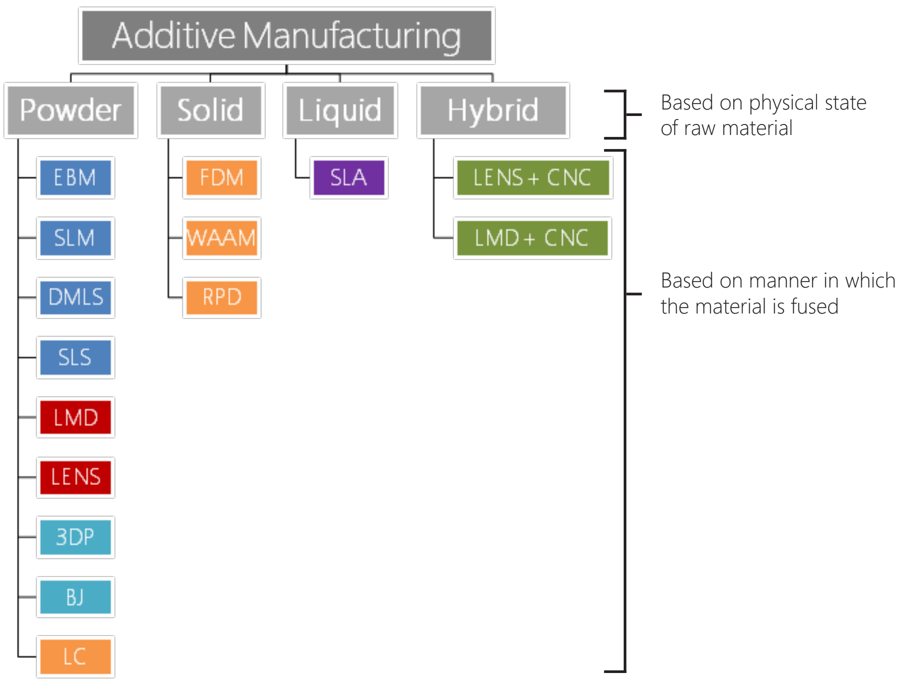


Figure 7. AM process classified in 2 categories.

Selective Laser Melting (SLM)

SLM uses a high energy laser beam to heat and melt the powdered variety of materials. The complete process is carried out in a protective environment to minimize chance of material oxidation and degradation (Uriondo A. et al., 2015). For SLM, only 10-20% of the total energy input is converted into laser beam (Gibson I. et al, 2010). Infrared heaters placed above the build chamber maintain the temperature of the powder bed around 90°C (Murr L.E. et al., 2012). The atmosphere present in SLM favors heat conduction. All these characteristics result in the cooling rate of the melt pool in SLM creating smaller grain sizes (Uriondo A. et al, 2015). However, this process typically has to deal with residual stresses (Gibson I. et al, 2010). The final part can achieve an elevated density in during the process, being the higher porosity level close to the surface of the part (Li J. et al., 2011; Arias-Gonzalez F. et al., 2013). In the aircraft industry, especially SLM is considered to be one of the candidates replacing casting or wrought produced parts (Zhang X. et al. 2019).

Selective Laser Sintering (SLS)

SLS uses a laser beam to melt and solidify, one layer at a time, powder materials like elastomeric and metals (Artis, 2012). SLS is able to produce metal parts directly, without any later machining being required (Kimble L.L., 1992).

Electron Beam Melting (EBM)

EBM uses a very high energy density electron beam, producing dense and void free parts. However, it can only process metals. This process is emerging as a high-quality substitute to laser melting (Thompson S. et al., 2013). In EBM, most of the energy applied to generate the beam is efficiently converted into electron's kinetic energy (Uriondo A. et al, 2015). Defocusing the electron beam over the complete powder bed heats the powder bed very quickly just before placing the next layer (Murr L.E. et al., 2012). Fatigue life is correlated to roughness and porosity of the surface finish, concluding that a high level of roughness results of a shorter fatigue life. Besides, this means that the fatigue life of SLM parts are higher than that of EBM (Greitemeir D. et al., 2012).

Direct Metal Laser Sintering (DMLS)

DMLS process applies a layer of metal powder and subsequently melts using a laser beam to create objects. This process produces metal parts with high accuracy and detailed resolution, good surface quality as well as mechanical properties (Dobransky J. et al., 2015; Günberger T. et al., 2015).

Fused Deposition Modeling (FDM)

FDM builds objects by extruding melted wire based polymers while moving it's nozzle in the XYZ axis (Artis, 2012). This process features low cost materials and easy to operate machines while low precision and low model building speeds are its limitations (Gorni A.A., 2001; Volpato N., 2007).

Wire and Arc Additive Manufacturing (WAAM)

WAAM is a wire-based system using a plasma arc to process that effectively delivers unrestricted wealth metal deposition. Since it is not constrained within a cabinet, larger components can be produced in vertical, horizontal and angled walls in forms of conic, close, crossover and intersection. The products obtained through WAAM are extremely high-quality and are even better than those produced by normal welding procedures as shown by studies (Hibbert L., 2014).

Stereolithography (SLA)

SLA uses light sensitive polymers which solidifies when exposed to UV radiation, the liquid polymer solidifies one layer at a time (Gorni A.A., 2001). This process is limited to light-sensitive polymers (Kruth J.P. et al., 1998). Besides a post-processing of removing part, washing and post-curing in an oven to improve part finish is obligated which significantly reduces application possibilities (Mançanares C.G. et al., 2014).

Laser Metal Deposition (LMD)
LMD is a process which melts the material with a high-powered laser while it is being put down (Uriondo A. et al, 2015). A five-axis LMD process is able to manufacture objects with overhanging geometry without support mechanisms. This process has an accuracy of 0.8 ± 0.9 mm and testing of its mechanical properties resulted into a wall density of more than 99.5% throughout an whole part (Liu R. et al., 2017). LMD technology is the best process to repair aerospace components, which feds metal powder directly onto the damaged portion of these parts and laser cure this to restore it to the original strength of the part (Kumar L.J. et al., 2017).

Laser Cladding (LC)
For LC, the powder is focused at the melting pool using either co-axial feeding or a single nozzle. This process involves the deposition, melting and solidification of raw materials in a moving melt pool (Hammake A.W., 1988). Residual stresses is a significant problem in this process (Gibson I. et al, 2010). The largest surface roughness has been measured for LC, especially perpendicular to the clad direction (Mazumder J. et al., 2000), meaning that it has a significant lower fatigue life.

3D Printing (3DP)
3DP is another powder bed-based AM process which selectively sprays a liquid binder, also called agglutinant (Grimm T., 2005), to solidify the powder on selective point to create a layer. Materials can vary between sand, glass or even metal. The largest available builds volume of this process is 1800 x 1000 x 700 mm (ExOne, n.d.). Production of parts are quick and of low cost (Huang S. et al., 2013). However, it has a low surface quality and a low overall strength of the final part (Mançanares C.G. et al., 2014).

Although a few times it has been claimed that some techniques produce almost fully dense components which don't require any post-processes Schiller (2015) claims the exact opposite: "None of the above mentioned techniques as a standalone method do provide a truly finished product in most cases. This means, some kind of post-processing techniques must be applied to achieve desired results either by heat treatment or milling" (Schiller G.J., 2015). Likewise, claims Qiu: "Nearly all additive manufactured parts for flight purposes will require some type of post-processing". Laser and EBM processes often produce parts with significant porosity, hot isostatic pressing (HIP) can significantly reduce porosity to increase strength and reliability (Qiu C.L. et al., 2014; Murr L.E. et al., 2011). Most researchers and engineers try to improve their designs by creating some kind of porous material, rather than a porous structure. The most popular porous material is the lattice material currently (Han P. 2017). The high cooling rates during AM processes produce small grain size, this increases the crack incubation period resulting in better fatigue properties of low temperature. The surface finish dominates the fatigue behavior rather than the porosity. However, AM parts represent a strong anisotropy due to the characteristics of the process. They are weakest in terms of tensile strength in the Z-building direction (Frazier W.E., 2014; Committee F42 A, 2013).

Nevertheless, hybrid manufacturing process seeks to resolve this challenge of providing a fully finished products within a single machine. This process produces quality finished parts by combining the precise accuracy of CNC machining and the freeform fabrication capabilities of the AM process (Schiller G.J., 2015; Liu R. et al., 2017). A hybrid manufacturing system combining the LMD process with milling developed by DMG Mori is able to print with varying layer thicknesses between 0.1 to 5 mm on the work area of 500 x 350mm. This hybrid manufacturing process is 10 times faster the current powder bed process (Mori D., 2014). Another five-axis hybrid system using the LENS process has a huge work are of 900 x 1500 x 900 mm with a deposition rate of 0.5kg/h (Optomec, 2014).

At last claims Zhang et al.: There is no answer to "Which AM process is best for aircraft". There is neither no definitive conclusion on "Which component cannot be fabricated by AM after all" (Zhang X. et al., 2019).

3.2.4 Conclusion AIQS2: Differences and types of AM techniques in aviation

Many different AM process examples are provided in the examined articles however, not all mentioned techniques are currently being used in the aviation industry. This conclusion does not immediately determine that the result found in this list of articles read is final. If something is not described or researched yet, does not necessarily need to mean that this is impossible or unimportant, it just means we don't have (access to this) information yet.

The articles provided insufficient comparison between printers and AM processes which results in not being able to make a statement about the most suitable AM for the aviation industry. In addition, the outcome show that research has mainly been done on metal printers while not much is done on plastic printers for parts production for the aviation setting.

Although multiple article claim some AM processes produce (almost) fully dense components which don't require any post-processes, conversely do claim Schiller (2015), Qiu (2014) and Murr (2011) the exact opposite.
None of the mentioned processes provide a truly finished product, it needs some kind of post-processing to achieve desired results.

Hybrid manufacturing process seeks to resolve this challenge, this process combines CNC machining with AM in one single machine and process to produce truly finished parts (Schiller G.J., 2015; Liu R. et al., 2017).

3.2.5 AIQS3 Results: Criteria to asses different AM techniques on usability in aviation

The third question which is analyzed is AIQS3: Criteria to asses different AM techniques on usability in aviation.

Listing of the mentioned keywords and terms answering AIQS3 are cited in Appendix B. Designated certification standards or criteria applicable for AM parts do not exist yet. The European Aviation Safety Agency (EASA) determines the current certification route as well for AM parts. These are as follow: material qualification, fabrication method qualification, design value definition, damage tolerance and fatigue evaluation (Mardaras J. et al., 2017). Due to the lack of standard qualification methods AM parts all qualified on a case by case study by the authorities such as EASA to ensure aircraft airworthiness (Uriondo et al., 2015).

For the purpose of making it possible to select AM machines based on criteria a list is composed. This list consists of: material variety, service quality, post finishing, precision, resistance to impact, flexural strength, prototype cost and post cure (Raulino B.R. 2011). As the qualification takes place on a case by case study, the importance of individual criteria similarly varies on each production case according to the user's needs for the parts and the specific situation (Mançanares C.G. et al., 2015). Figure 8 displays the results for these listed criteria for the 7 AM machines. Mançanares (2015) used an AM printers database to develop these results.

Besides, it should be noted that material is a constraining factor and plays an overwhelming role in the selection of an AM machine, since these technologies as a whole are related to specific materials (Mançanares C.G. et al., 2015). The properties of the source material for AM heavily influence the properties of the resulting part. Likewise leads the degree of interaction between the melting source and material can affect the final object's porosity and herewith the resolution (Shapiro A. et al., 2016). In case of powder materials, the grain size, porosity and degree of sintering can lead to different physical properties such as toughness, hardness, yield strength and surface finish (Chang F. et al., 2015; Averyanova M. et al., 2011).

Thereafter, statistical process control is needed in order to test, printed results on quality according to the needs of the part. Recommended is a minimum of at least 5 coupons printed together with the designated part is needed to test print results on tensile, fatigue and other tests per build. The size of the mechanical increments used during manufacturing, either in the movement of the laser beam or increment of the x-y axis, affects the final part (Shapiro A. et al., 2016).

Defects can be classified into two categories: in-

	SLA	TDP	SLS	FDM	DMLS	CJP	MJP
Variety of materials	Small	Medium	Large	Medium	Medium	Small	Small
Surface quality	Average	Good	Good	Average	Excellent	Good	Good
Post-finish	Average	Good	Good	Average	Excellent	Good	Good
Accuracy	Excellent	Average	Good	Average	Excellent	Average	Average
Resistance to impact	Average	Low	Good	Good	Excellent	Low	Low
Flexural strength	Low	Low	Excellent	Excellent	Excellent	Low	Low
Prototype cost	High	Medium	High	Low	High	Medium	Medium
Post cure	Yes	No	Yes	No	No	No	No

Developed by the authors

Figure 8. AM process assessment factors, Mançanares C.G. et al. (2015).

ternal defects and external defects, also known as surface defects. Defects can be classified into categories internal defects and surface defects. Surface defects Also known as external defects can be classified into categories as well inducing cracks or voids and inducing roughness or printing artifacts. Surface machining remains the most viable solution for fatigue critical applications but at the cost of limiting the geometrical complexity of the parts in order to make the machining feasible. Sandblasting and chemical milling processes can improve significantly the fatigue stress allowable, although not enough to bring it to the level of the machines parts (Mardaras J. et al., 2017).
Each of the various AM techniques have their own strengths and weaknesses. Standalone methods do not provide a truly finished product in most cases post processing techniques must be applied to achieve desired results either by heat treatment or milling. Hybrid techniques however seek to resolve the challenge, the process is composed of printing layers of material and then milling those layers. By utilizing milling as part of the build process how to reach interior services can have the same finished surface quality necessary in many aerospace applications (Schiller G.J. 2015). The hybrid process provides greater build capabilities in accuracy and surface quality for freedom fabrication (Liou F.W. et al. 2001).

Furthermore, automated surface finishing techniques are advised for its nature of traceability and repeatability, in contrast to hand finishing (Shapiro A. et al., 2016) which will be unique and different every single time. Different properties such as density, micro hardness, surface roughness and fatigue properties effect the eventual quality and usability of a component (Uhlmann E. et al., 2015). Layer thickness does have an important role for some features, the ones getting effected are summed up in Figure 9. The results shown in the table are only applicable on the case study of the originating article which used SLM to print titanium parts (Uhlmann E. et al., 2015).

As last, SAE International is an organization developing standards focusing on the transport sectors including aerospace. They have been working for a while on Aerospace Material Specifications specifically for AM. The first four standards are issued, while many others being worked hard on (Zhang X. et al., 2019).

Feature	Thin 10 – 30 µm	Thin 30 – 100 µm
Part resolution	high	ok
Surface quality	high	ok
Process stability	ok	high
Process velocity	low	high
Material costs	high	ok

Figure 9. Layer thickness selection, Uhlmann E. et al. (2015).

3.2.6 AIQS3 Conclusion: Criteria to asses different AM techniques on usability in aviation

Designated certification standards or criteria applicable for AM parts do not exist yet. Due to the lack of these standard qualification methods are currently produced AM parts qualified on a case by case study by the authorities such as EASA to ensure aircraft airworthiness.

Although there are no rules yet, we know at least that material plays an overwhelming role in the selection of an AM machine. Material is a very important constraining factor due to the fact AM processes as a whole are related to specific materials (Mançanares C.G. et al., 2015). Besides, the properties of the source material for AM heavily influence the properties of the resulting part produced with these.

Additionally, there is a need for statistical process control. With this can printed results be tested on quality according to the needs of the part. Automated techniques are advised for its nature of traceability and repeatability, in contrast to human process.

However, we can conclude that there are currently no fixed or listed criteria to test the different AM processes for possible usability in aviation found in the examined articles.

3.2.7 AIQS4 Results: Future potential, gaps and needs of AM in aviation

The fourth question which is analyzed is AIQS4: Future potential, gaps and needs of AM in aviation.

Listing of the mentioned keywords and terms answering AIQS4 are cited in Appendix B. Figure 10 shows a clustering of the keywords used in the articles and the number of article same keywords are mentioned.

The mostly mentioned need according to the read articles are the need of new AM materials, 47% of the article mentioned this exact need. The future of this technology relies on the continued development of existing materials in order to achieve more applicable materials to different situations (Shapiro A.A. et al., 2016; Uriondo A. et al. 2015). Likewise, a need for increased AM material choice and processes like nano-particle reinforcement pounder, layered metal polymer composite, micro forging (Zhang X. et al., 2019) are topics to mature. In the same way, a standard material characteristic database should get developed within the AM industry to provide mechanical properties fabricated by different AM processes such as specifications of the mechanical properties of materials and more detail on how parts made from these materials perform (Campbell T. et al. 2011).

Process and qualification related gaps and needs are formed by separate clusters for standards, testing, production-, quality qualification, etc. as displayed in table.
Testing and safety standards for AM in aerospace are still under development. There are no standard certification rules given that different AM technologies are still on their way to being fully matured (Sunil C. et al., 2015). These needs are critical for the future adaptation and acceptance of AM by aviation.
Industry specifications and standards for the processing of aerospace components must be developed. Developing integrated processes, sensing monitoring and control technologies are needed. As well as advanced non-destructive techniques capable of detecting critical defects with a high degree of certainty are needed (Uriondo A. et al. 2015). In process monitoring close loop feedback and building process structure property relationships model are needed for the ability of predictable repeatable consistent and uniform fabrication with AM (Bourell D.L. et al., 2019).
Besides, it is critical to develop post-production

qualification parameters in surface improvement techniques such as surface roughness characterization versus fatigue and associated surface finishing processes needs to be standardized to fully enable topology optimized AM parts (Mandaras J. et al., 2017). Equally important are statistical process control and qualification procedures. An open source and detailed database about the results of these statistical process control needs to be developed. This database will include gathered results of test coupons of different materials according the standardized qualification procedures and make it available for the complete industry. (Shapiro A.A. et al., 2016). Lastly for the process, standards in inspection methods needs to be defined to ensuring quality and safety required for the aeronautical industry (Uhlmann E. et al., 2015; Zhang X. et al., 2019).

Our current methods of analysis for solid structure such as defendant element methods are not applicable to additive lead design parts (Han P., 2017). Hereby are predictive software critically needed to correlate microstructure properties variable to size/type of defect to achieve consistently and accurately AM part production (Uriondo A. et al. 2015). Refined damage tolerance software will function in predicting the increasing geometrical complex AM part properties (Mandaras J. et al., 2017). Similarly will a physics-based software help to understand and predict material properties such as surface roughness or fatigue (Frazier W.E., 2010). For the future there is a need for a decision-making-support system based on machine database containing information about technical characteristics including machine assessment factors like surface quality, post processing, accuracy, etc. (Mançanares C.G. et al., 2015) helping manufacturers to choose rationally.

At the very last, aerospace design engineers must change the way they designed a part as they shifted from that additional method of subtracting material to the new method of adding material in order to maximize benefit taken of this technology (Han P., 2017). Because there is a tendency for designers to apply AM to existing design geared toward CM processes. Unfortunately, these strategies do not take advantage of the capabilities of these machines and often result in fabrication of parts that can be fabricated more cheaply and easily using traditional methods (Shapiro A. et al., 2016).

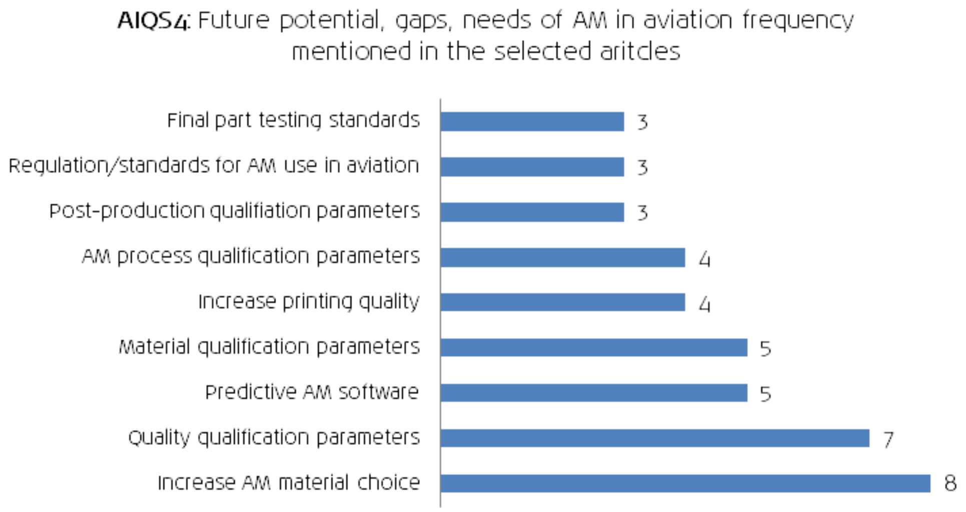


Figure 10. Results of AIQS4 frequency of mentioned needs, gaps and potetial of AM in aviation.

3.2.8 AIQS4 Conclusion: Future potential, gaps and needs of AM in aviation

There are fairly clear needs for AM in order to fully mature for the aviation industry.

The first and mostly mentioned need derived from the articles are the need of new AM materials, exactly 47% of the article mentioned this need. Together with a open source material database to provide mechanical properties fabricated by different AM processes. This will help in the decision process for AM process - material combination.

In the same way are standard qualification methods needed for materials, testing, production and quality for AM to get implemented by the aviation industry. Likewise are new predictive software needed which helps in analyzing designs for AM. This software is critically in correlating microstructure properties variable to size/type of defects before manufacturing to achieve consistently and accurately AM part production.

At the very last, not to be forgotten is the fact design engineers must change the way they design parts. According to the examined articles exists a tendency for designers to apply AM to existing design geared toward traditional processes. These strategies will not take advantage of the capabilities of AM and could often result in fabrication of parts that can be fabricated more cheaply and easily using traditional methods. Which could result into easily going back to old techniques. This change in designing parts could probably be done by (re)educating already graduated designers for the purpose of this (still new) technology in the aviation setting. While "design for AM" as an topic could be added to the curriculum of design engineering studies.

3.2.9 AIQS5 Results: Current use of AM in aviation

The fifth question which is analyzed is AIQS5: Current use of AM in aviation.

Listing of the mentioned keywords and terms answering AIQS5 are cited in Appendix B. Results from the literature research shows that AM is currently being used in the aviation for several different purposes such as, rapid prototyping, rapid tooling, direct part manufacturing and repair. Lots of examples are reported in the articles, although the same examples also do appear in multiple articles.

First of all, aircraft components can be grouped in their type of functionality on a aircraft (GE, 1999; Cutler J.L. et al., 2006; Biel E.H., 1993):

1. Structural components with a primary function is maintaining aircraft geometries, such as wings;
2. Functional components fulfill the primary purpose to provide flight functions, such as seats;
3. Auxiliary components are all non-structural and non-functional components, such as interior covers and bumpers;

Thus, we can see multiple examples appearing in these article of AM being applied in all three categories. It is impossible to create a complete overview about all existing 3D printed components. Due to the fact not all research and company developments are released for the sake of protection of knowledge to retain competitive advantage (Gleason D., 2019). Nevertheless, the results still helps to understanding and develop an idea about the technique being used in the aviation industry.

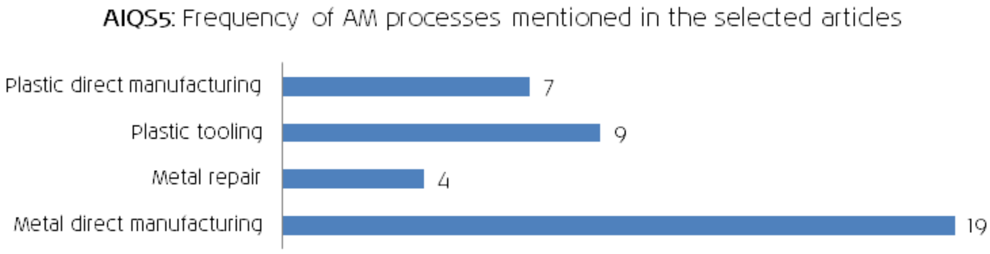


Figure 11. Results of AIQS5 frequency of mentioned current use of AM processes in avitiation.

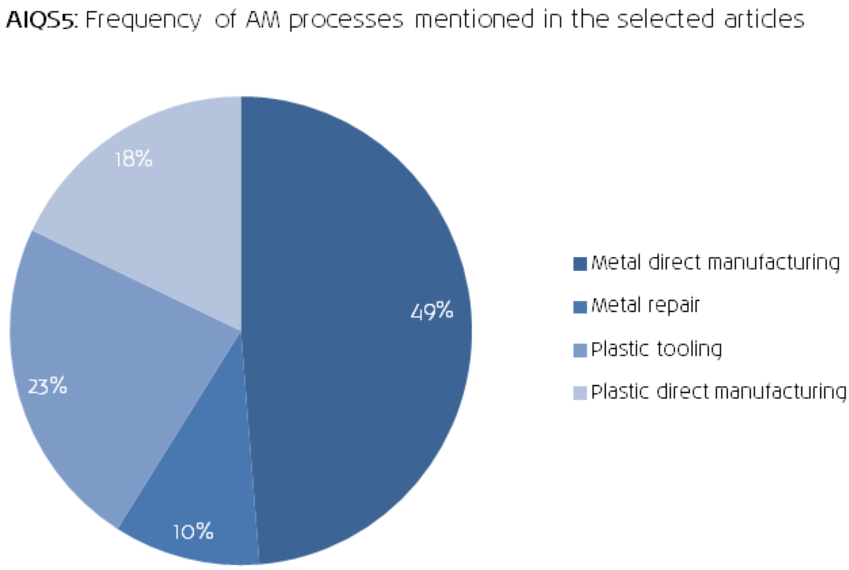


Figure 12. Results of AIQS5 frequency of mentioned current use of AM processes in avitiation.

Metal direct manufacturing

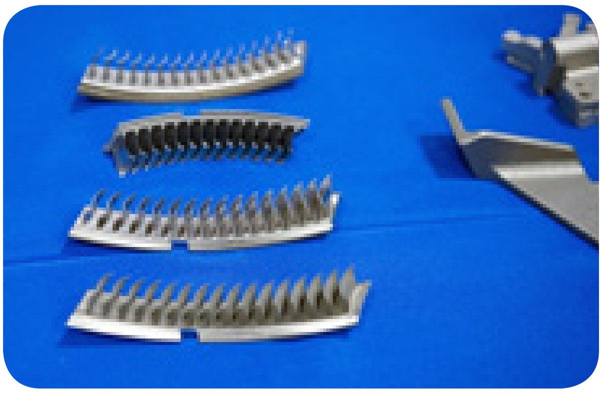
The total of reported examples in the examined articles show us a striking number of the listed components, 49% to be exact, are 3D printed metal components for direct use. The total of these components fall under the structural components category which have a critical effect on flying. This result is really important and demonstrates the development of 3D printing technology in process stability and control. Remarkably, just over 58% of all structural metal parts that are printed function as a critical engine part.

General Electric is currently 3D printing fuel nozzles for their high-bypass turbofan aircraft engine which will power the Boeing B737MAX and the Airbus A320neo aircrafts (Richard F., 2015). The 3D printed nozzles are already FAA certified, back in 2015 to be exact (GE9X, 2017) and are printed on the EOS printers using the DMLS technique. The new design integrates extra functionalities like cooling pathways and support ligaments, which results in five times the service life compared with the predecessor part. In addition, were designers able to reduced the number of brazes and welds from 25 to 5, the number of parts from 18 to 1 which resulted in 25% weight reduction for each nozzle (Liu R. et al. 2017; Kumar L.J. et al. 2017).

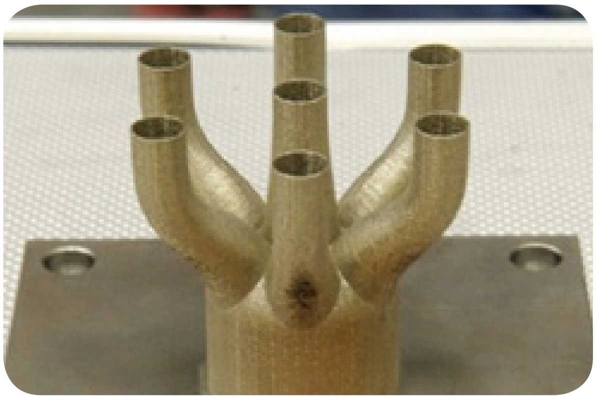
Rolls Royce 3D prints the front bearing housing, holding 48 aerofoils of their Trent-XWB 97 engine. This is the largest engine part printed in titanium making use of Electron Beam Melting (EBM). Using AM reduced the lead time by 30% compared to conventional manufacturing methods. The Trent-XWB is the sole engine type for the Airbus A350 (Anderson S. 2015; Morrison M., 2015).

The Safran group uses AM to produce guide vanes for the silver-crest business jet engines. These vanes integrates fuel manifolds with the combustion chamber converting assemblies into a single part. Besides, they 3D print hydrogen turbo pumps for their Vinci rocket engines. This technology helps them for speedy implementation of design changes and also for repair of components (Safran Magazine, 2014).

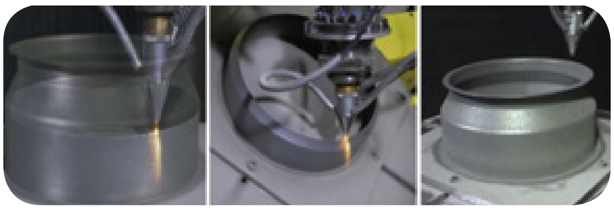
Pratt and Whitney 3D prints compressor stators and sync ring brackets for their PW1500G engines. These engines are used on Bombardier CSeries passenger aircrafts. AM helped saving 15 months in lead time and up to 50% in weight in a single part (Peach M., 2015).



NASA manufactures nickel-chromium alloy rocket injector parts for the J-2X engines using the SLM process. The costs are reduced by 35% while increasing the lead time and integrating the assembly from 115 parts to 2 in total. This integration and reduction of parts and connections made the injector structurally stronger and more reliable leading to the overall safety (Szondy D., 2012; Zhou F. et al., 2014).
NASA also uses SLM in order to 3D print copper rocket engine parts. AM making it possible to produce it locally at NASA within just 11 days (Metal Powder Report, 2015).



TWI additively manufactured a thin-walled helicopter engine combustion chamber using a five axis LMD process without support mechanisms. The build time was reduced from months to just 7.5 hours (T. Ltd., 2014).



Using the Binder Jet (BJ)process, ExOne produces the very first high-pressure CMC turbine nozzle segments with this technology (Liu R. et al. 2017).

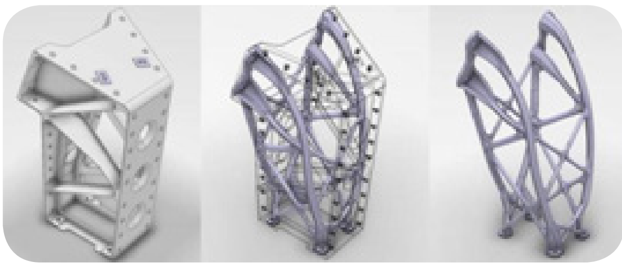
Lastly, hybrid systems are being used to 3D print components combining precise accuracy of CNC with freeform fabrication of AM to print stainless steel turbine housings (Mori D., 2014).

Exactly 25% of the metal examples are brackets / connectors.

Concept Laser developed a topology optimized cabin bracket connector used in the Airbus A350XWB with the SLM process. This design significantly reduces the weight by 30%. Toolless fabrication shortened the development time of the bracket by 75%, where it used to be 6 months now was 1 month (Concept Laser, 2014).

For another satellite, the Sentinel-1 Earth-observation satellite, is this time an antenna support developed and printed in aluminum-silicate-magnesium alloy by selective laser sintering (SLS). This created a lightweight parts enabling a mass reduction of 56% (Raviv D. et al., 2014).

Moreover, a new bracket has been designed and manufactured for the next Eurostar E3000 satellite. This new topology optimized aluminum bracket integrates 44 rivets and parts into 1 single part. Reducing the weight by 35% while increasing the stiffness up to 40% (Shapiro A.A. et al., 2016).



Last, EADS Innovations Works uses DMLS printing of EOS to manufacture titanium replacement parts of a previously cast steel nacelle hinge bracket on an Airbus A320. This optimization saved 10kg per set which comes down to a 75% reduction in raw material consumption (Warwick G., 2013).

Another 21% of the metal-printed parts are critical components which are related to the wing area of aircrafts.

Norsk Titanium developed together with Boeing a FAA approved structural component for the B787 back in 2017. This part is being manufactured with the Rapid Plasma Deposition (RPD) technique (Norsk Titanium, 2017) and functions as critical component between the wing and engine connection.

The Northwest Polytechnic University developed a large scale laser cladding cell. They are manufacturing a 5 meter tall central wing spar for the Chinese Comac C919 passenger airplanes. The university claims a similarity in the mechanical properties between the printed wing spar and the previously forged one (Anderson E., 2013).

Lockheed Martin collaborated with Sciaky, an industry-leading EBM process expert. Together they fabricated a wing spar for the Lockheed Martin F-35 and wing leading edges for the Dassault Falcon 5X (Trimble S., 2014).

Metal repair

The smallest group of examples were the metal repairs, which count for 10% of all examples in the examined articles. High-performance aerospace parts such as compressors, turbines blades and airfoils are in particular very expensive due to the fact these typically being fabricated from high-value materials and involve complex processing during manufacturing (Dey N.K., 2014). Because of these extreme cost for materials and labor for these components, it is necessary to repair those components instead of replacing them (Liu R. et al., 2017).

This is how the LENS process of Optomec is used to repair aircraft engine components. This technique uses a cobalt-based wear resistant material to repair the leading edge of T700 blisk airfoils made of steel. This process can add new material precisely to worn components in order to restore their geometry (Optomec, 2014).

RPM Innovations developed a comparable low-wattage LENS process and demonstrated its usability by repairing a titanium bearing housing from a gas turbine engine. The repair cost with this systems are 50% of the new pricing, plus it saves all the materials that would otherwise be scrapped. In addition, repairing took a few days compared to several weeks for a new housing (Mudge R.P. et al., 2007; RPM Innovations, n.d.).

Rolls Royce Deutschland is using a different process which is called LMD. They repair worn geometric surface features of their BR715 high-pressure turbine and high-pressure compressor front drum such as bosses, brackets and flanges. The repair is locally with just one layer deposited. This repair reduced the cost by 40% together with 40% reduction in turnaround time (Gasser A. et al., 2010; Kelbassa I. et al., 2008).

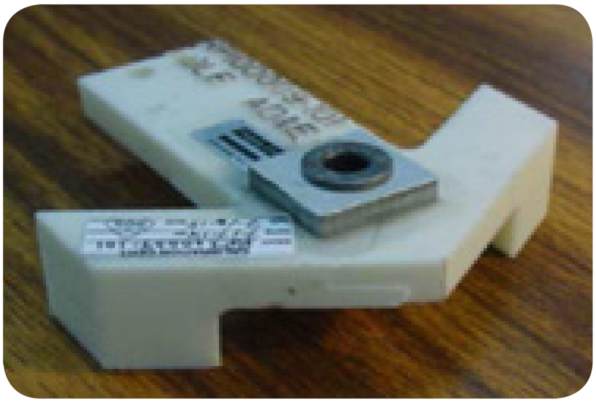
Plastic tooling

Plastic tooling examples is the second largest group after the metal direct manufacturing. This group contains 23% of the examples. This category is called the "low-hanging fruit" of the 3D printing arena. This is a metaphor used to get the ripe and easy delectable results first. If aerospace companies are only looking at flight applications to use AM, they will miss a significant opportunity for cost savings, faster turn times, lighter, etc. on benefits in their tooling departments (Schiller G.J., 2015).

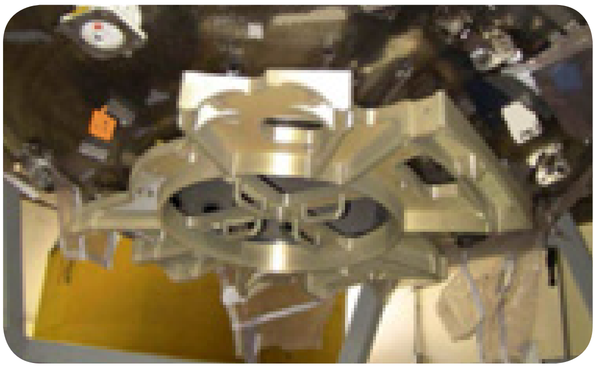
33,3% of the tooling examples reported in the articles were specifically using the benefits provide by AM for assembly purposes.

Examples of these types of tooling are as follow. Firstly, a drill template whereby tooling creation time is reduced by 80%.

Secondly, a fit check tool which has been redesigned due to the fact the traditional tool was breaking all the time during operations.

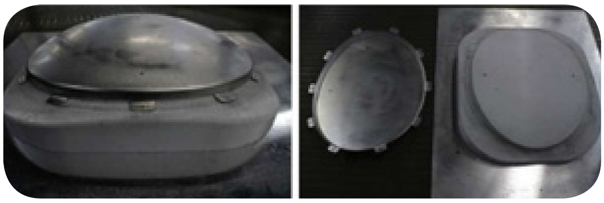


At last, a fitting alignment tool which was previously made out of metal, being very heavy and difficult to handle, which is now made of plastic. This resulted in 70% of labor savings due to the fact it was sufficient light so one single engineer could operate it. And in addition 90% cost reduction has been achieved (Schiller G.J., 2015).



The remaining 66,6% were tooling used for production. The additively manufacture parts are used in the creation of metal end-use components.

Piper aircraft uses the FDM process to manufacture fit-for-purpose plastic tooling for hydroforming aluminium structural components. Examples of these structural components are window pans, as well as inner frames, gussets, brackets, and skins. These FDM tooling reduced machining time by about 68% (Stratasys, 2011).

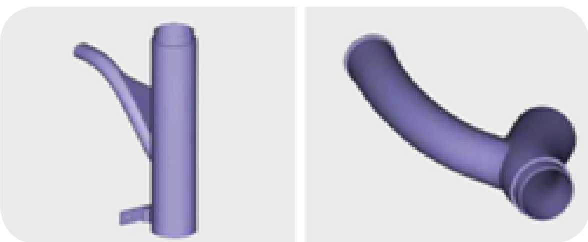


ExOne on the other hand developed a new powder bed based AM process called 3DP. They fabricate door hinge core castings for the Airbus A320 (ExOne, n.d.).

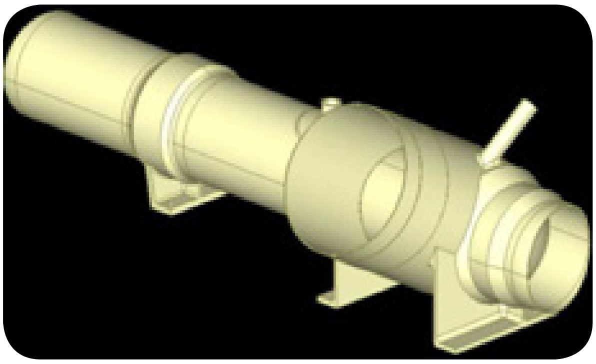
Plastic direct manufacturing

The last group are the plastic direct manufactured components, which counts for 18% of the total.

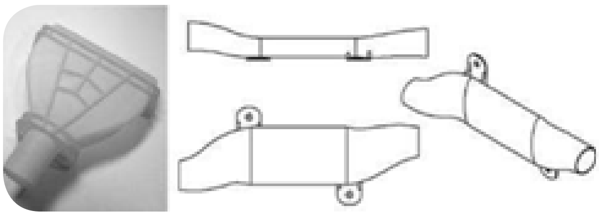
Bell helicopters 3D prints tough polycarbonate wiring conduits for their heavy-lift tilt rotor Osprey using FDM. They manufactured 5 complete sets counting 42 conduit models in total. This only took 2.5 days with FDM which would have taken 6 weeks with traditional manufacturing (Stratsys, 2015).



United Launch Alliance is baselining several thermoplastic components to fly with on missions, an environmental control system duct flowing conditioned air on sensitive equipment during launch is one reported example (Fischer F., 2014).



There are about 100 AM parts used for the air cooling ducts in the Super Hornet jets (Khajavi S.H. et al., 2014).



An MRO decided to 3D print blanking plates to close the gap of removed PCU in the armrest of aircraft seats. Typical manufacturing methods like injection molding results in around an 8 to 12 weeks turnaround time and the additional cost for tooling is quite high. According to authorities, materials used for aircraft interior applications need to be in compliance with flammability requirements (FAR25.853). Ultem9085 is specifically developed for FDM producing components in this region of application (Rehmenjan U.H., 2015).

BAE Systems manufactures and supply ready to use 3D printed plastic parts such as support struts on the air intake door, protective covers for cockpit radios and protective guards for power take-off shafts for their Squadrons of Tornado GR4 aircrafts (Sunil C. et al., 2015).

Finally, advice is given about the most likely for near-term AM adoption are component categories with non-critical load profiles, complex geometries and small to medium geometric volumes (Wohlers, 2013; Oak Ridge National Laboratory, 2010). For example, another similar opinion is shared by Rehmanjan in another article: "A good starting point for the usage of this technology and commercial aviation could be for non-structural, aesthetic cabin items to be 3D printed, maybe even just starting with business jet interiors and low usage spare parts" (Rehmanjan U.H., 2015).

3.2.10 AIQS5 Conclusion: Current use of AM in aviation

As we concluded in AIQS2: Differences and types of AM techniques in aviation, provide these articles information that research has mainly been done on metal printers for the aviation setting and not much on plastic printers.

The results of all mentioned examples of AM produced part for the aerospace industry confirm this as well. In these example parts, the distribution consists parts produced on 59% metal and 41% plastic printers. This bigger interest in research for metal printers have been reasoned by both Zhang et al. (2019) and Uriondo et al. (2015). This would be since large aircraft components are mainly made of metals (for most aircrafts), plus these printers are claimed to produce almost full dense components that are comparable with traditionally produced parts.

All metal fabricated parts are structural and this way critical components. These are mostly related to the engine or aircraft wing. This result is really important and demonstrates the development of 3D printing technology in process stability and control. Nevertheless, both metallic and nonmetallic parts fabricated by AM technology have potential applications in the aerospace industry according to Liu et al. (2017). Plastic tooling examples are the second largest group covered in the examined list of articles. This category is referred as the "low-hanging fruit" of the 3D printing arena, aerospace companies will miss a significant opportunity for cost savings, faster turn times, lighter, etc. benefits in their tooling departments if they would only look at flight applications to use AM.

Moreover, the advice for those who are about to implement AM can best start with non-critical and non-structural parts that are often located in aircraft cabins and consist of plastic. Finalizing about different AM processes, we can conclude from what we have learned. Just as Zhang et al. (2019) claims: There is no answer to "Which AM process is best for aircraft". There is neither no definitive conclusion on "Which component cannot be fabricated by AM after all".

3.3 Conclusion of the literature review

This paragraph provides a conclusion about the entire literature study chapter, found knowledge and resulting conclusions. Furthermore, it refers to the need of following steps after this literature investigation.

This literature review serves to answer the research questions at an academic level. Herewith is knowledge gained about the benefits of AM, different AM processes, criteria for the selection of AM processes, requirements for maturity of AM to be accepted and current use. The literature scope only covered the aviation industry given the focus of this project and to conduct targeted research.

The investigation and knowledge gained from literature was general and mainly focusing on AM in aviation and aerospace industry. The consequence is that found information cannot always be used immediately for KLM. For this reason, information obtained from the literature is used as the first step on this topic and to detect which subjects require even deeper research to make it usable for KLM in the continuation of this project.

But first, knowledge about KLM will be acquisitioned, what they may / may not be allowed to do and what the restrictions and rules of the authorities are in this area of the industry.

3.4 Literature gap

Many benefits of AM have been found in the articles, but these benefits are about what AM in general could mean for aviation and are not specified according to different AM processes. There is a possibility that different processes may differ in the types of benefits they can offer or will be stronger in certain benefits than other process. I miss the categorization and going a bit deeper by linking benefits to process. This could help rationalizing the selection of a process.

Currently, the benefits function as a rendering of results AM could provide the industry. But results also have consequences. This is outlined for some benefits, but not for all. I miss research results that reflect these consequences of benefits. An example of what I mean: "What are the consequences of the possibility of fast spare part lead times?" This could have an effect on cost reduction by shortening aircraft ground time during maintenance or maybe reduce labor time because stock employees have to keep track of these parts for a shorter period of time, etc. These type of information would enhance the reasoning for implementation of AM.

There are currently yet, insufficient standards for AM component certification and therefore no criteria that can be used to test various AM processes. So there is no possibility to test usability when new processes would be developed without trying them out. This means, the first thing needed are established criteria by the authorities where AM components with specific materials and criteria for specific aircraft locations such as cabin, engine, etc..

Furthermore, research is needed to identify possible aircraft components which could be 3D printed. This would bring an evolution to the industry. Because you are no longer selecting a production method after designing, but rather design and produce directly from AM. This could for example prevent designers revert to one of the traditional methods.

An in-depth research and development of predictive software is needed to simulate AM designed components without truly producing. Every AM process has its own advantages and disadvantages. If these would be included in the software and strength test, production process, predictive fails, etc. could be simulated, this could lead to acceleration of implementation of AM and could ensure cost reduction due to the fact of taking fewer steps in the process of finalizing a component to install in an aircraft.


KLM
KLM

4. Regulatory Bodies

The results of the literature review showed us the existence of certified 3D printed parts in the aviation industry. While on the contrary we've also learned that standards for testing, production-, quality qualification, etc. are still under development and do not exist yet for additive manufacturing (AM). For this reason it is important to make sure KLM is able to (re)design, produce and certify aircraft parts with AM.

The objective of this chapter, is to investigate what the rules and obligations are regarding production in this industry which is then compared to what KLM currently permitted to do or should do.

The European authority stakeholder in aviation safety is investigated first in order to understand this general obligations in this industry. The structure of this regulatory body will show the needed certificates when in possession confers production rights. A step deeper is then taken to find specific legislations to use AM and requirements for printers to produce certified airworthy components. After this, the entire route from designing until certification before use of a component is mapped. Finally, the part production route for MROs like KLM is mapped together with KLMs currently permits to achieve this.

Chapter structure

The method used is explained in §4.1. Furthermore starts the chapter by describing the European stakeholder for aviation safety in §4.2. From here is the used certification structure of EASA valid for this project elaborated in §4.3. This results in investigating the needs to use AM in aviation which gets treated in §4.4. Paragraph 4.5 explains the created route and steps which must be proceeded to design, produce and certify aircraft parts. Additionally is the current and wanted part production structure for KLM visualized and elaborated in §4.6. Together with the current permissions and valid restraints KLM has. The complete chapter is concluded in §4.7.

4.1 Method

The research for this chapter was done by investigating internal knowledge and conducting interviews on these topics with experts at KLM. This information is then validated with external sources obtained via web searches on Google.

The condensed EASA structure is mapped out together with Peter Dol, head of airworthiness. While the general route from design to certification and the step-by-step part production routes for MROs is co-development with the project leader of POA at KLM, Ian Breed.

4.2 Who is the European regulatory body?

The institution that is about aviation safety of the European Union is called EASA. This is an abbreviation of European Aviation Safety Agency. Where their main activities are regulation, standardization and certification at the European level. Done through collecting, monitoring and analyzing safety data to draft and advise on safety legislation.

> Its mission is to promote the highest common standards of safety and environmental protection in civil aviation.

([What does the Agency do?], 2013).

4.3 What is the structure of EASA?

The entire EASA structure is very large and complex. A selection of importance for the scope of this project has been made in collaboration with Peter Dol, head of airworthiness at KLM (25-3-2019) and illustrated in Figure 13. Condensing the information about the different certificates involved in the scope of the project will serve to can better interpreted.

Every (sub-)certificate comes with its own advantages and ensures organizations to execute something specified. Every application must be well considered because they are not free. Applying for, and holding a certificate contains charges and fees indebted by EASA ([Fees & Charges – FAQ], n.d.).

This means that KLM must have a good business case if a new certificate needs to be requested enabling part production with AM. A good view of the potential benefits with this step, will ensure the higher management to consider this investment as worthy. The specific costs of certificates are falling outside of my project and will therefore not be covered by me.

4.3.1 Initial Airworthiness

Initial Airworthiness is the first and critical domain of the EASA structure within this project scope of 3D printing aircraft parts. This domain includes one main certification called PART 21, which consists of a two sub-certificates, DOA and POA.

> Initial Airworthiness literally means the state that something is initially airworthy, safe to flying so to say.
>
> **Peter Dol** (25-3-2019)
> head of airworthiness @ KLM

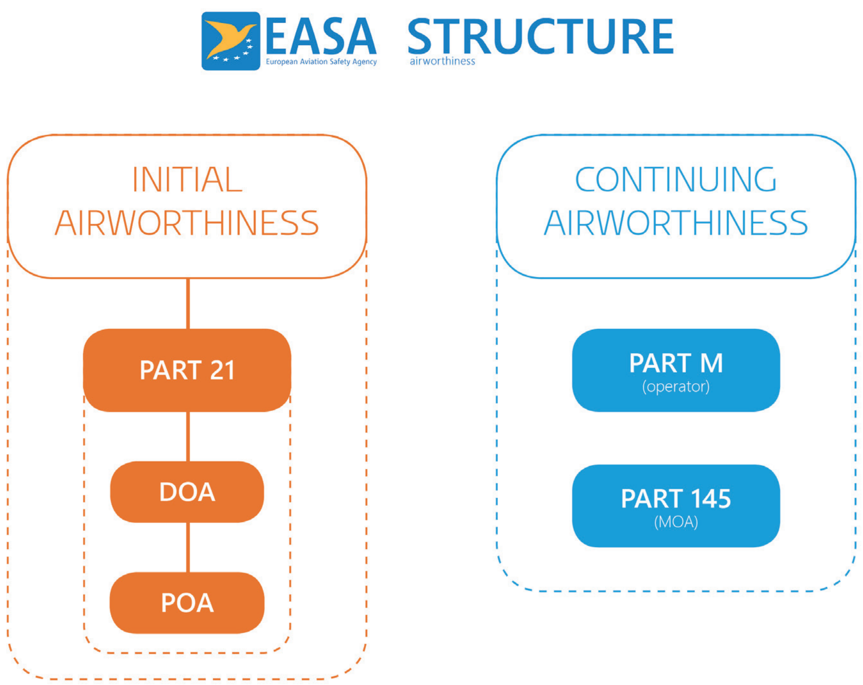


Figure 12. EASA airworthiness certificate structure.

Design Organization Approval

The abbreviation DOA means Design Organization Approval. It is the recognition that a organization has, which allows to execute design activities and certify the design by itself without further verification of EASA. Each DOA application has a defined scope and only gets approval by EASA to design and certify within this scope. With every DOA application, a scope is defined per organization to design and certify in. This means that there is no standard package that an organization can design with this approval, but is application dependant. An example for a defined scope of a DOA could be "plastic cabin parts" ([Design Organisations Approvals], n.d.).

Production Organization Approval

A Production Organization Approval (POA) holder is an organization which has approval to manufacture aircraft parts and appliances in conformity with approved data from the original manufacturer or DOA holder. This certificate allows organization to certify produced components with an EASA Form 1 without further verification of EASA. The Form 1 demonstrates a part being produced entirely according to approved design data. ([What's involved in an EASA Part 21 Subpart G Organisation?], 2016)

Just like the DOA, the same about scope definition applies for each POA application. Which means that POA certificates are not issued on one specific part or one specific production method.

4.3.2 Continuing Airworthiness

Continuing airworthiness means keeping an aircraft technically fit to fly, the condition it remains airworthy ([Continuing Airworthiness], 2018).

Continuing airworthiness includes several individual certificates, but only certificates within the scope of the project are treated.

> PART M is an organization approval which is mandatory for all commercial air transport companies, also known as Operators. Operators are responsible for creating a planning for scheduled maintenance, manage an approved maintenance program and ensure to have a contract with a certified maintenance company.

([The Difference between Part M and Part 145 Records], 2014).

> Whereas a PART 145 certified organization is the actual maintainer, also known as a MRO. These Maintenance and Repair Organizations (MROs) must retain detailed maintenance records and demonstrate it's done in accordance with all requirements by an appropriately approved certifying engineer.

([The Difference between Part M and Part 145 Records], 2014).

All of these individual certificates can be owned by a group of organizations or just one company. KLM group can be seen as a multi-group organization existing of smaller organization under a single roof such as, KLM Operator, KLM Engineering & Services and others which are not relevant to this project. KLM as an operator holds a PART M, KLM E&M can further split into smaller internal organizations which are responsible for maintenance, design, production, etc. . All of these separate organizations have different responsibilities and thus related to different certificates. But all together, they are ultimately linked to the KLM Group company.

> Employees of KLM can have multiple responsibility hats in this company structure which may have adverse consequences.
>
> **Peter Dol** (25-3-2019)
> head of airwortiness @ KLM

The explained adverse consequences by Peter will be reconstruct by an example. An employee gets the job to do a redesign (DOA) of a seat component with reoccurring failure. Simultaneously, this employee thinks of their abilities with the POA certification that they have, as well as the maintenance contracts they have made with operators (PART 145). Within this job setting employees could become jack of all trades and master of none. Which may inhibit innovation in the way that employees belief "innovation is someone else's job and not part of everyone's responsibilities", according to Ron Ashkenas (24-7-2012) from the Harvard Business Review.

4.4 What is needed to use AM in aviation

As we know do AM certification standards not exist while certified 3D printed parts do exist in the aviation industry. This paragraph digs deeper in the search for specific legislations to fully understand this contrast, how it's possible and what exactly is needed to produce these certified AM parts.

During interviews with internal experts at KLM emerged from the conversation with Peter Dol (25-3-2019), according to his experience and knowledge it is especially important to be able to demonstrate that standards and rules for general production are being complied and this can be demonstrated with required inspection moments to get certified by EASA to produce within your scope, to hold a POA so to say. Further added Ian Breed (29-3-2019) on this by claiming every POA holder is free to use AM since no production methods are specified during a POA issue. However, every organization is obliged to demonstrate these parts meet the quality and safety requirements of the part.

As we dug deeper we found several documents containing written information about this specific topic in the Certification Memoranda (CM) by EASA. Nevertheless, none of them provided specified criteria or rules about AM, but rather referred to general production rules for airworthy aircraft parts. The most interesting parts from this CM are quoted below ([Certification Memorandum], 2017).

> All aviation parts and products are required to meet the relevant certification specifications respectively (...) according to the type certification basis, e.g. regarding strength, durability, flammability etc., regardless of the material and process combination used to generate the engineering properties.

What is described here in the CM corresponds to the claim of Ian Breed. As we read cites EASA that it's most important expectation from a produced part is it's correspondence to the rules applicable to this.

> AM variability is to be shown to be controlled through material specifications in combination with process controls defined in process specifications, including post processing operations.

This says that organizations applying for the use of AM need to have (sufficient) control over the variability of this technique and must be able to demonstrate this control. Simpler said, users need to ensure repeatability of production and demonstrate how this repeatability is achieved.

> The significance of any change (...) to any particular organizations experience and will be assessed by EASA on a case by case basis.

There are no standards by EASA which result in every organization getting individually assessed on their control on repeatability.

> ... the applicant should demonstrate by test or experience, that the material is suitable for the intended use of the part being fabricated and that the material is being purchased per an approved material specification and controlled by approved inspection methods.

As we likewise consummated from the literature previously, we note the actual importance of material is in the entire process of AM produced parts being able to certify in aviation industry. So does EASA emphasize on, that an producing organization must be able to demonstrate that the used materials are suitable for the type of part and the rules applicable on the area where it will be used in an aircraft. In the second part of the sentence it is made clear that materials must be traceable with demonstrable results on the material specification.

Mançanares (2015) described this importance similarly: "Material is a constraining factor in the selection of an AM method, since these technologies as a whole are related to specific materials. Besides did Shapiro (2016) portray the future of AM relying developing new applicable materials to different situations.
In addition told Scott Sevcik, head of Stratasys FDM printers, in two different interviews conducted in 2017 how they currently print certified aviation parts without the existence of standards yet. "If you can show that you have a repeatable process that's consistently producing the same strong part, then that allows the FAA or EASA or any airworthiness authority to have confidence in the parts that are being produced through the technology. Which lends into its certification." "We work closely with aerospace original equipment manufacturers (OEMs) that have written material specifications for our ULTEM 9085 and ULTEM 1010 products. These materials are delivered to each of those specifications which enables OEM's to have the traceability and repeatability they require." ([Adding value with 3D printing], 2017) and (B. Read, 2017).

So the answer to the question on "how it is possible to produce certified 3D printed parts" seems really to boil down on having control of two key necessities, traceability and repeatability. Whereas repeatability only seems to be about the print process and traceability about the materials.

4.5 Design, Produce and Certification route

This paragraph exhibits the relationship between the various individual EASA certificates, which have been discussed in the previous chapter. The exhibition serve to develop an understanding about the individual steps Involved in the process from start (design) to finish (certification). This detailed structure of the complete production process also illustrate the required traceability and repeatability within this process. Besides, the coming information will help in better interpreting the previous statement of Peter Dol about the multiple responsibility hats in a company structure.

The illustration of this relationship (Figure 13) results from a co-development with Ian Breed (project leader POA) and the information derived from the CM of EASA that are quoted below. The outcome of this relationship is ultimately a designed, produced and certified 3D printed component ([Certification Memorandum], 2017).

> AM variability is to be shown to be controlled through material specifications in combination with process controls defined in process specifications, including post processing operations. As required by 21.A.31, these specifications (for both, material and process) as well as the method(s) of manufacture, shall be introduced in the type design under the DOA (design approval) applicant or holder responsibility. The significance of any change, including the introduction of new materials and processes, will be a function of part criticality and/or the magnitude of the change relative to any particular organizations experience and will be assessed by EASA on a case by case basis.

> Independent of the facility where parts are to be fabricated the applicant should demonstrate by test or experience, that the material is suitable for the intended use of the part being fabricated and that the material is being purchased per an approved material specification and controlled by approved inspection methods.

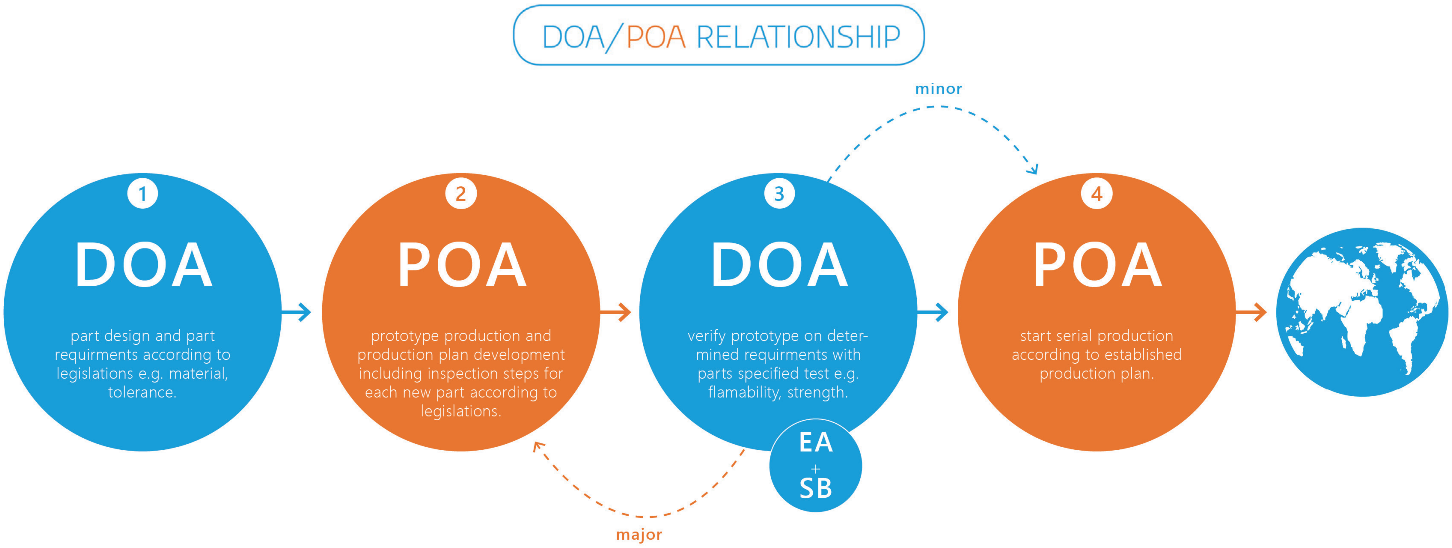


Figure 13. The DOA/POA relationship during design, production and certification.

Step 1
DOA holder will design the component completely in conformity with rules and legislations set by EASA for that type of component and set the requirements linked to the design. Think of:

- Material;
- Tolerance;
- Dimensions;
- Production method;
- Post-production process;

Step 2
POA holder produces a prototype according to these set requirements and compose a production plan specifically for this component. This plan is actually a roadmap like an IKEA-manual to ensure quality and repeatability for even the 1000th component. The production plan contains also inspection moments in the roadmap. Think of:

1. Clean up print bed;
2. Check data to set-up printer;
3. Inspect first layer;

Step 3
DOA receives prototype an examines the component on the set requirements in step 1 as well as test the prototype. These tests are component specific, some examples:

- Strength test;
- Flammability test;
- Toxicity test;

After tests are completed and everything is confirmed to be good an Engineering Authorization (EA) will be delivered. Hereafter will cabin engineers compose a new service bulletin (SB), which is a change in the maintenance manual to use this new component instead of the old.

Step 4
There are 3 options a DOA has when examining prototype. They can fully confirm prototype to which POA can start the serial production according to the set-up production plan in step 2. DOA could also come up with a "minor revision", these could be small changes in tolerances or dimensions which will not affect the overall component. These changes will be implemented to the serial production can start immediately.
DOA could also come with a "major revision", these are bigger changes which ensures POA to go back to step 2 where it should rewrite the production plan and produce the prototype according to this plan.

Step 5
All steps are finished, start installing and selling the component.

4.6 KLM E&M part production structure

Now we have learned and gather information about required certificates needed and valid necessities within the scope of the project, it's time to investigate to the extend KLM is currently permitted to do or what is still needs.

This investigation resulted into a illustration of the part production structure for MROs through which this is specified according to the current state of KLM herein. The illustration (Figure 14) shows step-by-step which certificate is needed during the process of producing parts and what tasks these certificate holders perform during each step.

The big light blue area covering multiple steps, is the border for the rights KLM currently has. Everything outside of this border has KLM no right to perform, this is exactly the "generic route" for part production offering more possibilities in contrast to the limited route of now.

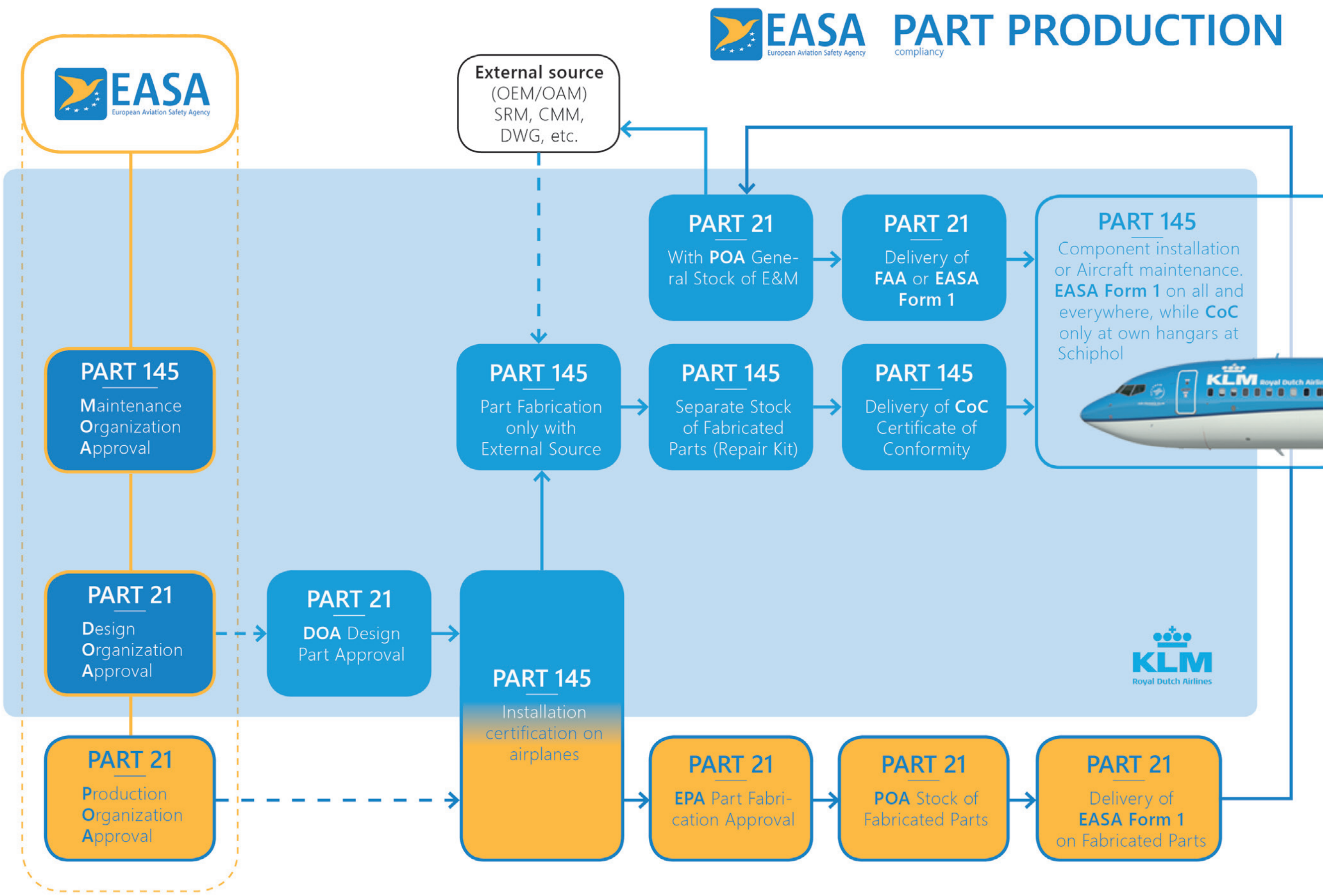


Figure 14. Part production structure for KLM E&M developed with Ian Breed.

4.6.1 What are the permissions for KLM?

The limited route for producing parts is through a DOA (PART 21) only. The DOA holder designs the component completely in conformity with rules and legislations set by EASA for that type of component and set the requirements linked to the design like tolerances. Because no POA is involved in this route, designing must take place with the help from external sources like the Original Equipment Manufacturer (OEM) or Original Aircraft Manufacturer (OAM).

Every component that is now being produced must be stored separated from the general stock of KLM E&M. Due to these components not officially being components, but being listed as repair kits. In other words, the chance of mixing these with real components by accident must be prevented.

At the end of this production route issues the DOA the produced parts with a Certificate of Conformity (CoC). Components with a CoC can only be installed on KLM aircrafts and only during maintenance at Schiphol.

KLM E&M owns a Design Organization Approval (DOA) since 2004, which can be tracked back on the official EASA website. The DOA scope of KLM in this case is designing and certifying components concerning modifications and repairs related to cabin, avionics and electronics. Figure 15 shows the full description of EASA ([Design Organisations Approvals], n.d.).

Country Name	DOA id	Organization	Initial Issue	Scope Description	Scope Permit to Fly
Netherlands	012	KLM E&M	17/3/2004	Changes and repairs to large aeroplanes related to cabin interiors, galleys or other interiors equipment, avionics and installation of avionics equipment, electrical systems and related structure and environmental control systems; Repairs and minor changes to large aeroplanes related to ECS/Ice and rain, powerplant systems, structure and hydro/mechanical systems; Minor changes and minor repairs to turbine engines.	Privilege to approve the flight conditions supporting permits to fly, within technical capability defined in the scope.

Figure 15. Original KLM DOA description by EASA.

Whilst organizations producing without a POA could be free in designing in their scope of DOA, they are still highly limited by EASA on the types of parts allowed to produce under the guise of repair. Figure 16 shows the exact list in the Maintenance Organization Exposition (MOE) under category 2.13.4.8 Fabrication of parts applicable for KLM E&M.

These rules only apply to parts that are actually taken into the air by the aircraft, and are not valid for tooling for personal use. As we have read in the literature study, the benefits that AM would offer for part production also applies on tooling. According to Schiller (2015), it would be unfortunate to miss this easy-to-achieve benefits. Since the possible opportunities AM can provide has been noticed by KLM, is the department of Engineering & Maintenance started using FDM printing to create their own tooling. They introduced this technology 1 year ago to benefit from it but mainly with the goal of building AM knowledge within the organization.

4.6.2 What are the restraints for KLM?

The generic production route still uses a DOA (PART 21), but adds a POA (PART 21) in the process. The DOA holders still designs the component in conformity with EASA and the set requirements for the type of component. In this route is external help superfluous.

Every component that is being produced within this route gets the title of being an EPA part (European Part Approval), these are officially be seen as components. They are accepted as official parts due to POA holders having the right to issue these with EASA Form 1 certificates. For this reason are these components allowed to be stored in the general warehouse of KLM E&M and can be installed on all aircrafts, at all facilities across the globe.

KLM E&M doesn't hold a POA certification and therefore cannot produce anything with an EASA Form 1. However, the application process for a POA started in March of 2019 which will take approximately 10 months according to Ian Breed, project leader POA application at KLM (18-3-2019).

KLM engineering & maintenance

Maintenance Organization Exposition

2.13.4.8 Fabrication of parts

KLM E&M fabricates aircraft-, engine- and component parts, only for the purpose of aircraft-, engine- and component maintenance under control of their own approved maintenance Organisation. Fabrication is limited to parts within the capabilities of KLM E&M.

The fabrication capabilities of KLM E&M are as follows:

- bushes, sleeves and shims
- secondary structural elements and skin panels
- control cables
- pipes
- electrical cable looms and assemblies
- formed and machined sheet metal panels for repairs
- placards
- seals

Figure 16. MOE list of product fabrication with DOA.

4.6.3 Third-party POA holder

Whilst knowing that KLM holds of a DOA and can design components and certify these designs by themselves, we also know that KLM doesn't hold a POA yet. However, KLM is currently in the application process for this certificate. Not to sit still in the meantime during the process with a duration of 10 months, KLM contracted a experienced third-party POA holder producing prints on demand. This strategic step has been taken to gain knowledge and experience within this new line of work.

They collaborate with Materialise, a Belgium based company with years of experience in 3D printing for the aviation industry. In addition to producing on-demand for third parties, they optimize OEM parts and sell them to the industry as EPA parts. These parts are optimizations of the OEM parts by reversed engineering to make them lighter, stronger, cheaper, etc. depending on the type of part.

Currently has KLM followed the generic part production route sketched in Figure 17. in its entirety with this collaboration. Whence the first printed airworthy part is flying with the 777 fleet of KLM. Due to this being a first try within this new route, a fairly simple component has been chosen according to Rik Steenkist (Manager Cabin Engineering at KLM). The develop part is a replacement of the standard soap bottle holder in the lavatories by a fully personalized tulip-shaped soap bottle holder.

Figure 17. Certified tulip-shaped KLM soap bottle holder, developd by KLM DOA and printed by Materialise POA.

4.7 Conclusion

A Design Organization Approval (DOA) and a Production Organization Approval (POA) are both needed in order to (re)design, produce and certify aircraft parts which are airworthy and allowed to fly. Both of these approval certifications are applied for a specified scope by EASA, for example "plastic cabin parts" and are not issued on one specific part or production method.

Research shows that there are no standards or specified rules regarding AM in aviation, although serves the same research the existence of currently flying certified printed parts. This contrast of information tells us printed parts are currently being certified according to legislations applicable to general production. This involves devising the entire process of part design and producing with the required inspection moments through which controls the two key necessities, traceability and repeatability. Whereas repeatability only seems to be about the print process and traceability about the materials. The whole process should be set up in such a way that every new employee who has to perform the same tasks for production can simply perform it while the quality of the end product could be ensured not being affected.

The Certification Memoranda (CM) by EASA correspondents and consolidates to the importance of material

in the entire process of AM produced parts becoming airworthy. Literature previously sketched the material as being a constraining factor in the selection of an AM method, since these technologies as a whole are related to specific materials. In addition confirms the CM and the POA expert at KLM that POA holder are free to use AM since no production methods are specified during a POA issue. The most important expectation from a produced part is it's correspondence to the rules applicable to this part.

KLM currently holds a DOA and can design components and certify these designs by themselves, but doesn't hold a POA yet. The request has been which takes approximately 10-months. For the meanwhile contracted KLM a third-party POA holder producing prints on demand. This collaboration is a plus for the project because it ensures the ability to actually 3D print aircraft parts which are allowed to fly while at the end of the time for this project the POA application process will not be finished yet.

Every certificate-holding department should be seen as a stand-alone company even though they are ultimately linked to the umbrella company, KLM Group. This could cause employees have multiple responsibility hats, which may inhibit innovation in the way that employees belief innovation is someone else's job and not part of everyone's responsibilities.

This direction is strengthened from the various discussions and observations within KLM. It seems that there is no real tendency to think outside the box on account of the many protocols and rules in the certifications, which simultaneously could have an effect on how people accept something fully new. That is why it is probably more sensible for this project to go in a direction where the step is smaller in the use of 3D printers for the production of airworthy aircraft parts and thereby also facilitates acceptance of this technology.

5. AM knowledge elaboration for KLM

Much knowledge has already been gained about AM with the literature research. The application of AM in the articles concerned examples from the general aviation/aerospace industry, which are not right away usable by KLM as a MRO. The ultimate focus of the project is finding out the possibilities AM offer KLM. This chapter, expands on the previously acquired knowledge about AM in the literature review and deepens in order to develop a more understandable and usable knowledge for KLM as a MRO. This elaboration expands on the noticed gap of the literature review in not linking the benefits to possible consequences. The elaboration of current AM use is specifically targeting online published information from similar MRO's like KLM. These direct competitors, will guide to a better understanding about the types of components, technique and benefits similar companies are using for AM production of airworthy parts.

Chapter structure

The method used for the chapter is explained in §5.1. Consequently are the benefits AM offer KLM specifically investigated in §5.2. Next is the elaborative research of current AM use by similar companies like KLM E&M treated in §5.3. The conclusion of the chapter is described in §5.4.

5.1 Method

The investigation is done through web searches on Google. The elaboration of AM benefits are examined with the use of experience from experts in the field of aviation who already use this technology combined with my own experiences in 3D printing.

5.2 Elaboration of Benefits AM offer Aviation

This complete project has started thanks to the interest of KLM in this new technology. This is because they have already identified some advantages in implementing AM, which is very interesting for KLM to be able to have these ideas. But it is more important to deliver a complete picture of all (possible) benefits the technology offers the aviation industry and so for KLM. This picture has been in illustrated in Figure 18.

The illustration will help KLM to better visualize and easier understand which areas could get affected when AM is implemented in the organization to produce parts. Together with the advantages clustered of AM as a technique. This notion will subsequently help in finding potential parts suitable to produce with this technique.

Experiences of Airbus, Etihad and Materialise of adopting 3D printers in producing aircraft parts served together with my own experience in forming the picture about the benefits. These experiences of experts are shared during the workshops about additive manufacturing organized by EASA in the years 2016 and 2017. ([2016 EASA Workshop on Additive Manufacturing], 2016) and ([2017 EASA Workshop on Additive Manufacturing], 2017).

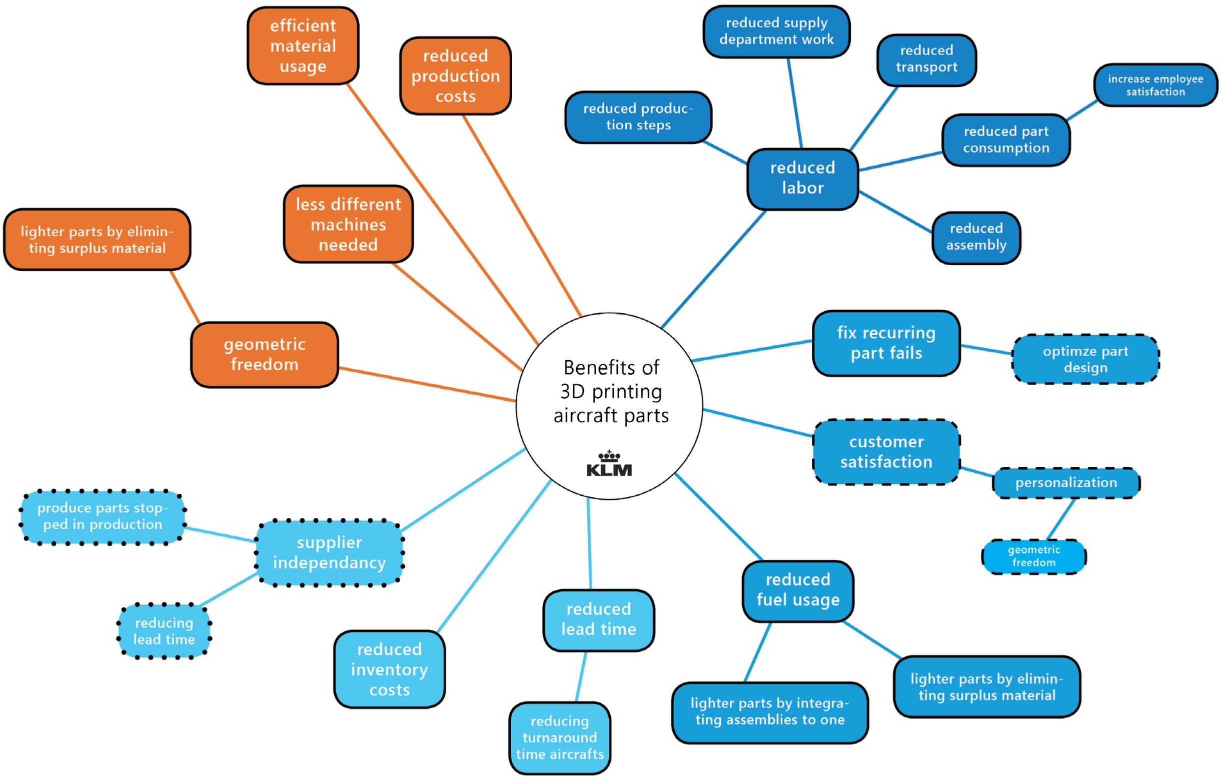


Figure 18. Elaboration diagram about benefits AM could offer KLM.

As might noticed are the illustrated benefits categorized in two levels. The first level uses different types of strokes in order to display the types of benefits AM is offering used for aircraft parts production.

= costs = control = customization

The first level is combined with the second level which make use of color coding. The diffe-rent colors demonstrate the area this benefit affects. Red, blue and green show the area at KLM which are getting effected by the imple-mentation of AM parts, while orange display the benefits of AM as an technique. In the end provides AM all the benefits, but it has been chosen to add AM technology as a separate cluster because this technology itself also offers benefits that could not be directly attributed to the consequences it has on KLM.

= supply in organization = organization

= labor in organization = AM technique

The first level is combined with the second level which make use of color coding. The diffe-rent colors demonstrate the area this benefit affects. Red, blue and green show the area at KLM which are getting effected by the imple-mentation of AM parts, while orange display the benefits of AM as an technique. In the end provides AM all the benefits, but it has been chosen to add AM technology as a separate cluster because this technology itself also offers benefits that could not be directly attributed to the consequences it has on KLM.

5.3 Elaboration of current AM use in Aviation

AM technologies are around for decades, but the developments in materials and reliability of the printing process have found (recently) their way into aviation. As we could see from the results of the literature review are various stakeholders from the aviation industry actively (exploring the) use of AM.

We have come across many different examples of printed parts targeting different aircraft areas in the literature study. A striking number of the listed components have a critical effect on flying while the total of these were made of metal. This outcome demonstrates the development of AM in process stability and control as a result of even critical parts getting printed and certified. It is very good to fully understand the possibilities and events happening concerning AM in aviation. This will sharpen the complete picture of AM in the industry and helps breaking prejudices for this technique. Besides, this information could help in developing an AM roadmap for the future of KLM.

But in the end the project revolves around the usability of this technology for KLM. For this reason plays the DOA scope an overwhelming role in defining the area KLM can use AM. This would be possible in the areas of cabin, avionics or electronics. As the cabin being the only area containing the most printable parts is this the most suitable area KLM should focus on. According to Buddy Zuijderduijn, manager cabin repair shop at KLM, consists the vast majority of an aircraft cabin of plastic parts.
To further increase applicability, a closer look has been taken at KLM's direct MRO competitors. Data from direct competitors, operators with MRO facilities, will guide to a better understanding and knowledge about what types of components, AM machines and benefits similar companies are using AM for. This is of course only a snapshot on the timeline, but yet it'll offer a better representation of the interest and possibilities of AM for these stakeholder.

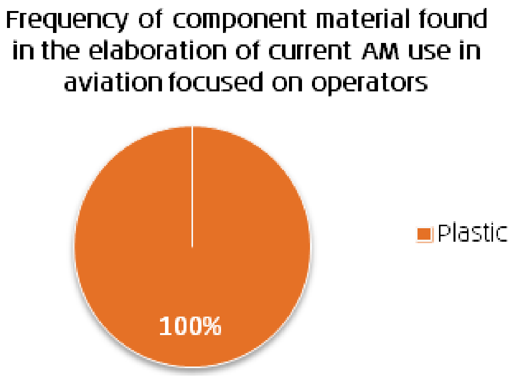


Figure 19. Type of AM use by KLM's direct operator competitors with MRO facilities.

This project is a perfect opportunity to investigate and display more of these possibilities with AM now and in the future. I consciously choose to focus solely on the possibilities now, and in this way stay within the scope of this project. Which is: "What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?". This topic is very interesting for KLM as well as for the industry and can made as broad as desired. Given the limited time in the project seems a wise choice to stay within the limits of the scope as outlined at the start.

A total of 11 printed components by MRO's are found through web searches on Google. Remarkably are all listed components made out of plastic and related to the cabin.
As we have learned from the literature review can aircraft components be grouped in their type of functionality on a aircraft (GE, 1999; Cutler J.L. et al., 2006; Biel E.H., 1993):
1. Structural components with a primary function is maintaining aircraft geometries, such as wings;

2. Functional components fulfill the primary purpose to provide flight functions, such as seats;
3. Auxiliary components are all non-structural and non-functional components, such as interior covers and bumpers;

None of these components are structural or have a critical effect on the aircrafts flying or safety. The biggest group which counts for 73% of the total are auxiliary parts covering, embodying or beautifying the interior of the aircraft like caps, air grills and LCD covers. The second group counting for 27% are functional components, which do provide flight functions and its absence will affect an action/task cannot be executed. Examples are air ducts, tables or electronic flight bag holders in the cockpit.

Frequency of component function found in the elaboration of current AM use in aviation focused on operators

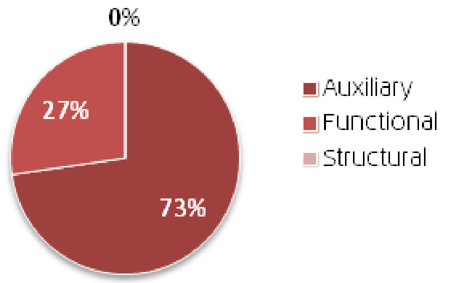


Figure 20. The functions of components, KLM's direct operator competitors with MRO facilities produce with AM.

A good example for a plastic functional part is the electronic flight bag support China Eastern Airlines is printing for various aircrafts in their fleet. This component is used to support the electornic devices pilots are using in the cockpit instead of the old-fashioned thick flight manuals. According to Stratays' polymer additive in the MRO presentation, printing of this component has resulted in a 72% cost reduction and a 90% leadtime reduction.

中國東方航空
CHINA EASTERN

Electronic flight bag support
A330, A320 and B737

Print tech. FDM
Partnership: Stratasys
Costs savings 72%
Leadtime 90%

Function: Functional
Material: Plastic
Visibility: Visible

The LCD shrouds Etihad Airways is printing for their aircraft is a great example of an auxiliary component used in the cabin. The function of this component is to create an embody around the LCD when mounted. It has a function of course, but this counts more for making it more beautiful rather than just keeping the monitor in place. The LCD could have been mounted very simply with nuts and bolts.

الاتحاد
ETIHAD

LCD shroud
B777

Print tech. FDM
Partnership: DIEHL
Costs effectiveness
Reduced weight 9 - 13%
Reduced leadtime

Function: Auxiliary
Material: Plastic
Visibility: Visible

The vast majority (91%) of the examined plastic components are fully visible to its users. This probably means that visible parts actually come into contact with users. This could increases the chance of failing faster or more often. Because they are in direct contact with variable use, also known as humans. This could also be a reason why visible components are in the majority. Due to AM's advantages, like reduced lead time, cost, customizations, logistic advantages, etc. fits well with this.

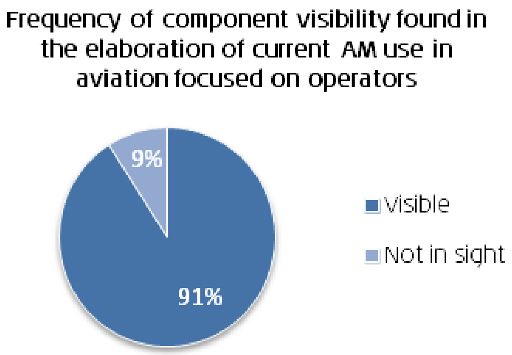


Figure 21. The visibilty of AM produced components by KLM's direct operator competitors with MRO facilities.

Two different AM processes were used in the examples examined, FDM and SLS. Almost two-thirds (64%) are produced using FDM, while the remaining 36% with SLS. There is a possibility that these results do not represent complete reality, because China Eastern Airlines has the most examples online and all are produced with FDM while others using SLS have fewer examples. However, it can be said that these were the only techniques used among the examples

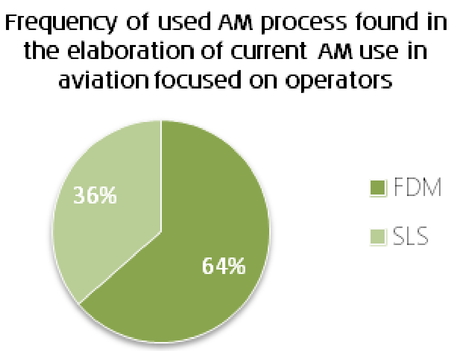


Figure 22. AM process used to produce the components by KLM's direct operator competitors with MRO facilities.

The mentioned benefits gained by using AM for these specific components by operators are listed and ranked. This resulted into the following graph. The two most used benefits are the lead time at first which is 31% of the total, which is followed by costs reduction as second with 26%..

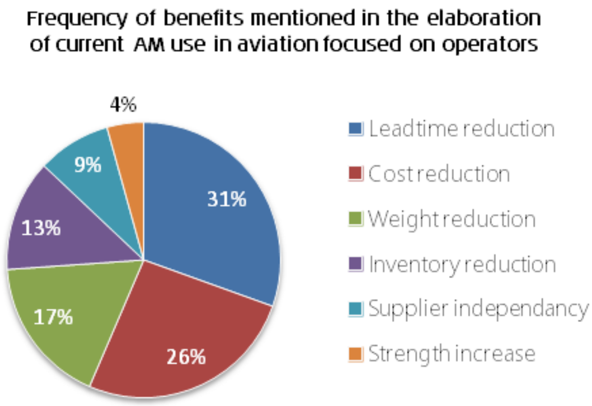


Figure 23. The mentioned benefits gained with AM produced components by KLM's direct operator competitors with MRO facilities.

5.4 Conclusion

An elaboration on the benefits is done to close the gap of the literature review by linking AM benefits to possible consequences. In this way, the previously found along with the new benefits could be grouped with possible consequences and visually presented for easy understanding. The results seems to affect cost reduction to a large extent like KLM's expectations. However, comes costs in many different forms as well as different areas in the organization rather than only in the form as purchase costs.
With the outcome, it makes more sense to expand the project direction to find and develop suitable parts for the various benefits of AM rather than only focusing on finding "the perfect" part reducing the costs best. In this way shall the project provide a better and more complete picture of the possibilities AM offer KLM which fits the main research question much better: "What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?".

The elaboration of the current use in aviation was necessary due to the fact that the results from the literature study do not match well with the target and expertise of KLM. Equivalent companies, operators with MRO facilities, were investigated to get a better picture. Data from direct competitors will guide to a better understanding and knowledge about what types of components, AM machines and benefits similar companies are using AM for. The research resulted in a list where all parts were made out of plastic and related to the cabin. All of these components were printed using FDM or SLS machines. The majority consisted of auxiliary components (73%) at which almost all parts were in sight (91%). The most mentioned benefits achieved with AM were lead time reduction (31%) and cost reduction (26%). While these advantages have a shared third place in the results of the literature study appearing in 47% of all examined articles

KLM's DOA scope, the results of the fellow MROs and the statement by Buddy Zuijderduijn, manager cabin repair shop at KLM, it can be concluded that KLM should focus on implementing AM for plastic cabin parts.

The next step will be the investigation into possible AM techniques that are available for use within the scope of KLM. The research should result whether and why an AM technique will or will not be suitable for this purpose.


KLM

6. Plastic AM knowledge elaboration for KLM

As we have seen in the literature, the focus was mainly on metal printers. A significant outcome of 80% of all emerging printers in the 17 articles examined were metal printers. Some articles even reasoned why these printers are important for the aviation industry. Zhang, et al. (2019) reasons the larger importance of metal AM for the aircraft since metals like aluminum or titanium are major components for most aircraft models. For this reason, more research is being done on popular metal AM like SLM, DMLS, EBM and WAAM for the aviation sector.

Now as it has been concluded that KLM should focus on implementing AM for plastic cabin parts in the previous chapter, a need arose to investigate the availability and usability of these plastic printers for this industry. First of all, criteria will be developed after investigation with which these processes can be trialed for usability in the aviation. Hereafter will the listed plastic AM processes be trialed.

Chapter structure

The chapter method is explained in §6.1. Additionally is the criteria selection for selecting plastic AM process for the aviation industry explained in §6.2. The next paragraph, §6.3, describes the process of printer selection on the basis of the prior set criteria. Ending with the conclusion in §6.4.

6.1 Method

The investigation for selection criteria is done by combining knowledge from the previous literature study and validation through web searches. Creating the list of plastic AM processes is done according ASTM categories (2012) for AM while trialing this list is done through Google searches conducted by combining <fill specific AM process here> + <fill selection criteria here> as search terms.

6.2 Selection criteria Plastic AM processes

Zhang et al. (2019) concludes that there is no answer to "Which AM process is best for aircraft" and neither a definitive conclusion on "Which component cannot be fabricated by AM after all".

The foregoing sentence of Zhang et al. (2019) is actually a summarizing conclusion of what we have also noted with the result of previous research. Due to the lack of standards on AM use in the aviation industry are current POA application whereby AM will be used issued on the basis of general production criteria standards of EASA.
The truthfulness of this statement is enhanced by the equivalent verdict by Peter Dol, that it's especially important to demonstrate standards for general production are being complied and this can be demonstrated with required inspection moments to get certified.

This means that in principle all AM processes can be used, simply because there are no standards available yet. It was considered to base the usability investigation of various plastic AM processes on the findings from the literature study and the paragraph "§5.3 Elaboration of current AM use in Aviation". However, seems this approach unwise to me after collecting the previous knowledge. We've learned that it is currently particularly important to sufficiently control the process and material including post-processing operations regardless of the AM process (EASA Certification Memoranda, 2017).

When an AM process is not used (yet) in the aviation industry, doesn't necessarily mean this can't be used at all. This conclusion has ensured the adjustment of the investigation approach, all plastic AM processes will be equally tested on their applicability in the aviation industry.

We have previously seen the use of material as criteria for testing AM processes in articles. Both Hodonou et al. (2019) and Mançanares et al. (2015) use material as the first and most important criteria to cluster or filter the various processes. Rules and standards for cabin materials already exists regardless AM, leading this criteria to fit the goal of the paragraph very well. So does Rhemanjan (2015) indicate the obligated compliance of aircraft interior components with the flammability requirements compiled in the standard called FAR 25.853.
According to the website of Ensignerplastics.com do these materials have to fulfill several technical requirements in order to help maintaining reasonable safety for the passengers in case of fire in the cabin. To become FAR 25.853-worthy, all materials are FST (Fire, Smoke and Toxicity) tested. When the test is passed, it is permitted to use this material for aircraft interior purposes. ([Plastics for aircraft interior applications], n.d.).

6.3 Selecting All Plastic AM processes

In this paragraph are all ASTM plastic AM processes getting trialed on their (possible) usability in the aviation industry. The assessment takes place on the basis of research into the availability of FAR 25.853 passed materials of the AM list. The investigation is conducted through Google searches done by the combination of <fill specific AM process here> + FAR 25.853 as search terms.

All AM processes are clustered according to the 7 categories of ASTM (2012) and only displayed when they use plastic materials (Figure 24).

The result of the online research leads to the following outcomes shown in figure 25. Only selective laser sintering (SLS), a powder passed process and fused deposition modeling (FDM), wire based material extrusion process have materials that are suitable for the use of aircraft interiors. Although currently other processes cannot be used in the aviation industry due to lack of FAR 25.853 passed materials, this result doesn't mean that they can never be used. Like Shapiro et al. (2016) and Uriondo et al. (2015) claimed in the literature study, the future of this technology relies on the continued development of existing materials in order to achieve more applicable materials to different situations.

VAT Polymerization	**PBF** (Powder Bed Fusion)	**ME** (Material Extrusion)	**BJ** (Binder Jetting)	**MJ** (Material Jetting)
SLA Stereo Lithography Apparatus	SLS Selective Laser Sintering	FDM Fused Deposition Modelling	BJ Binder Jetting	MJ Material Jetting
DLP Direct Light Processing	MJF Multi Jet Fusion			
CDLP Continuous DLP				

Figure 24. All plastic AM processes clustered according to the 7 ASTM (2012) categories.

AM process	SLA	DLP	CDLP	SLS	MJF	FDM	BJ	MJ
FAR passed	No	No	No	Yes	No	Yes	No	No
Material name	x	x	x	1. PA 2241 FR (Nylon based) 2. PA 606 FR (Nylon based) 3. Nylon 11 FR 4. Nylon 12 FR 5. DuraForm ® FR 100 6. DuraForm® FR1200 7. ProX® FR1200	x	1. Ultem™ 1010 Resin (PEI based) 2. Ultem™ 9085 Resin (PEI based) 3. PPSU (released in 2020)	x	x

Figure 25. Results of AM processes with suitable materials according to FAR25.853 aircraft cabin material requirements.

6.4 Conclusion

The lack of standards for AM in the aviation industry actually creates the possibility to use every AM processes in principle. For this reason are all plastic AM processes equally tested on their applicability in the aviation industry. As assessment criteria is material used due to the existence of rules and standards for these, which in this case is FAR 25.853. Cabin materials are required to maintain reasonable safety for passengers in case of fire in the aircraft interior.

Plastic AM processes assessed by this criteria resulted into SLS and FDM being the only two suitable processes for the aviation industry at the moment. However, this result doesn't mean that other processes can never be used. Other processes could be implemented in the industry whenever new FAR passed materials will be developed while the AM process can be sufficiently controlled ensuring repeatable quality for even the 1000th component.

With this step we arrive at the moment of the second part of the main research question, which is "in what way can suitable parts be selected". In the next chapter will suitable components searched, listed and selected. Which are getting (re)designed after the selection in the design phase of this project.


KLM

7. Selecting suitable parts for AM at KLM

With the foregoing knowledge, we are heading to the last part of this project and likewise the main research question. Which is (re)designing. But before this, the second part of the research question, "in what way can suitable parts be selected" must be answered first.

To be able to select components, focus criteria should be composed first. This is necessary to determine which type of components should and shouldn't be included in the selection. These criteria serve as limitations to refine the suitability of various types of parts and for viability of this approach. Once these focus conditions have been established, it is time to look and find these parts that fit within these criteria. After constructing the list of components, it's the turn for the final step: selecting the ultimate parts which will get (re)designed in the next phase of the project.

Chapter structure

The method used for the chapter is explained in §7.1. Consequently are the part criteria constructed in §7.2 to develop a border during selection of suitable parts. Next is the way of creating the list of suitable parts is explained in §7.3. Besides is the selection of parts from the list and the construction of the trade-off table elaborated in §7.4. Finally, is the conclusion of the chapter is taken care of in §7.5.

7.1 Method

There are several different methods used during the development of this chapter. In order to compose the focus criteria are multiple interviews conducted with KLM experts. These interviews were tackled in an unprepared manner and mainly had an exploratory goal.

In order to construct the list with various components a total of three different moments and activities are organized with KLM experts. The first workshop made use of group brainstorming at which participants were challenged to perform 3 creative sessions. The second activity assembles parts based on raw and actual data from the stock administration system that KLM uses. In the last workshop is brainstormed together using the method of answering pre-formulated assignments. These assignments are testable questions that actually provide an answer to another much broader question. The third workshop is again organized with internal experts from KLM E&M. More details and explanation about all applied methods can be found in the paragraphs and appendix.

After the list of components has been constructed, the selection procedure is applied. An elaborated trade-off table has been constructed called the weighted objective method. This trade-off table is composed in collaboration with KLM experts during a workshop organized for this purpose. Which resulted into a more objective weighing scores of the enlisted criteria the components list is judged on.

7.2 Part focus criteria

As you can imagine, contain aircraft lots of different parts and components. The Boeing 737 narrow-body plane for example, consists of a total of 367,000 parts (Linn A., 2010) to get a better feeling.

Logically, do large quantities of these parts differ in their functions. Different functions entail different rules. Numerous interviews were conducted during KLM's internal research, Appendix C. shows the exact list of spoken experts together with their position at KLM. These interviews were tackled in an unprepared manner and mainly had an exploratory goal to learn KLM itself, but also the rules and information applicable aviation wide but also MRO specific. For this reason, do these interviews result in the formation of knowledge and meaning about the various part types. As well as form an advice on how these various types will have to be taken into account in the way whether or not a part type should be produced by KLM. This advice will simultaneously serve during composition of the suitable parts list for this project. All various part types derived from the knowledge gained through these interviews are illustrated in Figure 26.

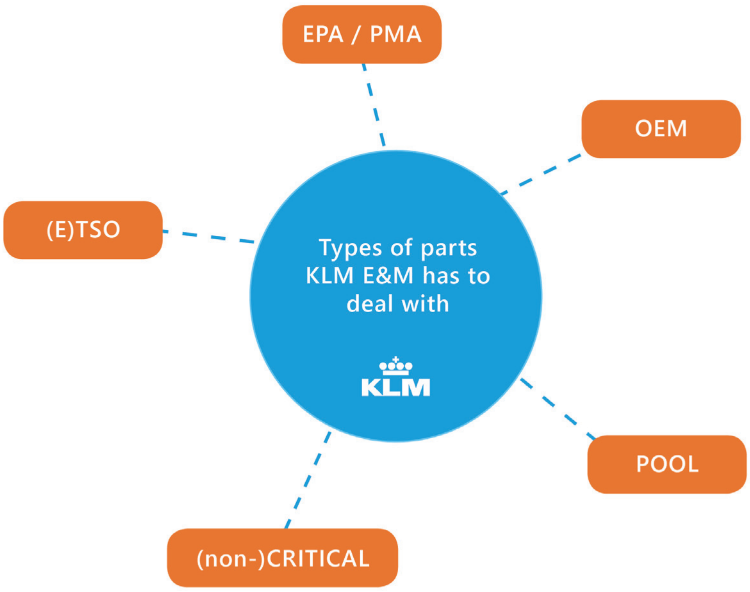


Figure 26.Constructed criteria for the selection of suitable parts for AM.

7.2.1 OEM parts

Original Equipment Manufacturer (OEM) is defined as a company which manufacturers parts that are used as components in finished products of another company. For example, car manufacturer BMW uses OEM Bosch as standard windscreen wipers on their cars. ([Parts OEM vs. genuine vs. aftermarkets], n.d.).

Advice: This is another branch of sport and by far out of scope for KLM. They focus on repair and modification parts for maintenance purposes only and should not want to become a full-time vendor producing parts. For this reason, this type of components should be neglected.

7.2.2 EPA / PMA parts

European Part Approval (EPA) and Part Manufacturer Approval (PMA) are both the same type of parts. The only difference is that EPA is the name for parts that are EASA approved (EU) and that PMA are FAA approved (USA). These are completely certified and legal to fly aftermarket options of more expensive OEM parts that aircraft manufacturer prescribes in their repair manuals. ([FEDERAL AVIATION REGULATIONS FOR PMA PARTS], n.d.).

Every part produced with an EASA Form 1 by KLM will automatically fall within this product category. In terms of safety, certification, etc., are these parts officially and completely fine. Unfortunately plays another factor an overwhelming role during the choice of using EPA/PMA or OEM parts, the human. During preparation of the maintenance contract with KLM E&M, each operator chooses the type of replacement parts they want on their aircrafts. OEM or aftermarket. Many Airline operators do not own their aircrafts, but lease them. In this case are lease companies also involved during the preparations of this maintenance contract. In this case are OEM parts are always chosen. The reason is very simple, OEM parts ensures aircrafts to retain their value better. Which therefore enables the lease companies to find new customers more easily for their aircrafts when needed, as well as charge higher amounts. Exactly like dealer maintained cars, where their maintenance booklets are stamped by the BMW dealer.

Advice: A smart solution could be devised to sell these parts to operators / lease companies that only want OEM. KLM is currently in the middle of a negotiation for starting an intermediate company with BOEING to "produce" these OEM parts. In this way will KLM optimize parts by combining their DOA and their knowledge gained during maintenance of these parts. KLM will in this case only redesign the parts with their DOA. Next will Boeing receive the fully optimized redesign, check it, produce it and put it on the market as an OEM part. In this way the aforementioned problem with the choice between EPA and OEM will be fixed while a win-win situation arises at which both companies share the profit.

7.2.3 POOL parts

Pool parts are parts which are removed from one aircraft, repaired / renovated and then brought to the warehouse as a "new" full functioning product. After which this part is mounted into another aircraft.

Advice: When KLM would produce pool parts, each contracting operator will have to be asked if they agree with this change into EPA parts produced by KLM. Operators who have an OEM agreement like mentioned before will find this very difficult to accept. This will only happen if all 30+ operators accept this. In case even 1 operator won't accept the EPA part, it means that the pool inventory system gets separated. This separation won't be cost-effectiveness in terms of warehouse, labor and possibility of errors. For this reason, this type of components should be neglected.

7.2.4 CRITICAL parts

Critical parts are characterized by the fact that the failure, malfunction or absence result in an unsafe condition. These parts are non-structural and non-functional components which don't affect flight safety, flight control or flight structure. These parts could fall into both auxiliary and functional component categories according to the functionality grouping used by GE (1999), Cutler et al. (2006) and Biel (1993). ([Flight Safety Critical Aircraft Part Law and Legal Definition], n.d.).

Advice: Avoid these parts! As we have read in the literature study, we see that AM is already being used for metal and critical components. But this is only done by OEMs dealing with these components, such as GE and Rolls Royce who are fully specialized in their branch. For this reason, exactly the same reason used under OEM parts applies in this case as well.

Focusing on non-critical and minimal (or not) mechanically loaded parts, will increase the chance of obtaining certification for a component (faster). Due to the fact of these components have less requirements ensuring easier achievement and faster. Besides, these components are also advised by Rehmanjan (2015), Wohlers (2013) and the Oak Ridge National Laboratory (2010) for near-term AM adoption.

7.2.5 (E)TSO parts

European Technical Standard Order (ETSO) for Europe and just Technical Standard Order (TSO) for USA. Both are exactly the same type of parts. (E)TSO parts are complete products, assemblies of products or just parts of products which are certified in both design and production. Because these parts are theoretically installable in any aircraft, they don't carry inherent installation eligibility. ([FAA TSO & TSOA Explained], 2018).

> **Advice:** (E)TSO products, assemblies or parts can be maintained by others like KLM E&M but are obligated to only follow the provided maintenance instruction manual by the original manufacturer.
> It is forbidden to modify this manual or use other than prescribed components. When this is still done, the (E)TSO certificate will be withdrawn. This category should be avoided as much as possible. If there are many promising products from this category, it must be carefully investigated whether the entire product, assembly or just a parts falls under these regulations. In this way it is still possible to tackle these parts.

7.2.6 List of criteria

This paragraph uses the findings and conclusions from previous chapters together with advice from the last paragraph to draw conclusions and thus establish a list of criteria that will be used during composing of suitable parts for this project.

The difference in role of the categories OEM or EPA/PMA only matters when produced parts by KLM E&M will be sold or installed on other aircrafts. When they are installed on own KLM aircraft, this bureaucratic problem of requesting approval from all operators does not apply.

Because KLM is still in a very early phase of designing and producing parts with an EASA Form 1, it is pretty unwise to already limit. If these parts are only implemented in their own fleet. It would still have a major effect in terms of the overall goal of the project and first step in AM by KLM.

The DOA ensures the focus on the cabin, while the expertise of Buddy Zuijderduijn and the result from the research of KLMs MRO competitors results in the focus on plastic and non-critical parts. Having described this, the total criteria list looks as follows.

The selected parts should be...

1. ... non-critical parts (§7.2.4)
2. ... none pool parts (§7.2.3)
3. ... none (E)TSO parts (§7.2.5)
4. ... plastic parts (§5.3)
5. ... cabin parts (§5.3)

7.3 part listing

A total of 3 moments were applied in different ways and methods to find suitable components for this project. Figure 27. Illustrates these 3 moments and the specific focus of the project at the moment the activity was executed. This focus displays the direction of the enlisted parts during these moments.

Workshop I
(cost reduction)

SAP raw data excel
(cost reduction)

Workshop II
(AM benefits)

Figure 27. Three moments of activities executed to construct the suitable parts list for the project.

At the beginning of the project, the focus was only on how to reduce costs at KLM E&M during maintenance and repair by implementing AM. This ensured the focus in the first two moments only being on cost driven direction. As the project began to take shape, it was decided to no longer just focus on trying to reduce the costs for KLM E&M by implementing AM, but to actually explore and investigate the ways and possibilities AM could bring in for KLM. As a result, it was decided to create a vision for KLM in which the benefits of AM, as described in paragraph "§5.2 Elaboration of Benefits AM offer Aviation", are worked out by redesigning a selected part for each benefit. This will ensure that we can paint a better picture of the possibilities AM really can offer KLM. With this change in approach the project fits perfectly with the main objective and main research question of the project again. Which certainly results in a larger and more usable result. After this change, a new moment has been organized in order to possibly find better suitable components fitting the new approach.

Each moment is briefly explained in this paragraph. The complete set-up of these can be read in Appendix D.

Workshop I

- The main goal of the workshop was finding components reducing maintenance cost in KLM E&M;
- The workshop was done together with 12 participants from the direct field of E&M;
- Presentation acting as steam course about AM and what KLM already does with this;
- Used method are 3 different types of creative sessions;
    - Mind mapping
    - Battle for the top
    - Select & draw

SAP raw data excel

- The main goal of the workshop was finding components reducing maintenance cost in KLM E&M;
- This process is done together with one data analyst and one depot leader of unserviceable parts;
- Used method is raw data derived from SAP stock administration system KLM uses;

Workshop II

- The main goal of the workshop was finding components for each benefits AM offers KLM;
- The workshop was done together with 7 participants from the direct field of E&M;
- Used method was brainstorming and answering formulated assignments for each benefit AM offers;

From all the activities combined, a list of suitable components are enumerated for each benefit that AM offers KLM. The complete list of components can be found in Appendix E. The mentioned benefits are, faster lead time, integrating assemblies, reducing weight, customization and reducing purchase cost. All enumerated components will pass through the selection procedure whereby they get tested against criteria. One component will ultimately be selected for every benefit, which will subsequently worked out in the design phase.

The elaboration of these components will serve to create the AM vision for KLM and will show what AM can offer in different ways by working out 1 component specific selected for that benefit. These components currently have the problem which can possibly be remedied with the advantage of AM for which they have been chosen. All other benefits that AM offers rather than the main benefit become side concerns and not the main objective for this component. Besides, the redesigned part should be made printable, strong enough for use and meets all the specific requirements that will be listed in the final development phase.

7.4 Selecting parts

As the list of parts has been created during the 3 different sessions explained in the previous paragraph, the time had come to select suitable components for the 5 benefits that AM could offer KLM. This is done based on the selection method "weighted objective" (Roozenburg and Eekels, 1998). The weighted objective method assigns scores to the degree a component satisfies a criterion. However, might each listed criteria differ in their importance. For this reason are different criteria assigned with a weight, which allows taking different importance's between criteria into account during selection.

To set up a well-considered weighted objective method, a workshop was organized with KLM experts. Doing this together with KLM multiple experts will serve to make this procedure not only become certainly more objective but also better grounded. The list of criteria is derived

Trade-off table criteria
Faster lead time
Integrating assemblies
Reduce weight
Increase product life cycle
Opportunity of complex geometry
Customization
Increase employer satisfaction
Increase customer satisfaction
Fix recurring fail issues
Reduce purchase costs
Reduce supplier dependency
Increase buy-to-fly ratio (waste material reduce)
Reduce labor time
Reduce TAT (Turn Around Time)
Reduce fuel consumption
Attractiveness for KLM (Marketing potential of AM)
Possible implementation speed

Figure 28. The list of criteria created for the trade-off table.

from the previous results in paragraph §5.2 Elaboration of Benefits AM offer Aviation. These criteria are therefore a reflection of the concluded benefit - consequence combinations AM could offer KLM. Figure 28. displays the eventual enlisted criteria's for the trade-off table, some of the enlisted criteria feel very similar but differ sufficiently to take them separately.

Moreover is the created list of criteria discussed and refined. Additionally are the criteria rated on the importance according to 8 KLM experts Appendix F. All experts are from the field of E&M and participated in previous workshops in constructing the parts list. They were asked to use their expertise to rate the criteria from 1 to 5. This rate represents the importance of a particular criterion to judge a component with, 1 means very unimportant while 5 means very important. The average of all outcomes is taken to determine the weighing score requirements. Hereafter are preconditions constructed per criteria determining the meaning of the score scale from 1 to 5. This step is likewise performed together during the workshop. This ensures the assessment becoming less subjective and more determined and in this way increasing the academic level of the assessment.

Eventually, the complete list of components is assessed based on the weighted objective method using the gathered knowledge and information during the organized activities about these components (§7.3 Part listing). A 0 score is given when not enough information was available to rate a component on the derived scale. This ensures this criterion becoming excluded in the assessment of this component. Assessing the entire parts list resulted in the selection of components per benefit, displayed in Figure 29. The complete workshop setup and steps can be read in Appendix F.

AM benefits	Selected components
Faster lead time	Seat armrest
Integrating assemblies	Handicap handrail
Reduce weight	Befold seat tables
Customization	Window shades
Reduce purchase costs	Business class cabin bumpers

Figure 29. Results of selected parts for each AM benefit with the use of the trade-off table.

7.5 Conclusion

Conducted interviews with KLM experts during internal research lead to a different perspective on the various types of existing components. Aircrafts contain lots of different parts and components. The Boeing 737 narrow-body plane, for example consists of a total of 367,000 parts. These perspectives resulted in a list of focus criteria used to determine a type of components should and shouldn't be included in the selection process. Which sounds like, "The selected parts should be...

1. ... non-critical parts (§7.2.4)
2. ... none pool parts (§7.2.3)
3. ... none (E)TSO parts (§7.2.5)
4. ... plastic parts (§5.3)
5. ... cabin parts (§5.3)

The scope of the first two organized activities to find parts were on finding parts which had the biggest impact on cost reduction. This was since the focus of the project was on how to reduce costs at KLM E&M during maintenance and repair by implementing AM. As the project began to take shape, it was decided to change the project approach into actually exploring and investigating ways and possibilities AM could bring in for KLM. In this way would a vision created which will serve in better positioning the possibilities that this technology offers KLM.

Executing the weighted objective method which has been set up together with KLM experts helped the selection procedure becoming more reasoned which leads to a well-founded argumentation. As these experts have more experience and could hereby better rate the importance of listed criteria and since the average is taken from their input to determine the weighing score per criteria. Besides, the parts are tested on these criteria with preconditioned score scale from 1-5 established with these experts. A 0 score is given when not enough information was available to rate a component on the derived scale. This ensures this criterion becoming excluded in the assessment of this component. The results after assessing the list resulted in the components per benefit displayed in Figure 30.

AM benefits	Selected components
Faster lead time	Seat armrest
Integrating assemblies	Handicap handrail
Reduce weight	Befold seat tables
Customization	Window shades
Reduce purchase costs	Business class cabin bumpers

Figure 30. Results of selected parts for each AM benefit with the use of the trade-off table.

After completion of the research phase and selecting the components, the next step will be (re)designing the five components according to the AM benefit it's connected to. The (re)design should mainly focus on achieving the greatest success in the AM benefit under which it has been chosen, ofcourse it is allowed to include other benefits when possible. In this way, it could videlicet clarify the vision by helping to easier deduce the main benefit it serves.


KLM

8. Design phase

As the chapter name represents, the focus will be on developing and designing. Through this chapter does the project enter the last part of the project and main research question, "in what way can selected suitable parts get (re)designed".

In the prior chapter a list of suitable parts has been selected. Nevertheless, in case of some selections we are actually talking about product categories rather than a specific part. For this reason, it is extremely important that specific part numbers must be selected.

After finishing the list of parts, a standard template has been constructed with which each part will be further elaborated. This template serves in helping the redesign process. Each section of this template is explained in advance of the redesign process, why they are important and how they have been executed. Four comparison aspects are determined, which shows whether an improvement or deterioration has been achieved when compared with the original part. Testing the part on printability and strength are of extreme importance. The result of these tests will automatically demonstrate the validation of the determined comparison aspects. Consequently, are the 5 selected components developed in the redesign process according to the constructed template and new concepts are created. At last is the most promising concept selected to fully develop in the next, final phase of the project.

Chapter structure

The method used for the chapter is explained in §8.1. Next are part numbers selected in §8.2 with a new developed route for the product categories in the prior chapter. Paragraph §8.3 explains the approach on determination of comparison aspects between the redesign and original part. Consequently is the importance and setting up of the test on printability for redesigned parts described in §8.4. Besides, is a strength analysis set up in §8.5, for the redesigned parts which also functions as validation of the determined comparison aspects. Paragraph §8.6 contains the elaborate concept development phase. After the completion of each concept for the 5 AM benefits, gets the one with the biggest potential selected in §8.7 using the prior trade-off table. Finally, is the conclusion of the chapter is taken care of in §8.8.

8.1 Method

There was no route for finding any part numbers, this workflow is at the same time different than the usual workflow KLM employees use. For this reason is a new workflow created to find and select specific part numbers. This route is created by combining two separate KLM experts from the field.

For the determination of the 4 comparison aspects: price, delivery time, weight and quantity of parts, are different approaches executed. The quantity of parts can easily be counted in the created concept model, while the other aspects require a little more research and speculation to make a good estimation. The lead time gets determined by an assumption. The weight and price are determined by pre-constructed formulas using the ratio method with an AM printed part developed by a KLM expert.

A new method has been created to test on printability. All components will be redesigned for AM, but there may still be reasons why a component is not suitable for printing. Testing on suitability has to do with 2 conditions, the function requirements of the component and printer specifications. Each listed component function requirement is linked to printer specifications. When one starts by selecting the required function, it will automatically end up with the printer specifications. The resulted specifications can be seen as limitations of a process and as design guidelines. Testing the strength of the redesigned concept is done through simulating determined maximum use forces on the CAD models using the Finite Element Method (FEM). DINED an anthropometric data tool is utilized for the determination of the maximum use forces.

Consequently are the 5 selected components developed in the redesign process according to the constructed template and new concepts are created. To be able to trace the potential impact of the redesigned component that will be printed, it was investigated how often it occurs in total in KLM's fleet. Information about the entire fleet can be found on KLM's website ([KLM fleet information], n.d.). The fleet interiors were investigated dependent on the redesigned component. Consequently are the parts counted by hand on the found floor plans of the interiors. At last, are the 5 developed concepts judged with the previously constructed trade-off table.

8.2 Selecting part numbers

We constructed together with experts and using several methods a list of possible components for AM benefits for KLM in the previous chapter. The selection and choice of the most suitable components for the 5 benefits that AM offers has resulted in 5 components. In order to make it possible to work out and redesign these selected components, specific part numbers must be selected. Furthermore, this will ensure that the new design can also be compared to the original part on improvement.

This selection of specific part numbers was made in collaboration with experts from the cabin engineering, material planning and unserviceable depot departments. Combining their knowledge in separate fields served in completing this complicated task. This search process was encountered difficulty due to KLM search systems and employees normally start a search from a part number basis. Which means you can search and find information if you have a part number, but cannot search for part

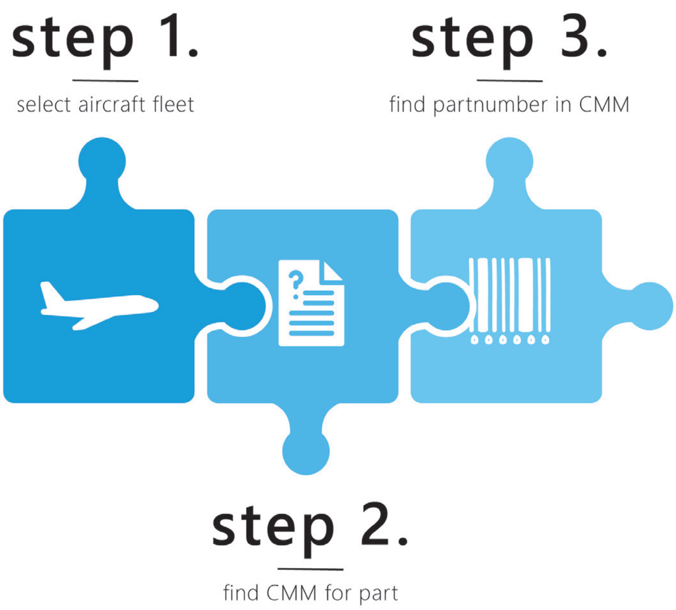


Figure 31. New created route to find part numbers for prior selected product categories for the AM benefits.

numbers if you just have information. For this reason, part numbers have been selected using the Component Maintenance Manual (CMM). Several manuals have been searched per component in order to be able to fish the required part numbers. During the selection process, the AM benefits for which the components are selected were leading but to be able to select a CMM an aircraft fleet selection was required first. Logic has been used selecting these fleets on most frequent occurrence in order to increase possible impact when AM would be implemented. Figure 31. illustrated the order of complete part number selection process.

The execution of the selection of part numbers resulted in the table displayed in figure 32.

Two types of handrails were investigated for the possibility of integrating assemblies. Both the handrail in the Boeing 737 and the handrails in the Boeing 777 and 787 consisted of several separate parts. Nevertheless, these assemblies were already optimized as much as possible and the individual parts consisted solely of hanging method and screws. For this reason, the second-best part in the previous part selection has been chosen to work out, the toilet paper holder.

AM benefits	Selected components	Part number	Aircraft type
Faster lead time	Seat armrest	F0479566	777 & 787 fleets
Integrating assemblies	Handicap handrail	x	x
Reduce weight	Befold seat tables	470-00-500-01	777 fleet
Customization	Window shades	411W1602-6A	777 fleet
Reduce purchase costs	Business class cabin bumpers	F0494959	777 & 787 fleets

Figure 32. Results of selected part numbers for the 5 AM benefits.

AM benefits	Selected components	Part number	Aircraft type
Faster lead time	Seat armrest	F0479566	777 & 787 fleets
Integrating assemblies*	Toilet paper holder*	0FS3500A04G01*	777 & 787 fleets*
Reduce weight	Befold seat tables	470-00-500-01	777 fleet
Customization	Window shades	411W1602-6A	777 fleet
Reduce purchase costs	Business class cabin bumpers	F0494959	777 & 787 fleets

Figure 33. Updated results of selected part numbers for the 5 AM benefits.

8.3 Determining comparison aspects

Several factual aspects are listed for each chosen component, this ensures the possibility to easily compare a new concept with the original. This comparison will serve as a base for drawing up an overview, which shows whether an improvement or deterioration has been achieved with the concept.

The factual aspects collected about the original part are the price, delivery time, weight and quantity of parts. These same aspects must be traced for the new concept to enable comparison. The quantity of parts can easily be counted in the concept, while the other aspects require a little more research and speculation to make a good estimation.

Determining the weight and price will be done by pre-constructed formulas using the ratio method with an AM printed part developed by Tolga Inan (Engineer Repair Lab at KLM) and produced by Materialise (contracted third party POA holder). This redesigned part is produced in both FDM, Ultem9085 and SLS, PA2241FR. As we know from paragraph §6.3 Selecting all plastic AM processes, are those suitable materials to use in the aircraft cabin.

8.3.1 Weight determination

The complete development of the formulas and explanation of the ratio method can be found in Appendix G. Every estimated outcome made with these is based only on the volume of 3D drawn models in CAD software. We should be aware that the choice of infill before printing a part will have a direct effect on weight, while the CAD model will remain the same in volume. On the contrary, does the estimated outcomes represent the maximum possible weight of the part with 100% infill, read as solid. Since the formula is based on the model of Tolga, printed with 100% infill. For this reason, does the formula currently sufficient enough to make a good estimation.

$$\textbf{concept weight in kg SLS PA2241FR} = \frac{(0{,}072\ kg * \textbf{volume concept CAD in mm}^3)}{53761\ \ mm^3}$$

$$\textbf{concept weight in kg FDM Ultem9085} = \frac{(0{,}076\ kg * \textbf{volume concept CAD in mm}^3)}{53761\ mm^3}$$

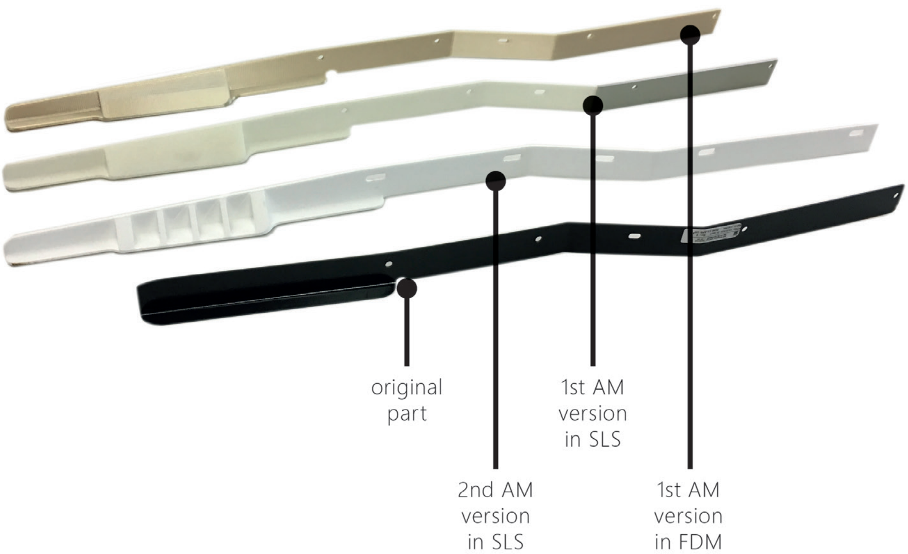


Figure 34. A picture of the original, SLS and FDM printed part Tolga Inan has developed.

8.3.2 Price determination

$$\textit{concept price in € SLS PA2241FR} = \frac{(€70 * \textit{volume concept CAD in } mm^3)}{53761\ mm^3}$$

$$\textit{concept price in € FDM Ultem9085} = \frac{(€244 * \textit{volume concept CAD in } mm^3)}{53761\ mm^3}$$

Similarly can detailed explanation of the developed formula to the determine the price be found in Appendix G. Again are the outcomes based on the CAD model volume, please note that the price calculated with these formulas serve only as an indication and may differ from the price when more quantities are purchased from Materialise or when production will be done by KLM printers. Besides, the volume of the model is not the only aspect on which a price is based. For this reason, the quality of the results with the formulas will be tested with 5 models. This validation will be done, using the online cost calculator Materialise offers via https://i.materialise.com/en/3dprint. The complete process can be read in Appendix G, but the bottom line of validation process results in the conclusion that the formulas are insufficiently accurate. However, could the use of these formulas to estimate the price be enough during this level of the project. Nevertheless, they should be improved with the new knowledge. The average difference between the formula and online calculator for the 5 models should be into account. This results in the following formula.

$$\textit{concept price in € SLS PA2241FR} = \frac{(€70 * \textit{volume concept CAD in } mm^3)}{53761\ mm^3} * \mathbf{1,164}$$

$$\textit{concept price in € FDM Ultem9085} = \frac{(€244 * \textit{volume concept CAD in } mm^3)}{53761\ mm^3} * \mathbf{0,988}$$

We should be aware that companies that supply prints on demand will use a different method of price calculation than produced on own printers. One of these on-demand printers, Shapeways, explains that they are taking model volume, machine space, number of parts, bounding box volume, support volume and production costs like labor, quality control, machine maintenance and other supporting services required to 3D print your product into account when determining the price ([How are prices calculated?], n.d.). Materialise add to this by explaining the price can be based on model volume, orientation, box around model, density, quantity, required machine volume and startup costs ([Pricing Info], n.d.).

For these reasons, the calculated results with the formulas can only be used to quick and dirty estimations during the development of a new part. When production is made with own printers, the prices will differ greatly and will mainly be based on labor, material price and machine costs.

8.3.3 Lead time determination

For a complete comparison between the original and redesigned part does the last aspect be missing, lead time. A good or realistic lead time estimation is quite difficult because it is very dependent on various stand-alone conditions. Some examples of these conditions are: material, AM process, model orientation, CAD model, number of parts on print bed, printer brand, printing time, post process, etc.

According to Materialise depends lead time on model complexity, material and post process. For a standard delivery is the average shipping within 10 business days. The number of 10 days could be the reason that these companies are delivering prints on demand services. This service could influence the lead time in case many orders are placed by various customers. The lead time will automatically get affect and the waiting list will increase, while this cannot be the case when printing is done on own machines. Nevertheless we can conclude the possibility of faster production, because shipping within 48 hours is also offered for a fee. ([Lead Times Materialise], n.d). 3Dprint UK offers a similar "priority" service where models are shipped within 2-4 days, while standard 7-12 days is reserved for lead time ([Lead Times 3Dprint UK], n.d).

The fact these printing on demand companies can deliver this fast lead time service of 2 days tells enough about the possibilities. It is currently not important to distinguish what the exact delivery time will be for each concept. For this reason, will 2 days lead time be used for the new concepts developed in this section.

8.4 Test on printability

It is extremely important to check the selected components for printability at all times during the design process. After all, it would be a great pity if a part was fully developed and it appears that it cannot be printed at all by current printers. Of course the selected components will be redesigned for AM, but there may still be reasons why a component is not suitable for printing. For this reason, this paragraph sets out an approach to test on suitability.

My knowledge tells me that testing on suitability has to do with 2 conditions, the function requirements of the component and printer specifications. The approach starts with the function requirements of the component and tests these with the printer specifications on feasibility/suitability.

A general list of function requirements has been drawn up for components. This list can be used as a checklist for each components and ensures that the wheel does not have to be reinvented for each new component. New function requirements could be added to the list and gradually make it more complete. But what it looks like now, it consists of the following requirements:

1. Aesthetic quality;
2. Flexibility;
3. Strength;
4. Impact resistance;
5. Wear resistance;
6. Chemical resistance;
7. Waterthightness;
8. Airthightness;
9. Humidity Resistance;
10. Temperature resistance;

During the development phase should be determined which of this function requirements apply for each component. Each function requirements should thereafter be linked to enlisted printer specifications in order to be able to make a statement about the suitability of these components. The printer specifications can be seen as both criteria and design guidelines. The current list of printer specifications has been compiled based on the book [A practical Guide to Design for Additive Manufacturing] by O. Diegel et al. (2019) and the [Knowledge base] of 3D hubs:

1. Material overhang angle: The maximum angle a wall can be printed without support;
2. Wall thickness: The minimum wall thickness which can be printed without a fail;
3. Horizontal bridges: The maximum span which can be printed without support;
4. Circular pins: The minimum dimensions of both horizontal and vertical pins which can be printed without a fail;
5. Circular holes: The minimum dimensions of both horizontal and vertical pins which can be printed without a fail;
6. Emboss & Engrave details: The minimum dimensions for emboss or engrave de tails which can be printed without a fail;
7. Minimum features: Minimum size of general features which can be printed without a fail;
8. Tolerance / Accuracy: The dimensional accu racy an AM process can print with;
9. Post process: The possible processes after printing;

<table>
<tr><th></th><th>FDM (plastic)</th><th>SLS (plastic)</th></tr>
<tr><td>Material overhang angle</td><td>> 45° support needed</td><td>no support needed</td></tr>
<tr><td>Wall thickness</td><td><table>
<tr><td>Process variable</td><td colspan="2">Wall thickness (t)</td></tr>
<tr><td>Layer thickness</td><td>Minimum</td><td>Recommended minimum</td></tr>
<tr><td>0.18 mm (0.0071 in.)</td><td>0.36 mm (0.014 in.)</td><td>0.72 mm (0.028 in.)</td></tr>
<tr><td>0.25 mm (0.0098 in.)</td><td>0.50 mm (0.02 in.)</td><td>1.00 mm (0.039 in.)</td></tr>
<tr><td>0.33 mm (0.013 in.)</td><td>0.66 mm (0.026 in.)</td><td>1.32 mm (0.052 in.)</td></tr>
</table></td><td><table>
<tr><td>Minimum wall thickness (t)</td><td>Recommended minimum wall thickness (t)</td></tr>
<tr><td>0.6–0.8 mm (0.031 in.)</td><td>1.0 mm (0.039 in.)</td></tr>
</table></td></tr>
<tr><td>Horizontal bridges</td><td>10 mm</td><td>no support needed</td></tr>
<tr><td>Circular pins</td><td><table>
<tr><td>Minimum diameter for vertical pins (v)</td><td>Minimum diameter for horizontal pins (h)</td></tr>
<tr><td>2.0 mm (0.079 in.)</td><td>2.0 mm (0.079 in.)</td></tr>
</table></td><td><table>
<tr><td>Minimum diameter for vertical pins (v)</td><td>Minimum diameter for horizontal pins (h)</td></tr>
<tr><td>0.8 mm (0.031 in.)</td><td>0.8 mm (0.031 in.)</td></tr>
</table></td></tr>
<tr><td>Circular holes</td><td><table>
<tr><td>Required diameter (d)</td><td>CAD model diameter</td></tr>
<tr><td>5.0 mm (0.197 in.)
10.0 mm (0.394 in.)
15.0 mm (0.591 in.)
20.0 mm (0.787 in.)</td><td>5.2 mm (0.205 in.)
10.2 mm (0.402 in.)
15.2 mm (0.598 in.)
20.2 mm (0.795 in.)</td></tr>
</table></td><td><table>
<tr><td>Process variable</td><td colspan="2">Minimum diameter</td></tr>
<tr><td>Wall thickness</td><td>Vertical hole (v)</td><td>Horizontal hole (h)</td></tr>
<tr><td>1 mm (0.039 in.)</td><td>0.5 mm (0.019 in.)</td><td>1.3 mm (0.051 in.)</td></tr>
<tr><td>4 mm (0.157 in.)</td><td>0.8 mm (0.031 in.)</td><td>1.75 mm (0.069 in.)</td></tr>
<tr><td>8 mm (0.314 in.)</td><td>1.5 mm (0.059 in.)</td><td>2.0 mm (0.079 in.)</td></tr>
</table></td></tr>
<tr><td>Emboss & Engrave details</td><td>0,6 mm wide & 2 mm high</td><td>1 mm wide & 1 mm high</td></tr>
<tr><td>Minimum features</td><td>2 mm</td><td>0,8 mm</td></tr>
<tr><td>Tolerance / Accuracy</td><td>±0,5%</td><td>±0,3%</td></tr>
<tr><td>Post process</td><td>Support removal, Sanding, Cold welding, Gap filling, Polishing, Priming and Painting, Vapor smoothing, Dipping, Epoxy coating, Metal</td><td>Powder removal, Vibro polish, Dyeing, Spray paint, Lacquering, Watertightness, Metal coating</td></tr>
</table>

Figure 35. Table of printing specifications for FDM and SLS printing.

The process of testing for printability starts by determining the required function requirements for each component. Every function requirement is linked to related printer specifications. With the found printer specifications, the possibility arises to make a statement about the potential suitability of a component to print. This relation results in:

1. Aesthetic quality;
    - Material overhang angle
    - Minimum features
    - Post process
2. Flexibility;
    - Wall thickness
    - Tolerance / Accuracy
    - Material
3. Strength;
    - Wall thickness
    - Horizontal bridges
    - Tolerance / Accuracy
    - Material
4. Impact resistance;
    - Wall thickness
    - Minimum features
    - Post process
    - Material
5. Wear resistance;
    - Wall thickness
    - Post process
    - Material
6. Chemical resistance;
    - Post process
    - Material
7. Waterthightness;
    - Tolerance / Accuracy
    - Post process
8. Airthightness;
    - Tolerance / Accuracy
    - Post process
9. Humidity Resistance;
    - Post process
    - Material
10. Temperature resistance;
    - Wall thickness
    - Post process
    - Material

8.5 Test on strength

Various ways of making provisions on aspects of the redesigned concepts have been highlighted in the previous paragraphs. Strength is the last and actually the most important aspect to test each concept on. Because whenever a new concept would not be strong enough, it automatically portrays the uselessness of the product and invalidates any previous provision. Likewise, when it can be shown that the redesigned concept is strong enough, the result will automatically demonstrate the validation of the determined comparison aspects. Because of this, the strength test must be done before previous comparison aspects are determined.

However, strength requirements cannot be determined for each component. This is due to the fact even KLM does not have a hold on all requirement information, as been told by Arlette van der Veer.

> Parts that are supplied directly by Boeing when purchasing an aircraft such as armrests, seat tables, etc. are tested and certified by upon delivery. This resulted in KLM not needing knowledge about the requirements so far.
>
> **Arlette v/d Veer** (31-7-2019)
> project manager @ KLM

When such a part will be produced by KLM, the test for certification will be taken in-house. Conforming to Arlette (31-7-2019), will every new part tested on standard cabin requirements by the Central Engineering department of KLM. These standard cabin requirements would be sufficient in case a component is not a structural nor has a critical function.

Due to the unknown strength requirements for each component, they will be tested on maximum forces during use which ensures sufficient results to make a statement about the strength of a component. A free online tool to utilize anthropometric data, called DINED is used to determine the maximum use forces. This online tool is a project of the Applied Ergonomics and Design Department of the TU Delft faculty of Industrial Design Engineering since 1980.

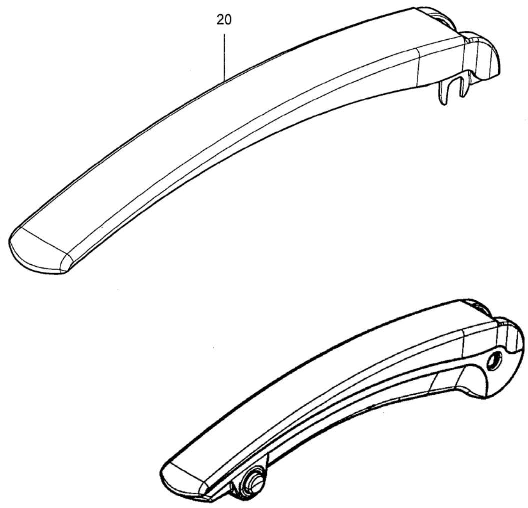
Determined maximum use forces are consequently simulated on the CAD models using the Finite Element Method (FEM). This method simulates the forces on the CAD models and analyzes the structural responses and consequences. This result provides the ability to make a statement about the strength of a component.

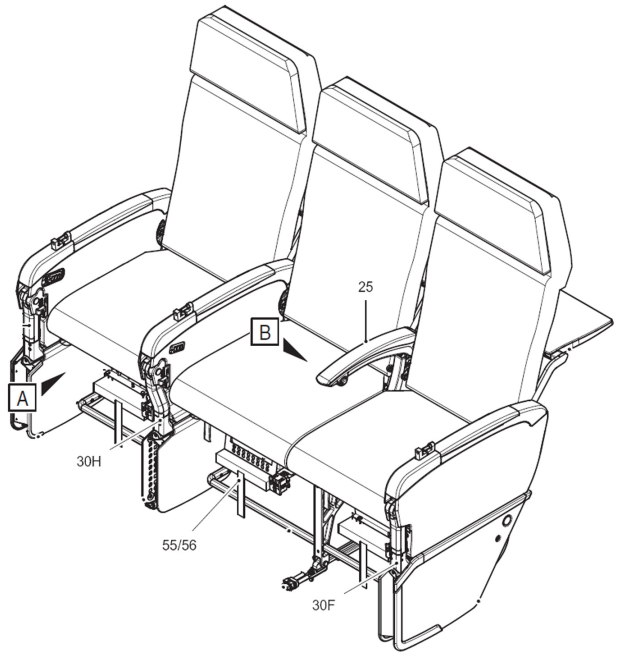
The elaboration and results of this approach can be read in the following paragraph during the development of the concepts.

Zodiac seat armrest

P/N F0479566

The Zodiac seat armrest are the economy armrests used on specific KLM fleet. These armrests are attached on seats and mainly function to provide an ergonomic sit position for passengers. Besides, they ensure deviding passenger area per seat.





These Zodiac sear armrest are used in the economy class of the 777 and 787 fleet. The 777-200 carries 334 of these armrest, the 777-300 carries 340, 787-9 carries 316 while the big brother 787-10 carries 384 of these armrests. The current KLM fleet exist out of 15 777-200 aircrafts, 14 of 777-300, 13 of 787-9 and 1 of 787-10. The number below indicates the potential use of the redesigned AM produced part ([KLM fleet information], n.d.).

14.262 armrests

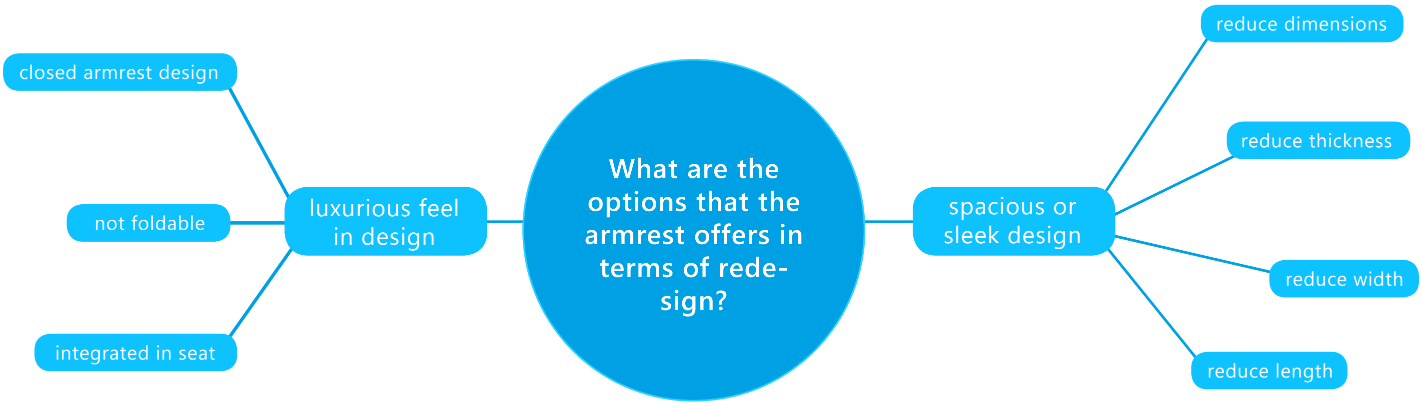
This is the economy class interior of one of the KLM 777 aircrafts.

186,90 EUR per piece

83 days lead time

0,186 KG weight

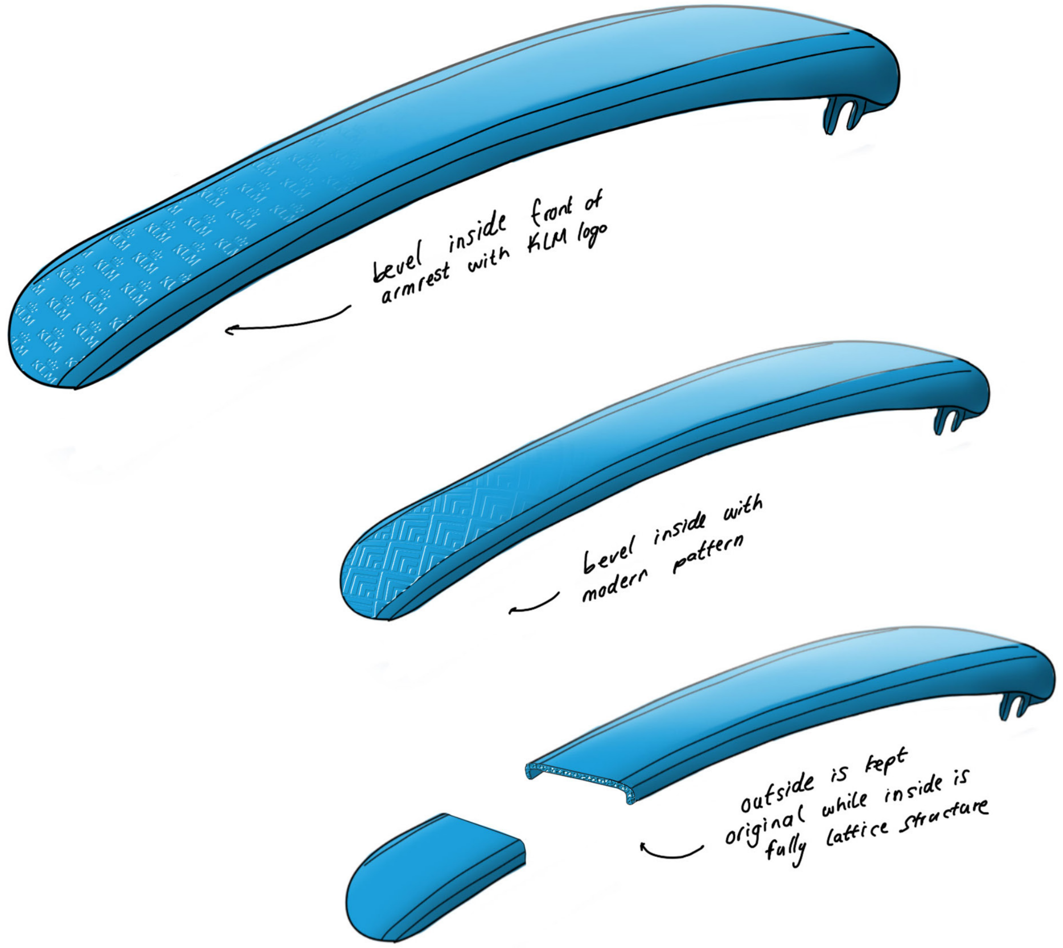
6 part assembly

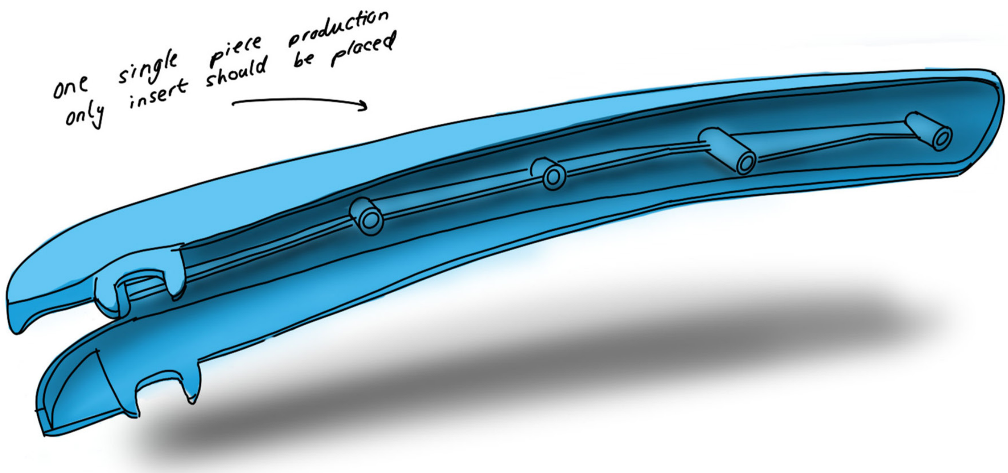


A rather fast and simple mindmap is carried out in order to write down thoughts for ideation. The Zodiac seat armrest has been chosen to enhance its current lead time. However, lead time is not directly or only design related. Substituting only the production method by AM could lead to reaching the goal. Nevertheless, the mind map has been used to find redesign possibilities for this component.

These pictures are used as a source of inspiration used during ideation and redesigning. What is mentioned in the mind map is actually reflected in the inspiration photos. Fuller, large-sized and closed design seats aim to provide a more luxurious feel while sleek designed seats without a closed design have smaller parts and provide a more spacious feeling. The difference in both seats is probably that the big and closed design is used in fewer quantities in the business class while the sleek is being used in larger numbers in the economy class. This is probably also the reason these seats are designed to make it look more spacious. Because the Zodiac armrest also comes from economy class, it is important to focus more on making it more sleek and provide spaciousness.

Redesign phase





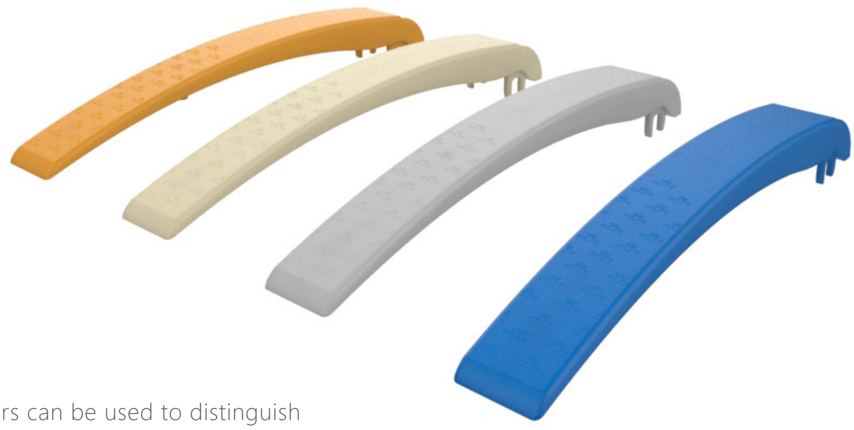
CAD phase

The logo deboss is only in the front of the armrest to prevent uneven surface on the elbow area for passengers.

The screwthreads inserts will be fused like the original.

The back is kept fairly simple.

The armrest could delivered in several different colors.



Different colors can be used to distinguish different seats types of economy comfort and econonmy class in the cabin.

FEM analysis

DINED is an anthropometric database, which results in limited information about the applicable forces and is more focused on body dimension. The exertion of force by pushing with two hands on the Zodiac armrest while standing up has been selected as the most suitable maximum use scenario.

P95 male with an age between 20-30 are chosen as the target audience for the analysis to really create a use scenario with maximum forces. This group is the strongest compared to older men or all women. P95 is the methodology based on simulating potential scenarios with Monte Carlo simulations, where the P stands for Percentile *([Terminology explained], 2016).* Thus, does P95 in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

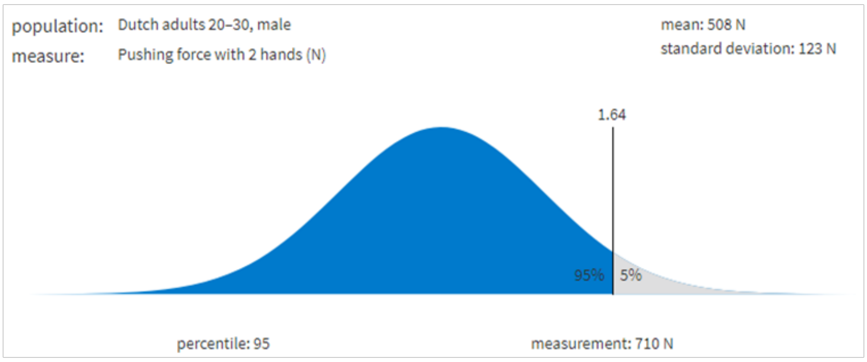
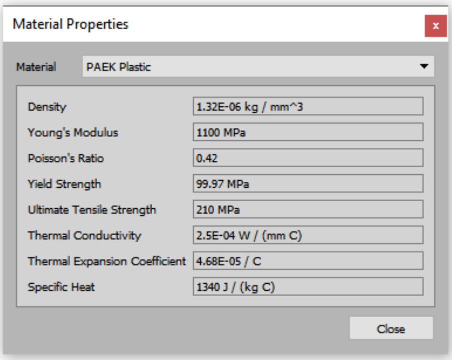


Figure 36. Result of DINED pushing with two hands P95 male, 20-30 age.

Material choice

Because suitable AM cabin materials such as Ultem9085 and PA2241FR, described in paragraph “6.3 Selecting All Plastic AM processes”, were not available in the FEM analysis software, a different material was required to choose. The choice fell on PAEK plastic, due to the fact this material being family with the Ultem9085 and therefore become the closest to reality. The material properties of PAEK plastic according to Fusion360 software, version 2.0.6045, are as following.



Material Properties

Material: PAEK Plastic

Density	1.32E-06 kg / mm^3
Young's Modulus	1100 MPa
Poisson's Ratio	0.42
Yield Strength	99.97 MPa
Ultimate Tensile Strength	210 MPa
Thermal Conductivity	2.5E-04 W / (mm C)
Thermal Expansion Coefficient	4.68E-05 / C
Specific Heat	1340 J / (kg C)

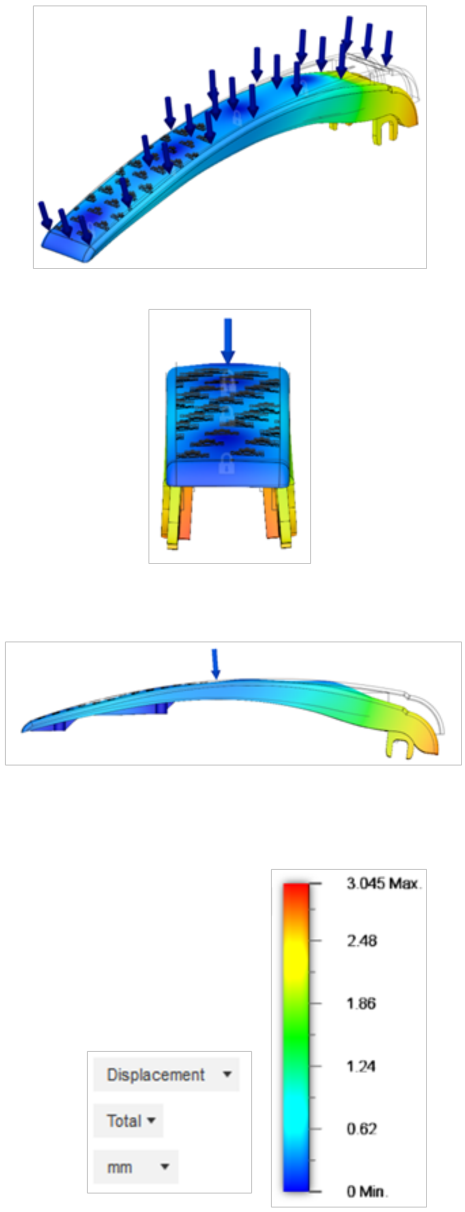
Close

Figure 37. Material proposition of PAEK from software Fusion360.

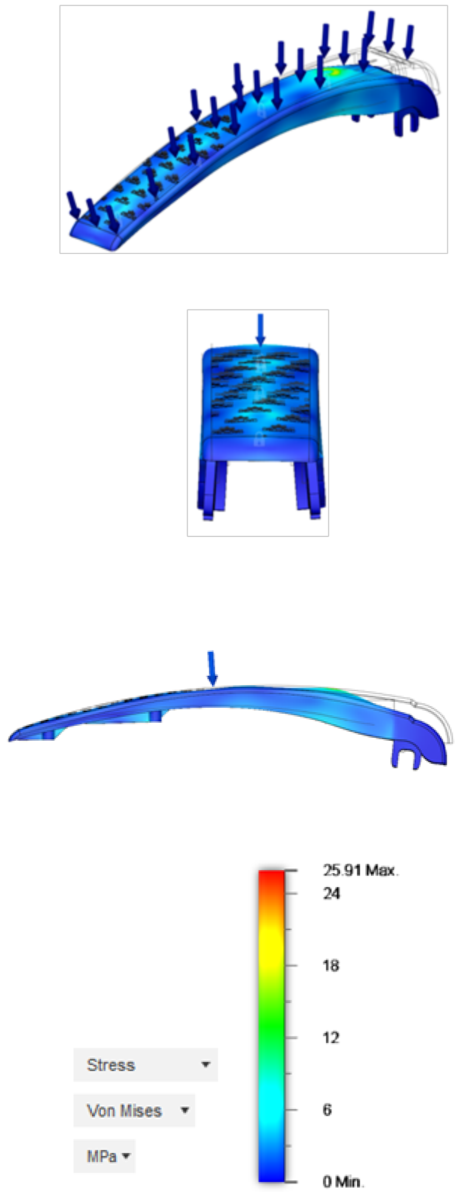
Results FEM

Yield strength is the is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation *(J.S. Kalra, 2019).* The force is gradually distributed because it represent the scenario better. When someone will use both hands to excert force, this will almost completely cover the whole surface of the armrest. In the scenario where a gradual distributed force of 710N is applied on the top surface of the armrest, is the recorded maximum stress in the material almost 26MPa. While the yield strength of the material is 99MPa. This means that the part will deform elastically and return to its original shape without any problem. During the application of this force the maximum displacement will be 3mm. This result tells us that the armrest has successfully passed the test and with this demonstrates to be sufficiently strong.

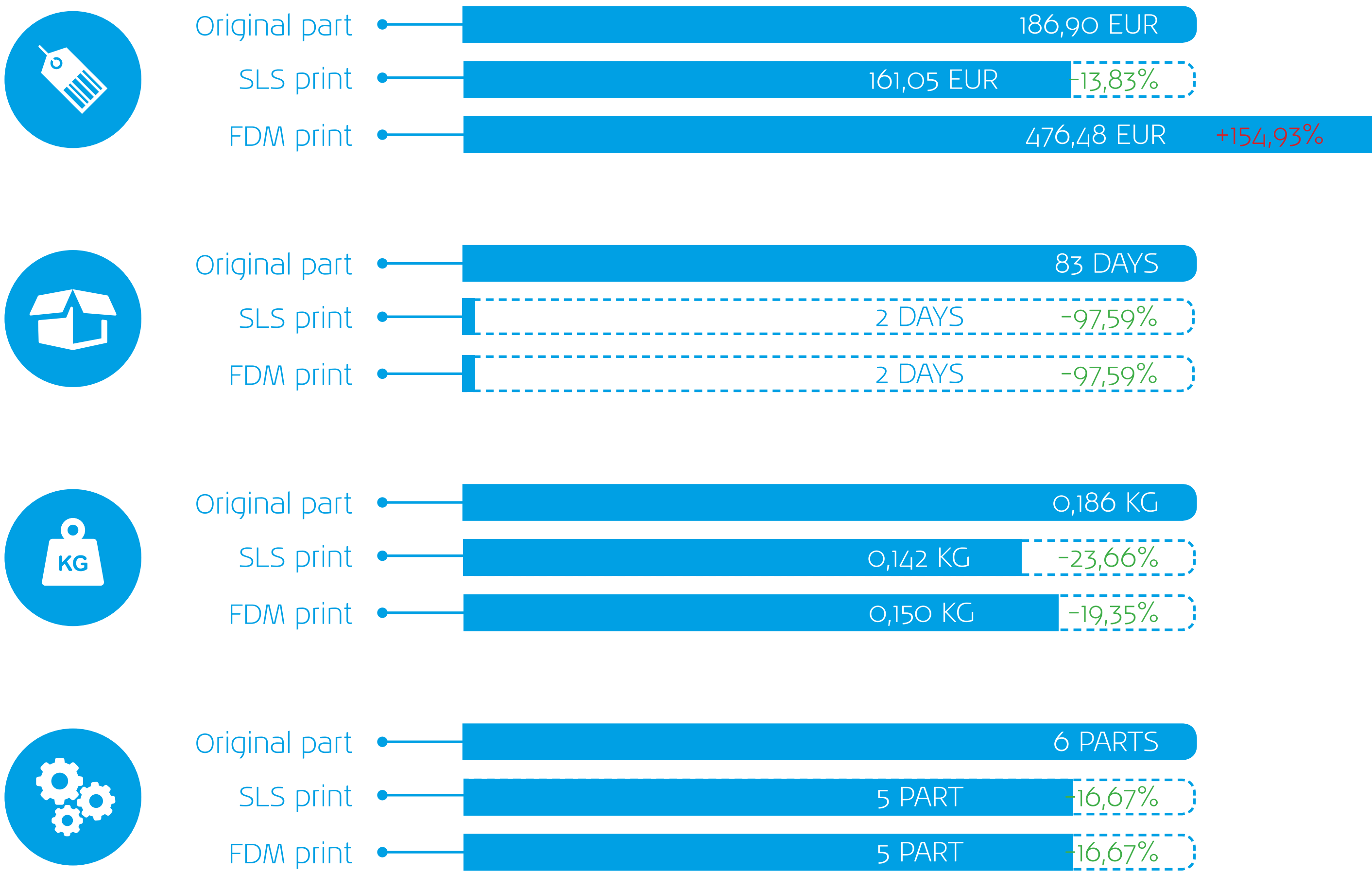
Displacement (in mm)



Stress (in MPa)



Compare results



Is it printable?

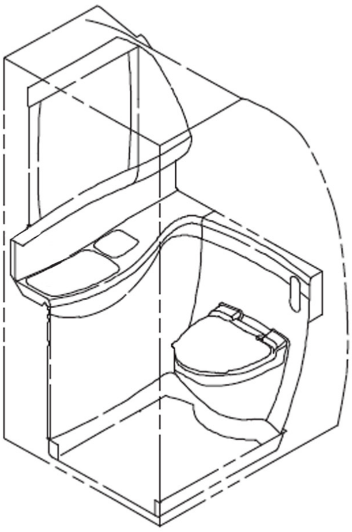
Aesthetic quality	Flexibility	Strength	Impact resistance	Wear resistance	Chemical resistance	Water-thightness	Air-thightness	Humidity resistance	Temperature resistance
●					●	●			

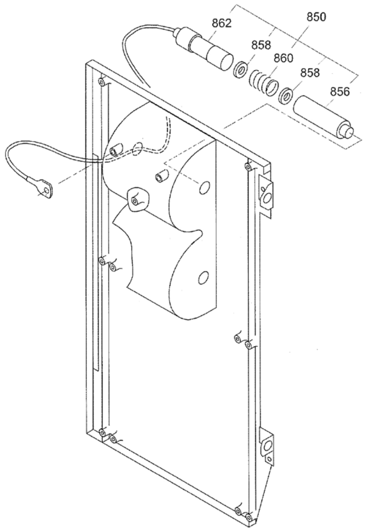
There is no limiting problem for this component, during redesigning the component are the material overhang angle, minimum feature size, tolerance, and post process sufficiently taken into account. Aesthetic quality is very important because this part will be used by passengers directly and can watched for hours. The criteria waterthightness and chemical resistance are important because this part will be cleaned as well sweat will be absorbed by passengers holding the armrest.

Lavatory toilet paper holder

P/N 0FS3500A04G01

The lavatory toilet paper holder fuctions to hold toilet paper in the lavatories. It has a spring load mechanisme to get the holder in and out form its place. The complete holder machanism is attached by a metal wire to the backplate, this prevents it from getting lost.





This specific type of toilet paper holder is used on both the 777 and 787 fleet. The 777-200 includes 5 and 777-300, 7 lavatories. While both the 787-9 and 787-10 include 6 lavatories. All lavatoeries contain 2 of these hoders. There are 15x 777-200, 14x 777-300, 13x 787-9 and 1x 787-10 flying in the KLM fleet. The number below indicates the potential use of the redesigned AM produced part ([KLM fleet information], n.d.).

514 toilet paper holders

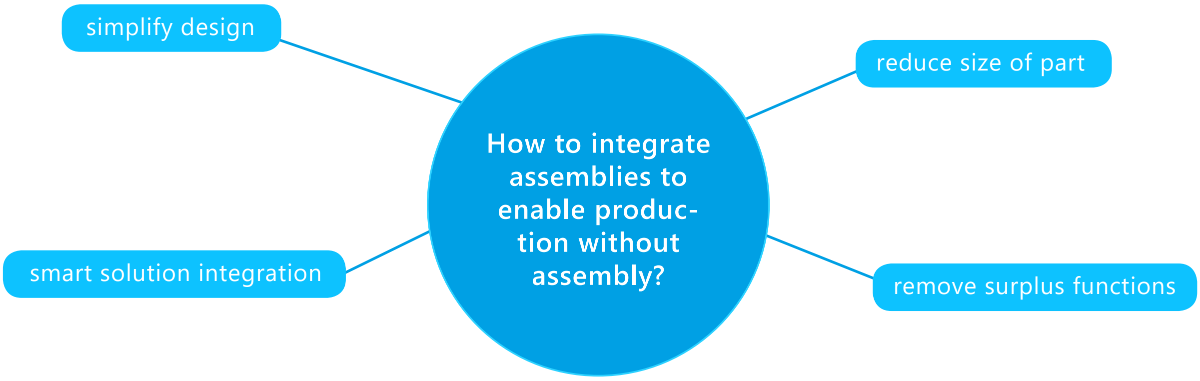
This is one of the lavatories used in the KLM 777 aircrafts.

240,06 EUR per piece

138 days lead time

0,042 KG weight

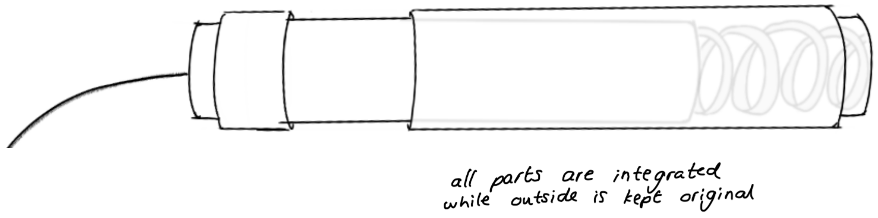
8 parts assembly

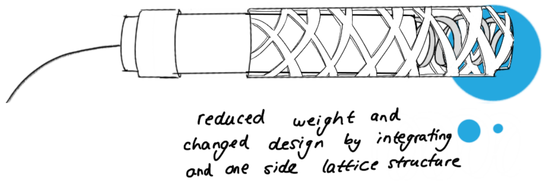


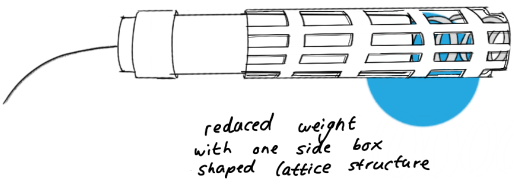
The mindmap created for the toilet roll holder is mainly focusing integrating assemblies which would enable to produce the complete assembly as one single part. This could be done in multiple ways like mentioned in the mindmap, but simply be done by redesigning the component for AM by stitching the seperate parts together making it one piece. Even functonal parts like springs could be printed with AM enabling the integrationg of smart solutions.

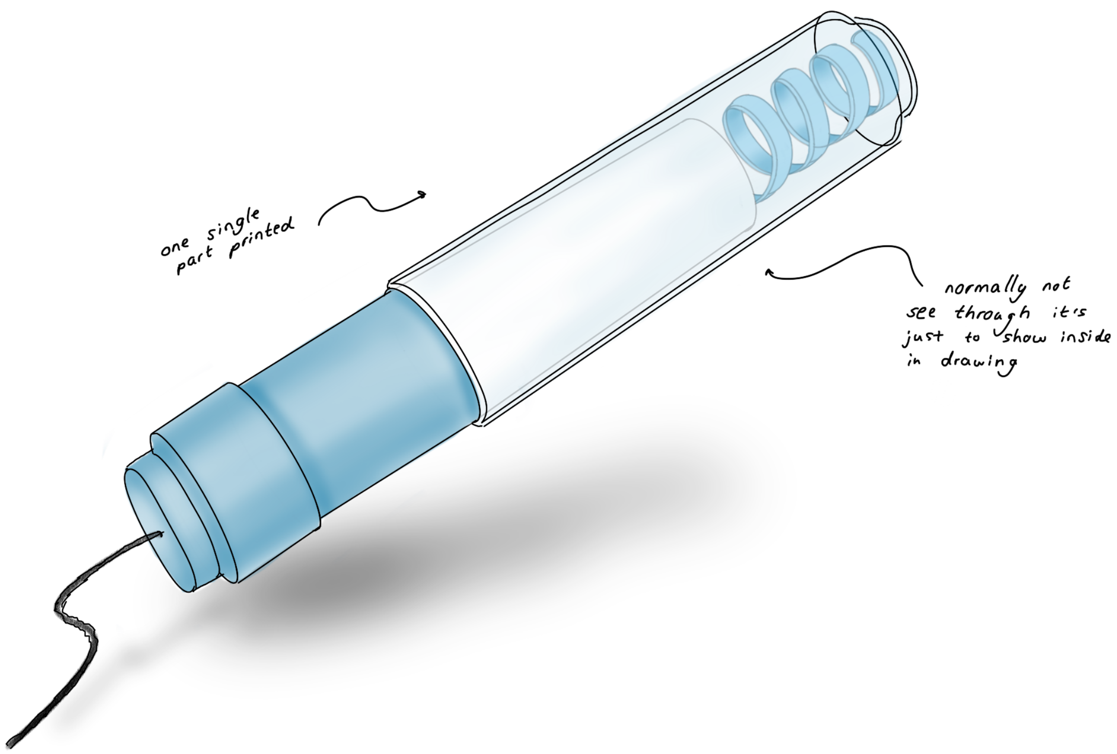
The inspiration pictures display mainly the products which are traditionally made out of multiple seperate parts, but are now printed as one single piece with AM. This certainly applies to both the turquoise dress and the high heeled slippers. The garden chair is produced with another method, but still represents integrating assemblies. Chairs exist traditionally out multiple separate parts while this one is produce in one go. The last inpiration is the printed spring egg holder. This product displays AMs abilty in producing products and integrating extra functions like springs which in this case could be used for the toilet paper holder.

Redesign phase



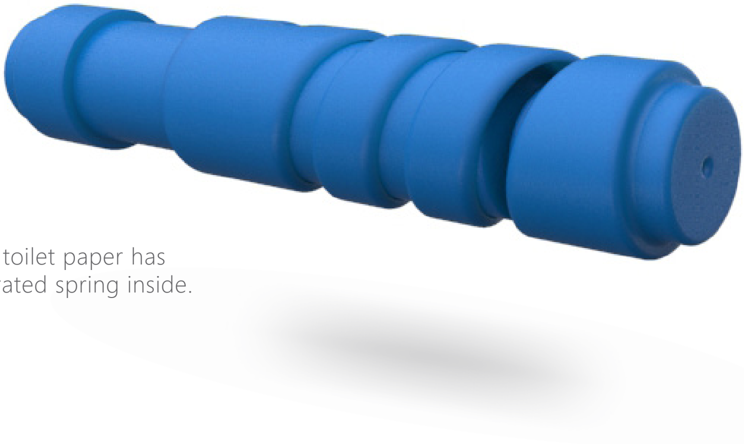




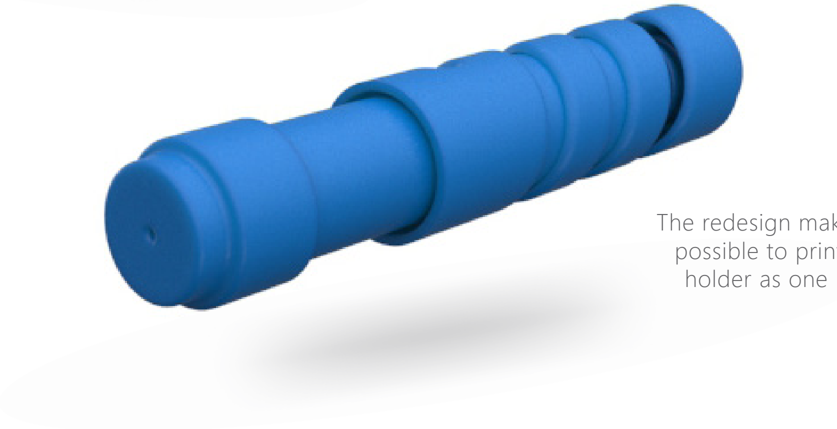


CAD phase

This picture is just made
to show the inside of
the redesign.



The new toilet paper has
an integrated spring inside.



The redesign makes it
possible to print the
holder as one part.

Different color options could
be delivered depending on the
lavatory design.

FEM analysis

DINED is an anthropometric database, which results in limited information about the applicable forces and is more focused on body dimension. The exertion of force by pressing the spring of the lavatory toilet paper holder has been selected as the most suitable maximum use scenario.

P95 male with an age between 20-30 are chosen as the target audience for the analysis to really create a use scenario with maximum forces. This group is the strongest compared to older men or all women. P95 is the methodology based on simulating potential scenarios with Monte Carlo simulations, where the P stands for Percentile *([Terminology explained], 2016)*. Thus, does P95 in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

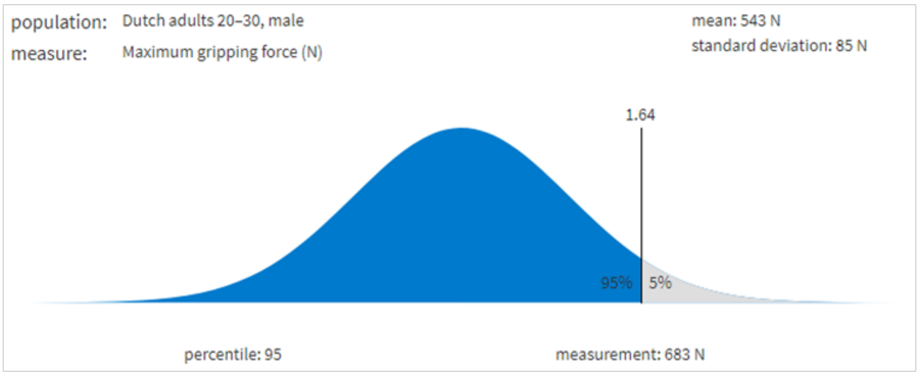


Figure 38. Result of DINED maximum gripping force P95 male, 20-30 age.

Material choice

Because suitable AM cabin materials such as Ultem9085 and PA2241FR, described in paragraph "6.3 Selecting All Plastic AM processes", were not available in the FEM analysis software, a different material was required to choose. The choice fell on PAEK plastic, due to the fact this material being family with the Ultem9085 and therefore become the closest to reality. The material properties of PAEK plastic according to Fusion360 software, version 2.0.6045, are as following.

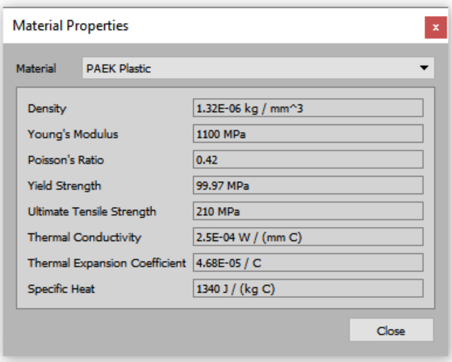
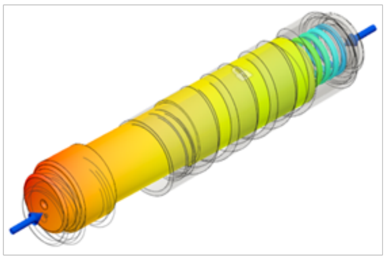


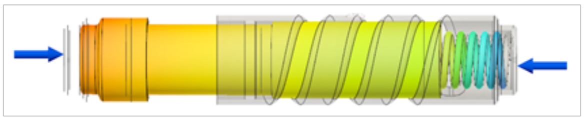
Figure 39. Material proposition of PAEK from software Fusion360.

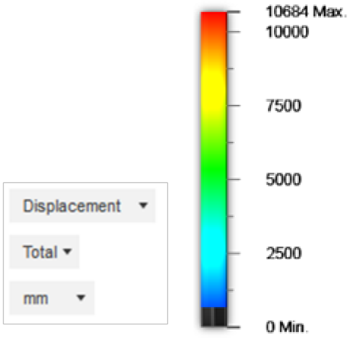
Results FEM

Yield strength is the is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation *(J.S. Kalra, 2019)*. The total force is devided and applied on both sides of the roll holder. This represent the scenario realistically. When someone will push in the toilet roll holder, both sides would receive force. In the scenario where the force of 683N is applied divided on both sides of the toilet roll holder, is the recorded maximum stress in the material of the spring 391MPa. While the yield strength of the material is 99MPa. This would normally means that the part will deform permanently and fail. However, because the static stress analysis takes into account the material requirements and does not take spring function into account, the result cannot be assumed to be completely true. It is highly recommended to test print this part multiple times to iterate on the spring function in case this part would be selected as the concept to further develop.

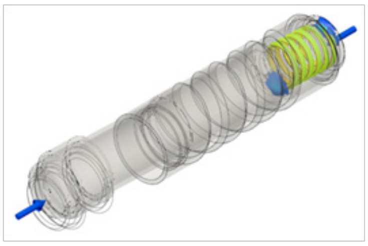
Displacement (in mm)

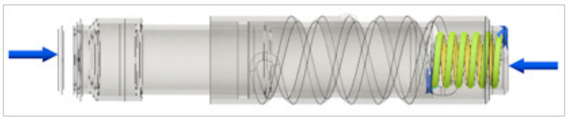


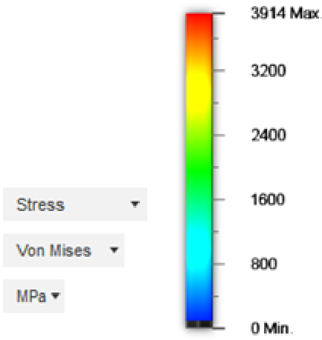




Stress (in MPa)







Compare results

Original part	240,06 EUR	
SLS print	30,62 EUR	-87,24%
FDM print	90,62 EUR	-62,25%

Original part	138 DAYS	
SLS print	2 DAYS	-98,55%
FDM print	2 DAYS	-98,55%

Original part	0,042 KG	
SLS print	0,027 KG	-35,71%
FDM print	0,029 KG	-30,95%

Original part	8 PARTS	
SLS print	1 PART	-87,50%
FDM print	1 PART	-87,50%

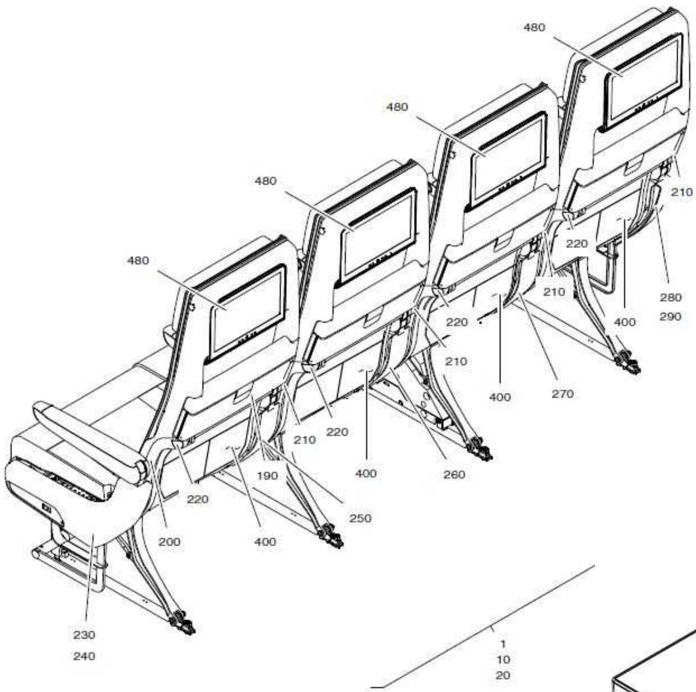
Is it printable?

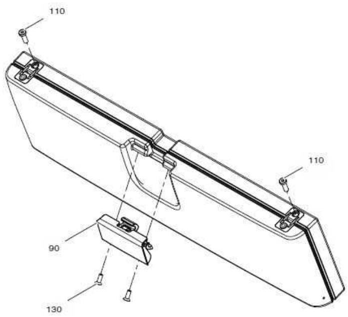
Aesthetic quality	Flexibility	Strength	Impact resistance	Wear resistance	Chemical resistance	Water-thightness	Air-thightness	Humidity resistance	Temperature resistance
	●		●	●					

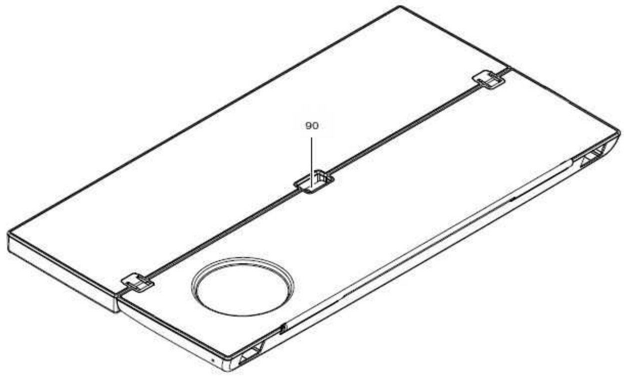
There is no limiting problem for this component. This component can be printed in both FDM as SLS and is redesigned by taking wall thickness, minimum feature size, and post process into account. Besides, because SLS prints with powdered material results produced parts being more brittle. For this reason, FDM seems to be more suitbale for this part. Due to an integrated spring as printed along with the component, it is always necessary to make some test prints to test and itterate on the impact resistance, flexibility and weat resistance of the spring function.

Recaro bi-fold seat table P/N 470-00-500-01

The Recaro bi-fold seat table is a foldable traytable mounted at the back of each aircraft seat. It contains a hinge mechanism to open and close the table and at the same time a closing hook mechanism to securely attach the table to the seat. In case a table cannot be attached securly, the specific seat gets blocked and cannot be sold. When this seat is on the corridor side, the entire row is blocked.







These Recaro bi-fold tables are used in the economy class of the 777 fleet, on both the 777-200 and 777-300. The 777-200 carries 286 while the bigger 777-300 carries 374 economy class seats with the attached bi-fold tables. There are currently 15 aircrafts of the 200 and 14 of the 300 on duty in the KLM fleet. The number below indicates the potential use of the redesigned AM produced part ([KLM fleet information], n.d.).

9.526 bi-fold tables

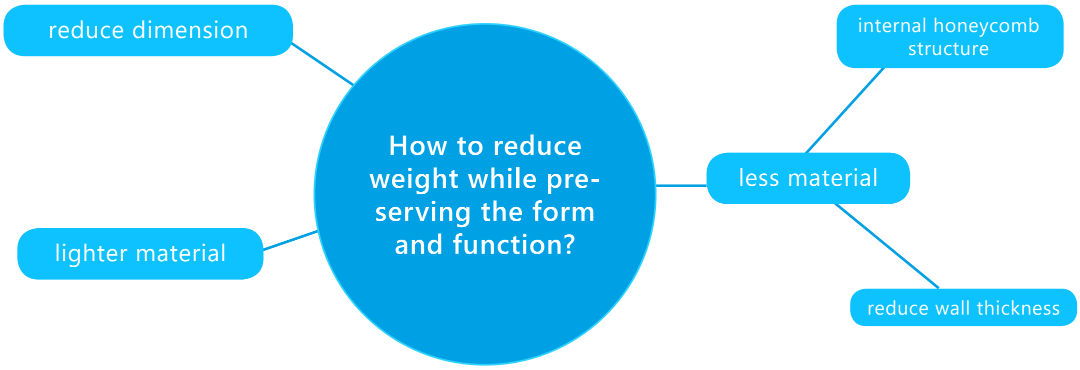
This is the economy class interior of one of the KLM 777 aircrafts.

342,38 EUR per piece

56 days lead time

0,584 KG weight

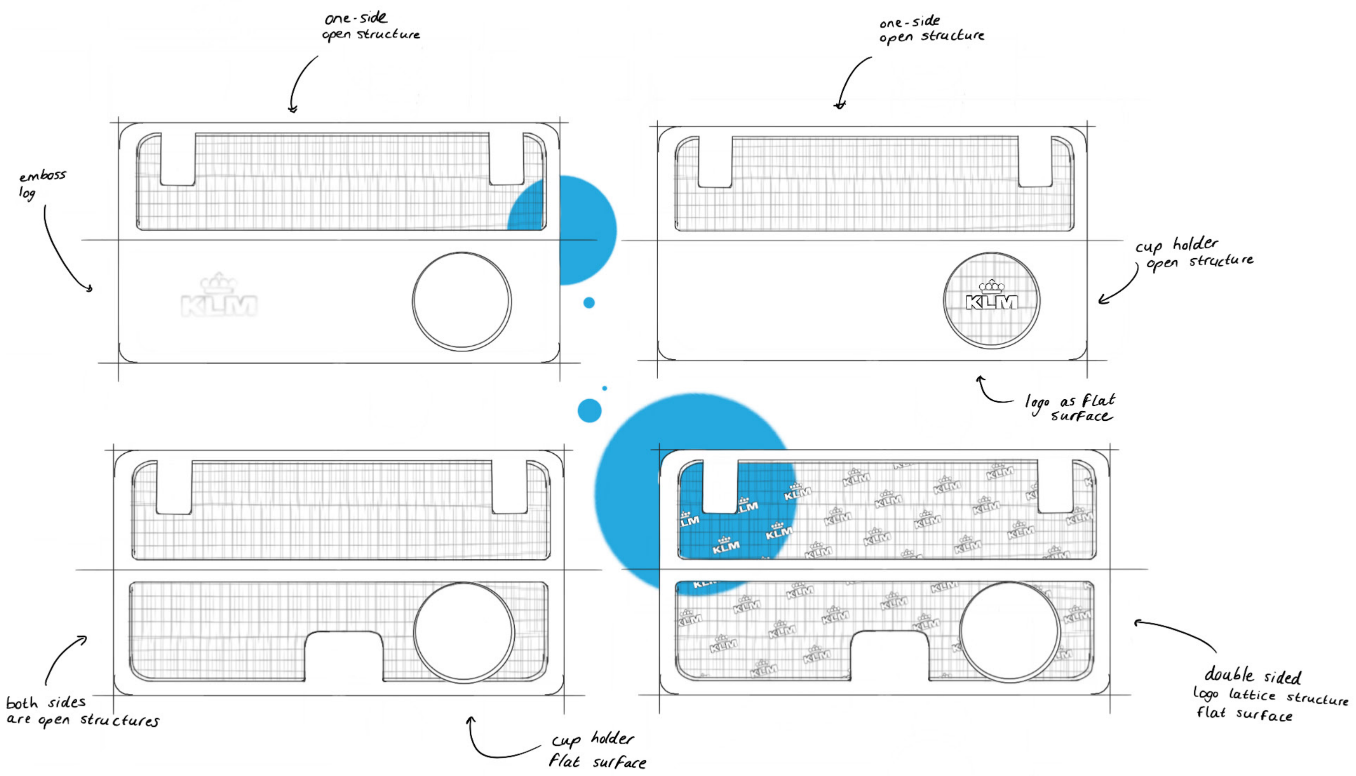
26 parts assembly

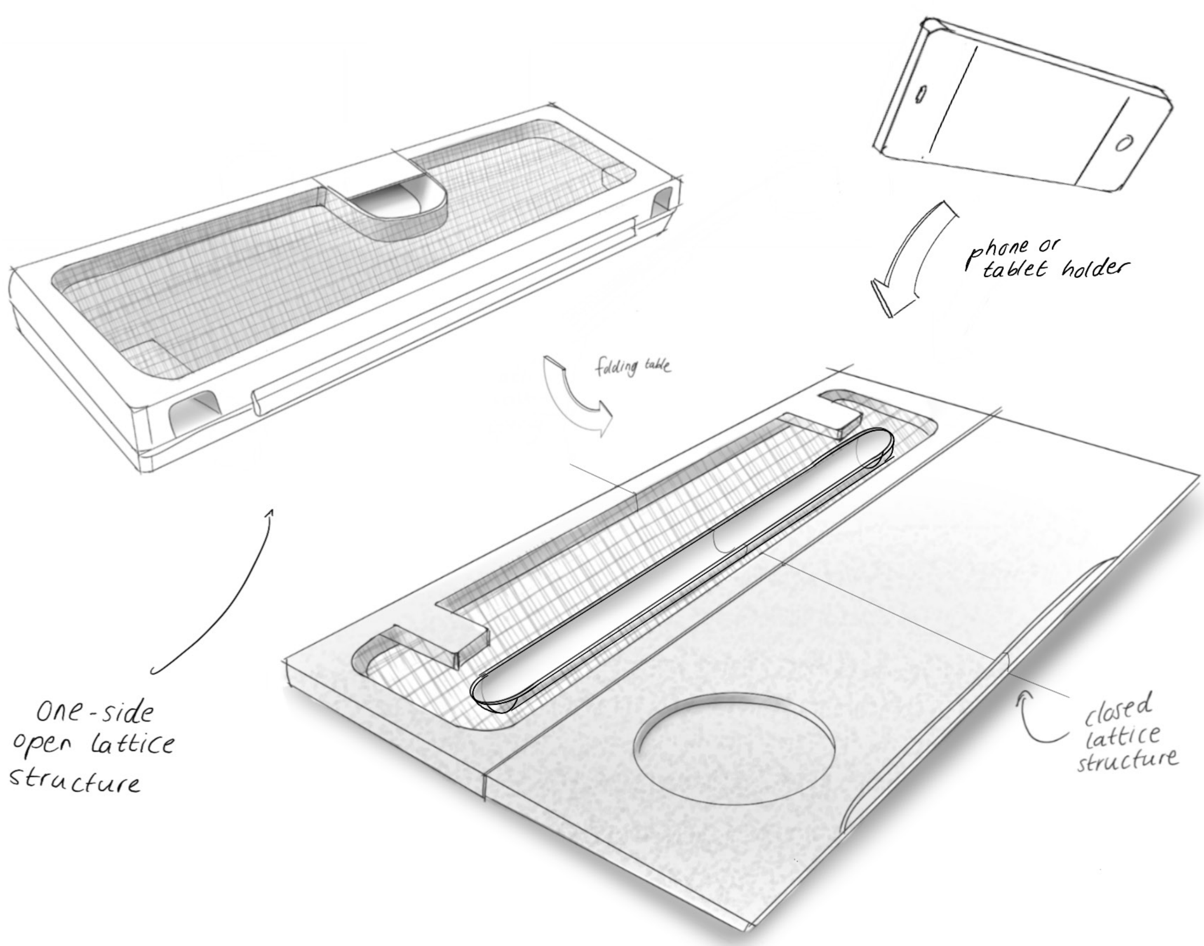


A rather fast and simple mindmap is carried out with the aim of solidifying what has been built up with experience in terms of knowledge. The mind map only focuses on how to reduce weight while the bi-fold table has a lot more potential for handling the other AM benefits. This has been chosen as reducing weight is the main focus why this component has been chosen.

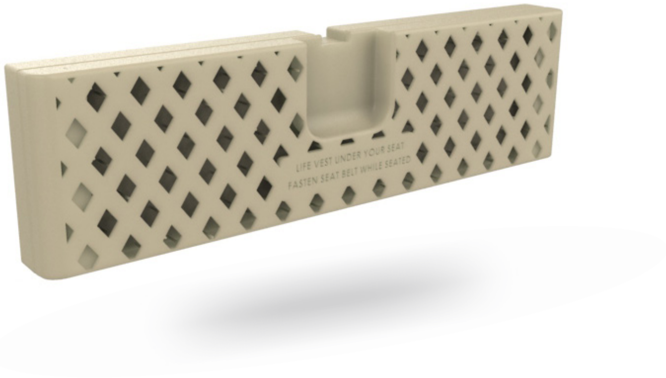
These pictures are used as a source of inspiration during ideation for redesigning th bi-fold table with the main focus on reducing weight. All inspiration examples show overlapping possibilities, removing surplus material while the form is being preserved.

Redesign phase





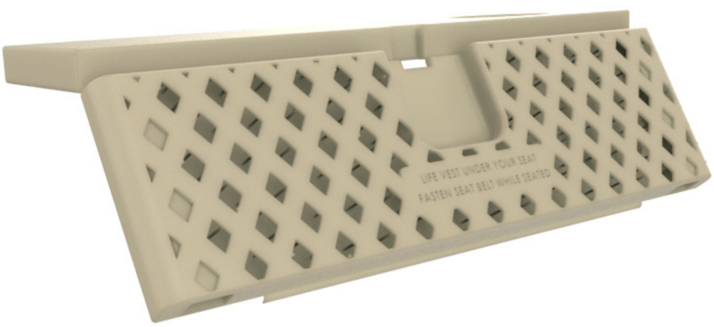
CAD phase



This is the way how the folded table will greet passengers in its closed position. Only in this position is the internal lattice structure visable. This visibiliy creates an interesting structure and design.

The second position is the half opened position which remained completely the same

The full opened position looks very similar, but contains an interesting new feature, phone/tablet holder.



A conscious choice has been made about how to display the internal structure. For ease of cleaning, the open structure has only been applied on the only side which is not used for the purpose of eating or drinking.

Color can be used again to show chair types, economy comfort or economy class.

FEM analysis

DINED is an anthropometric database, which results in limited information about the applicable forces and is more focused on body dimension. The exertion of force by pushing with two hands on one part of the Recaro bi-fold seat table while standing up has been selected as the most suitable maximum use scenario.

P95 male with an age between 20-30 are chosen as the target audience for the analysis to really create a use scenario with maximum forces. This group is the strongest compared to older men or all women. P95 is the methodology based on simulating potential scenarios with Monte Carlo simulations, where the P stands for Percentile *([Terminology explained], 2016).* Thus, does P95 in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

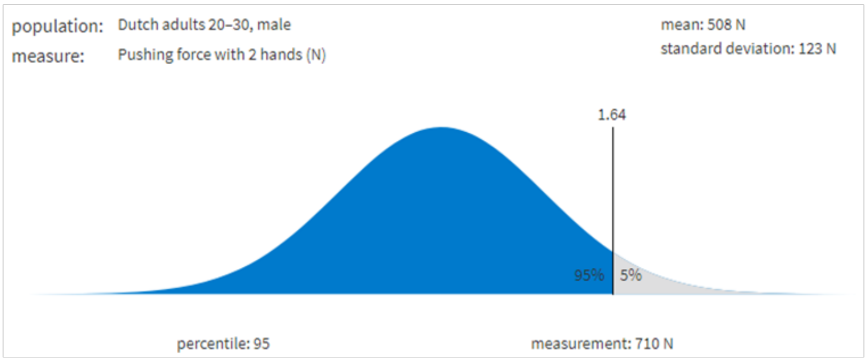
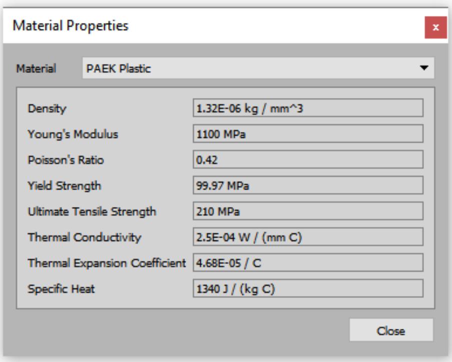


Figure 40. Result of DINED pushing with two hands P95 male, 20-30 age.

Material choice

Because suitable AM cabin materials such as Ultem9085 and PA2241FR, described in paragraph "6.3 Selecting All Plastic AM processes", were not available in the FEM analysis software, a different material was required to choose. The choice fell on PAEK plastic, due to the fact this material being family with the Ultem9085 and therefore become the closest to reality. The material properties of PAEK plastic according to Fusion360 software, version 2.0.6045, are as following.



Material Properties

Material: PAEK Plastic

Density	1.32E-06 kg / mm^3
Young's Modulus	1100 MPa
Poisson's Ratio	0.42
Yield Strength	99.97 MPa
Ultimate Tensile Strength	210 MPa
Thermal Conductivity	2.5E-04 W / (mm C)
Thermal Expansion Coefficient	4.68E-05 / C
Specific Heat	1340 J / (kg C)

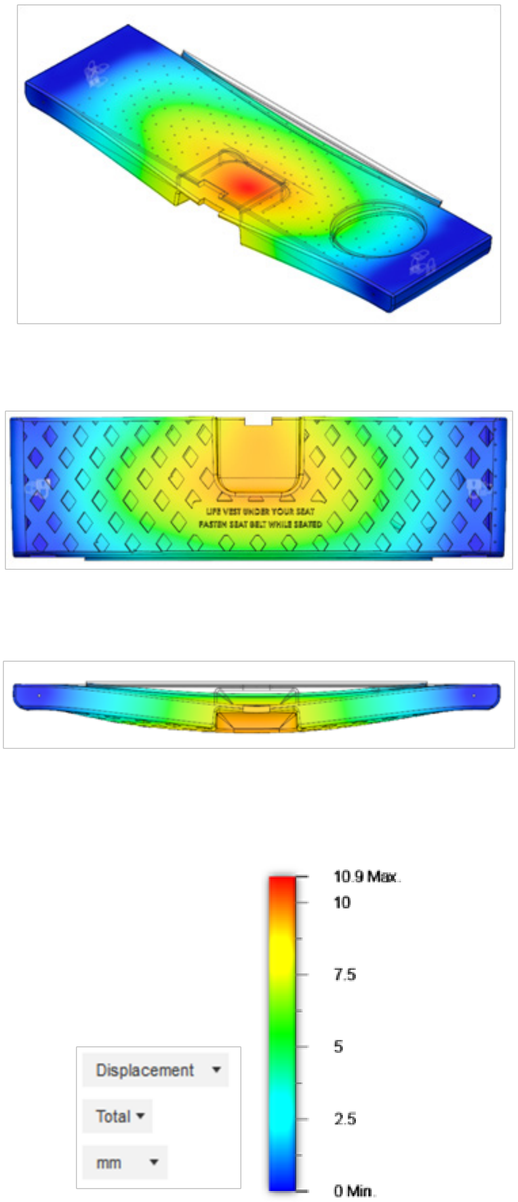
Close

Figure 41. Material proposition of PAEK from software Fusion360.

Results FEM

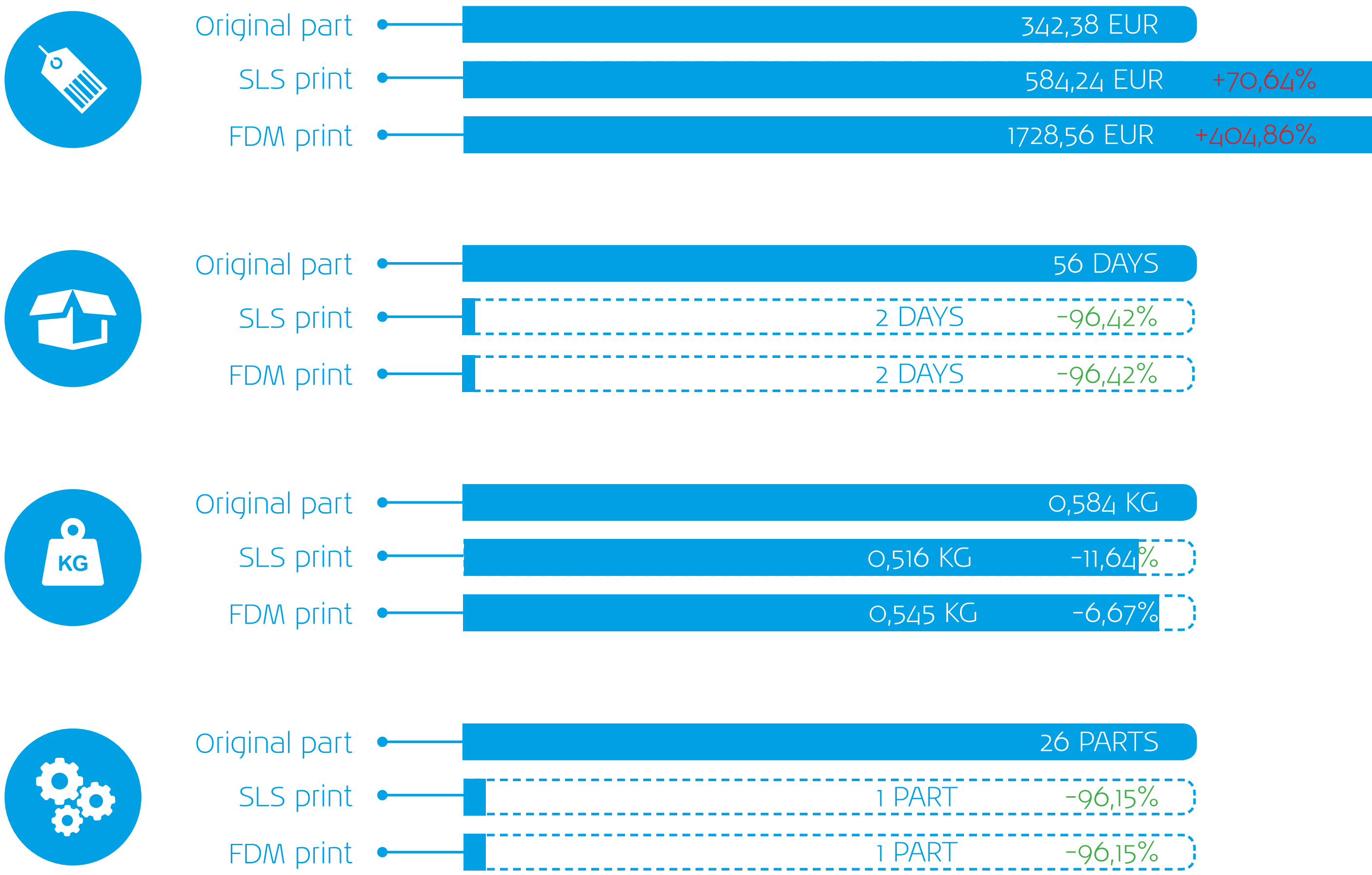
Yield strength is the is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation *(J.S. Kalra, 2019).* The force is gradually distributed because this represent the scenario more realistically. When someone will use both hands to excert force, one will almost completely cover the whole surface of the table. In the scenario where a gradual distributed force of 710N is applied on the top surface of the seat table, is the recorded maximum stress in the material 96MPa. While the yield strength of the material is 99MPa. This means that the part will deform elastically and return to its original shape without any problem. During the application of this force the maximum displacement will be 11mm. This result tells us that the seat table with the honeycomb structure has just successfully passed the test and with this demonstrates to be sufficiently strong. It is recommended to pay more attention to the structure when this part would be selected as the concept to further develop.

Displacement (in mm)

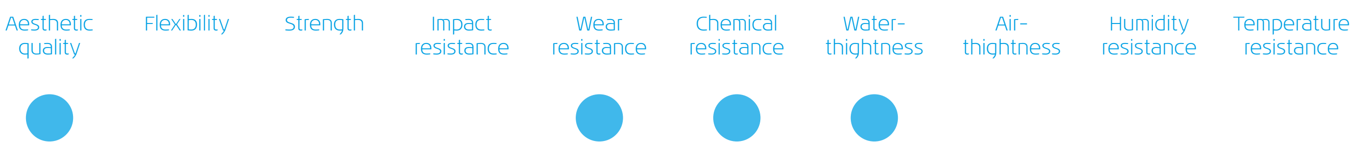


Stress (in MPa)

Compare results



Is it printable?

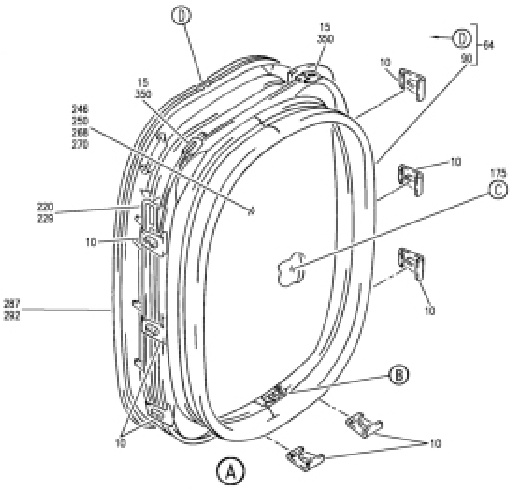


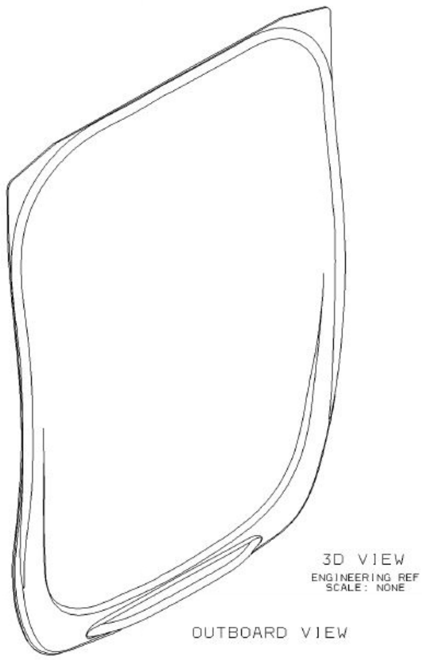
This component is printable. It has been redesigned by taking wall thickness, minimum feature size, into account. Due to its lattice structure, large horizontal bridges and fine details like text, it seems more suitable for SLS printing. For these reasons and because this part directly through the passenger, the aesthetic quality is very important. The aspect for wear resistance is important because the table is opened and closed by printed hinges to be able to use. The criteria waterthightness and chemical resistance are of importance because this part will be cleaned as well as be used by passengers to consume food and drink on it. This makes hygiene very important. The post processing is very important here because SLS is naturally porous and can absorb very well. A watertightness post process is needed.

Boeing window shades

P/N 411W1602-6A

The Boeing window shades are the passenger window shades. It is the only moveable part in de window assembly, passengers are dealing with. This part is being used to close the window from outside lights. Aircraft shades are obligeted to block outside lights especially during intercontinental flights where sunrise and sunset can occur more than one time.





These specific Boeing window shades are used on the 777 fleet, on both the 777-200 and 777-300. The 777-200 contains a total of 114 passenger windows while the bigger 777-300 contains 146 windows. There are currently 15 aircrafts of the 200 and 14 of the 300 on duty in the KLM fleet. The number below indicates the potential use of the redesigned AM produced part ([KLM fleet information], n.d.).

3.754 window shades

This is the economy class interior of one of the KLM 777 aircrafts.

282,15 EUR per piece

3 days lead time

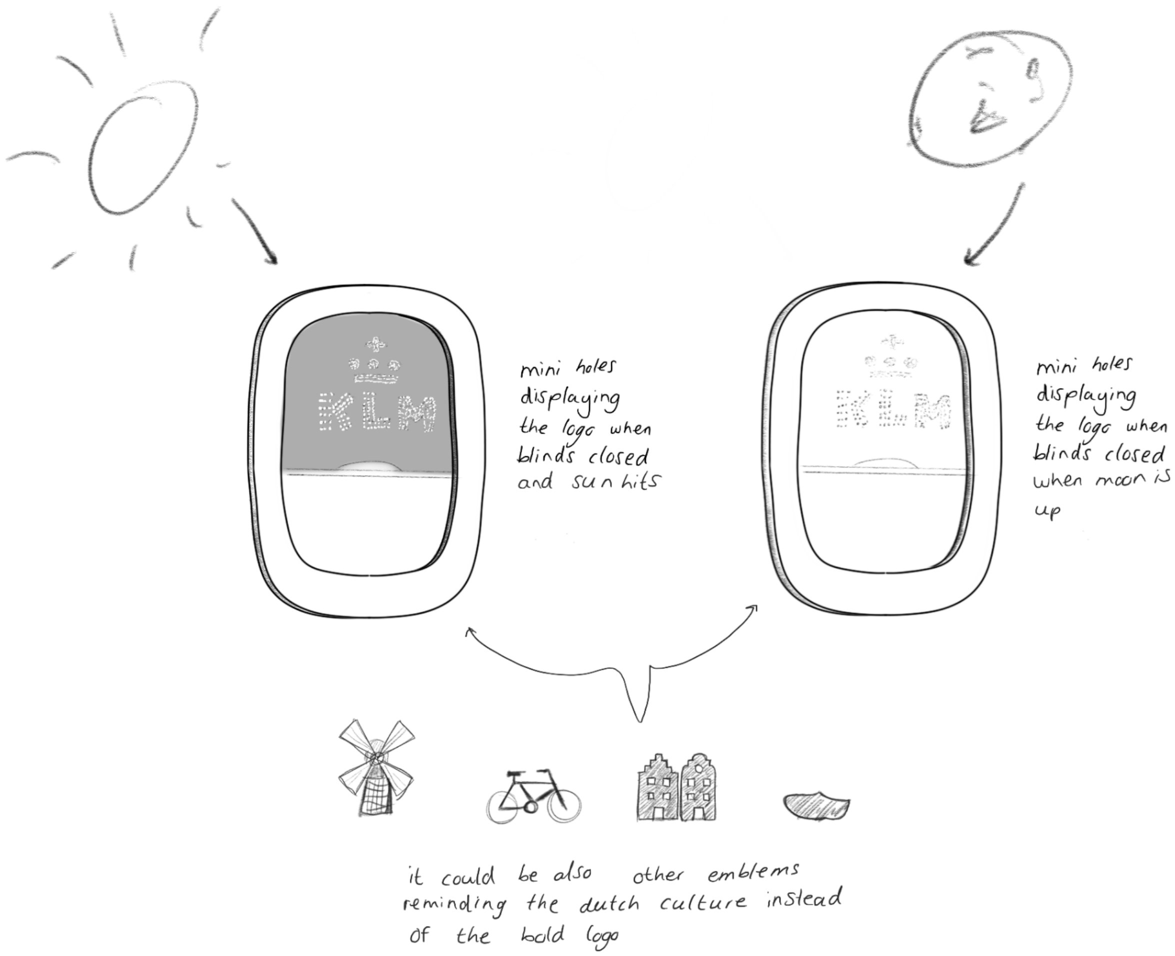
0,218 KG weight

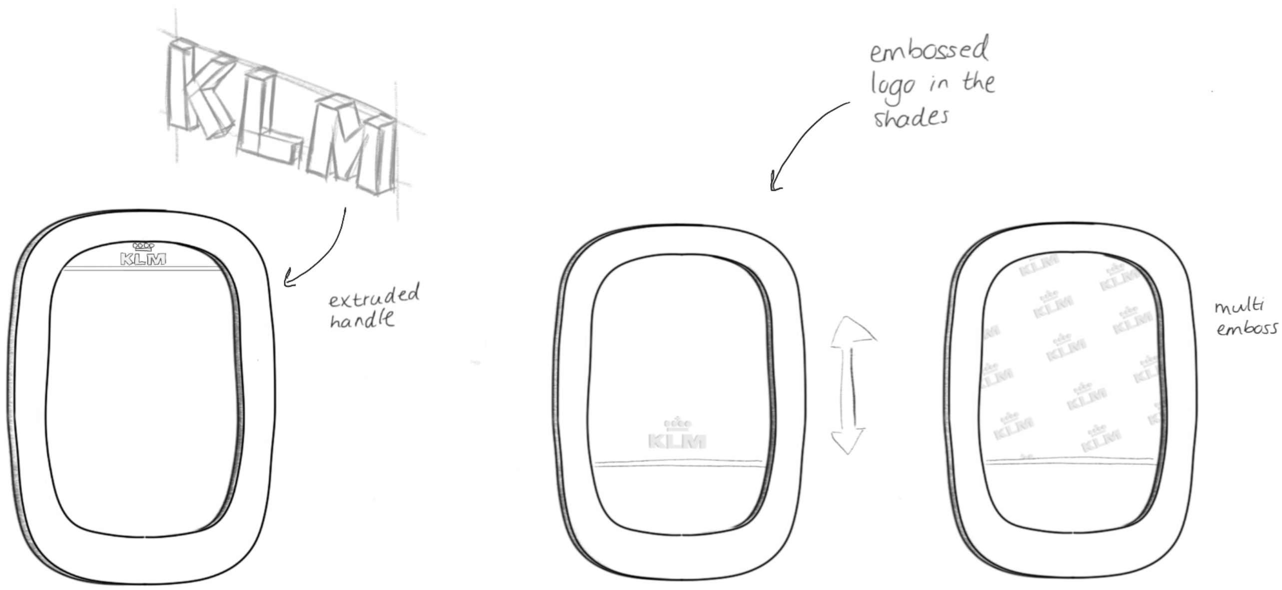
3 part assembly

A rather fast and simple mindmap is carried out in order to write down the thoughts. The window shade has been chosen under the benefit AM cluster customization. AM makes small batch prodcution available, which is a perfect oppurtunity for customization and tailor the window shade to KLM needs. It could help to personalize the cabin interior.

These pictures are used as a source of inspiration. New aircraft interiors are using lights and shapes to provide a more luxurious and spacious feeling. The lampshades show an interesting interplay between the falling light on thick and thin wall thicknesses that ensure the appearance of various shapes.

Redesign phase





CAD phase

When no light on the outside has the redesign nothing special when seen from the inside of the cabin.

When the shade is closed while light is shining on it the KLM logo arises "magically".

This "magic" happens due the logo being debossed on the outside of the shade. Material being thinner on this area makes this happen.

For the rest is the design kept completely traditional so that it fits in with the current assembly.

FEM analysis

DINED is an anthropometric database, which results in limited information about the applicable forces and is more focused on body dimension. The exertion of force by pulling with one hand on the Boeing window shade while being fully closed has been selected as the most suitable maximum use scenario.

P95 male with an age between 20-30 are chosen as the target audience for the analysis to really create a use scenario with maximum forces. This group is the strongest compared to older men or all women. P95 is the methodology based on simulating potential scenarios with Monte Carlo simulations, where the P stands for Percentile *([Terminology explained], 2016).* Thus, does P95 in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

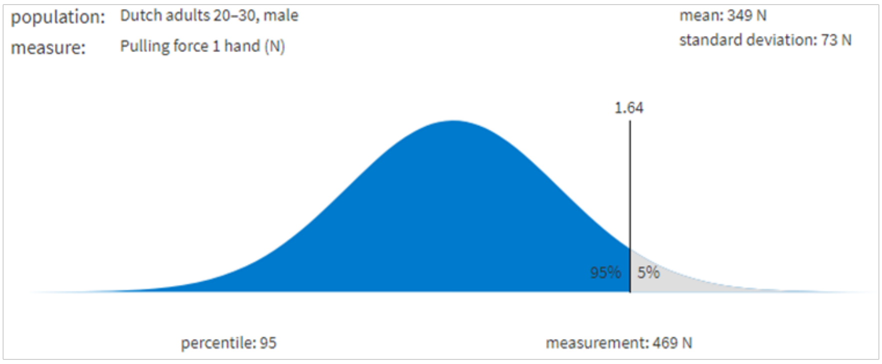


Figure 42. Result of DINED pulling force with one hand P95 male, 20-30 age.

Material choice

Because suitable AM cabin materials such as Ultem9085 and PA2241FR, described in paragraph "6.3 Selecting All Plastic AM processes", were not available in the FEM analysis software, a different material was required to choose. The choice fell on PAEK plastic, due to the fact this material being family with the Ultem9085 and therefore become the closest to reality. The material properties of PAEK plastic according to Fusion360 software, version 2.0.6045, are as following.

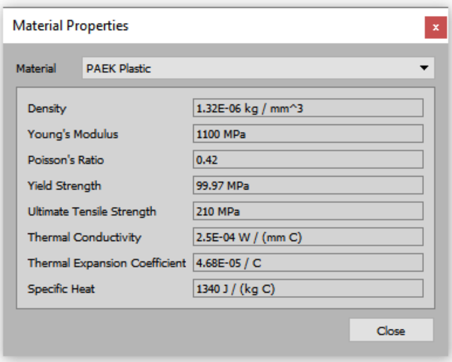
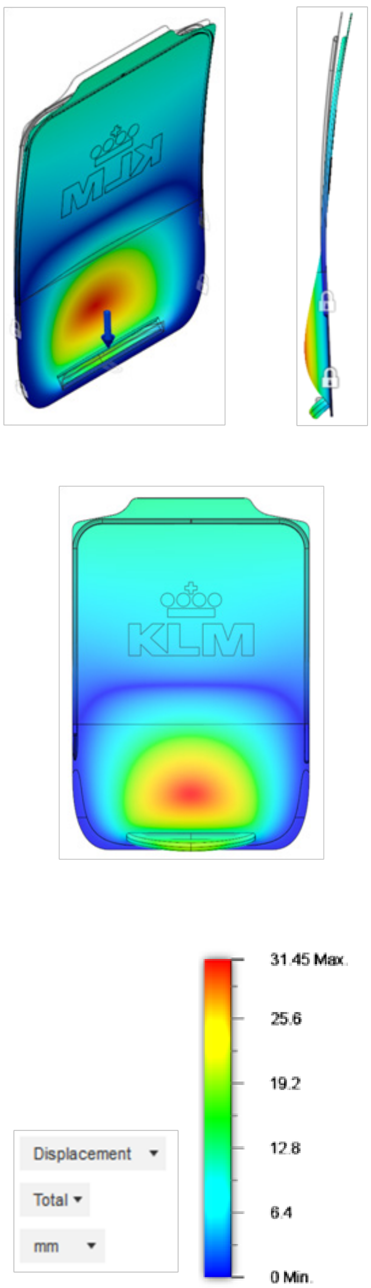


Figure 43. Material proposition of PAEK from software Fusion360.

Results FEM

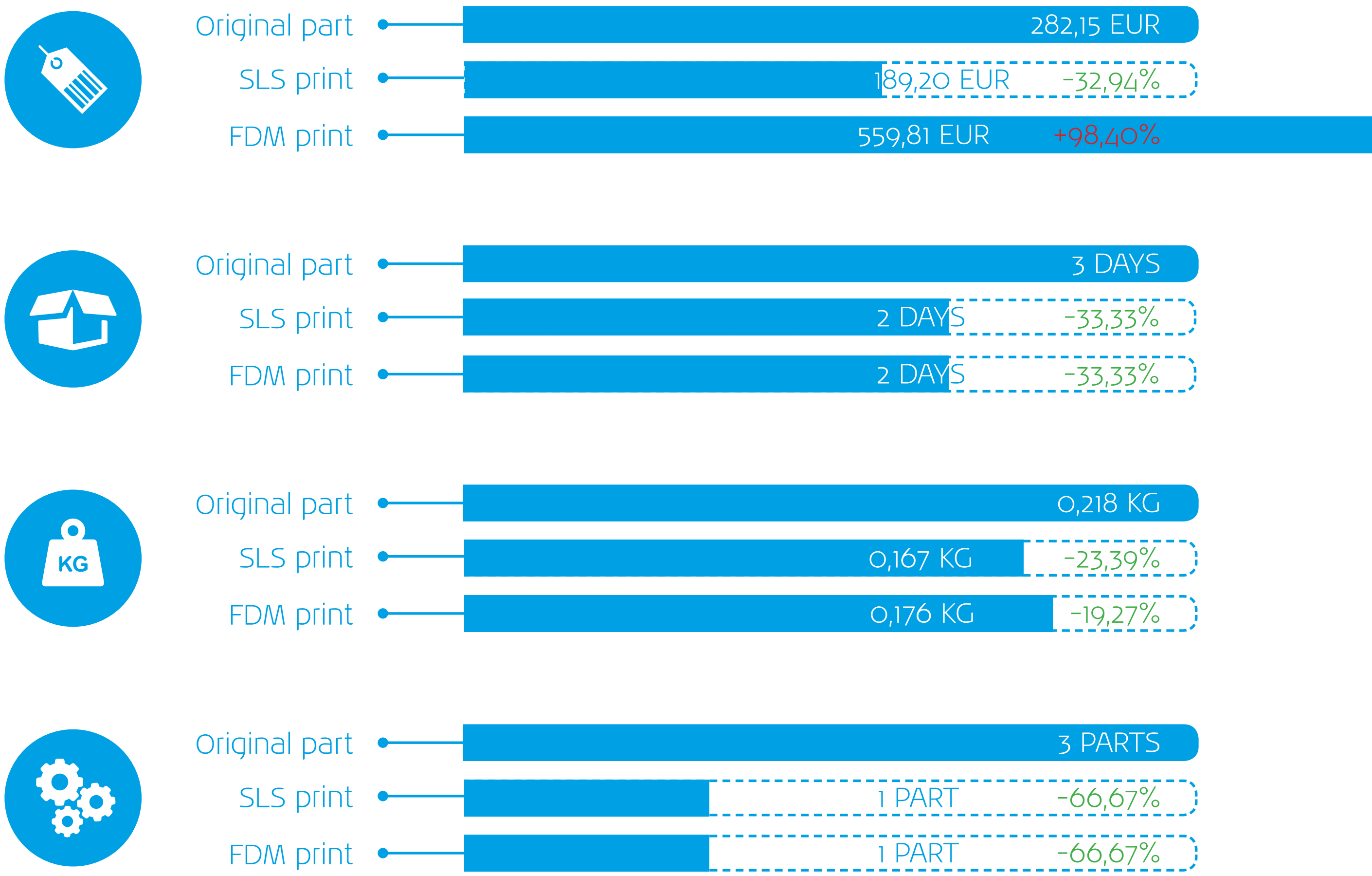
Yield strength is the is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation *(J.S. Kalra, 2019).* The force is gradually distributed on the protruding lip used to move the window shade. This represents the scenario best. When someone will use its fingers to excert force to move the shade, one will almost completely cover the whole surface of this protruding lip. In the scenario where a gradual distributed force of 469N is applied on the top surface of the pull lip of the window shade, is the recorded maximum stress in the material 77MPa. While the yield strength of the material is 99MPa. This means that the part will deform elastically and return to its original shape without any problem. During the application of this force the maximum displacement will be 31mm. The displacement results are unrealistic result, because it is impossible to fully apply the pull force with 1 hand on a small lip where only finger tips will fit. Therefore, it could be concluded that the result tells us that the window shade has successfully passed the test and with this demonstrates to be sufficiently strong.

Displacement (in mm)



Stress (in MPa)

Compare results



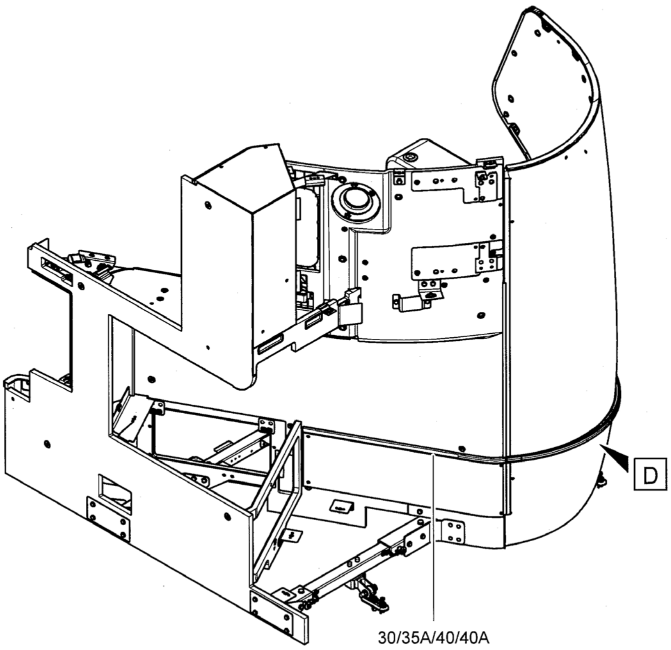
Is it printable?

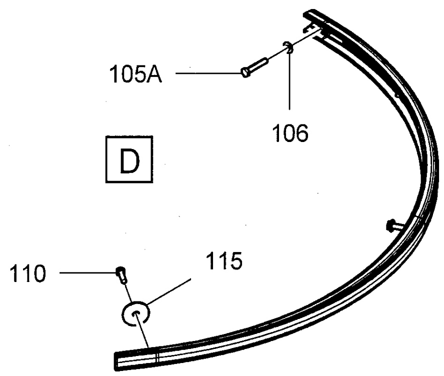
There is no limiting problem which inhibits printing this component. It has been redesigned by taking wall thickness, minimum feature size, material overhang and post process into account. Aesthetic quality is very important because this part is right at eye level of passengers and can be watched for hours. Furthermore, the criteria wear resistance is important due to the fact this component is being used by moving. Given the better ability of fine detail production and the large price differece seems SLS to fit better for this component.

Zodiac Business Class cabin bumper

P/N F0494959

The Zodiac Business Class cabin bumpers are metal looking plastic bumpers protecting the seat cabin from galley trolleys or passenger suitcases bumping in. These bumpers capture the energy of the impact from these trolleys or suitcases. Even minor damages to these bumpers ensure replacement due these being in the business class. KLM has high standards and offer great quality to passengers traveling business class.





These specific Boeing window shades are used on the 787 fleet, on both the 787-9 and the new 787-10. The 787-9 contains 30 business class cabins while the bigger 787-10 contains 34 cabins. There are currently 13 aircrafts of the 9 and just 1 of the 10 flying in the KLM fleet. The number below indicates the potential use of the redesigned AM produced part ([KLM fleet information], n.d.).

424 business class cabin bumpers

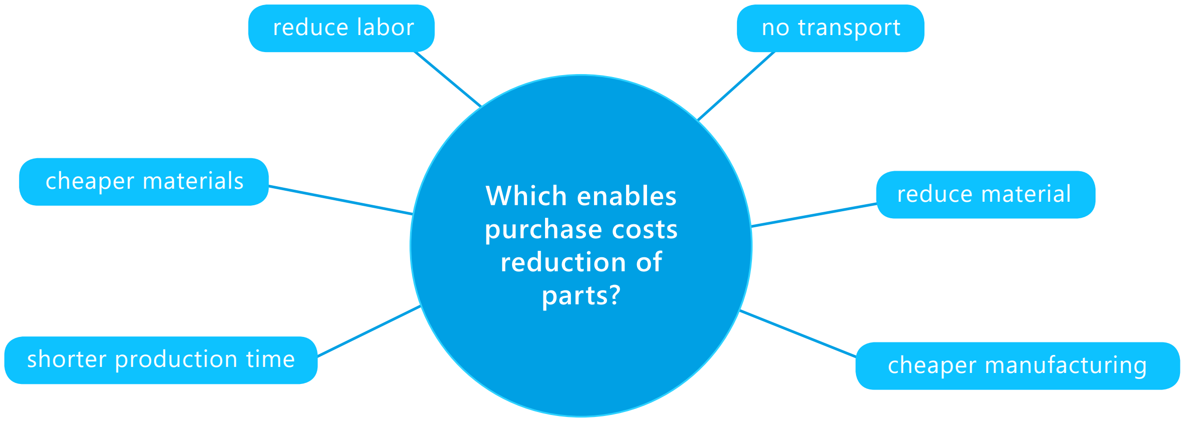
This is the business class interior of one of the KLM 787 aircrafts.

3691,30 EUR per piece

168 days lead time

0,095 KG weight

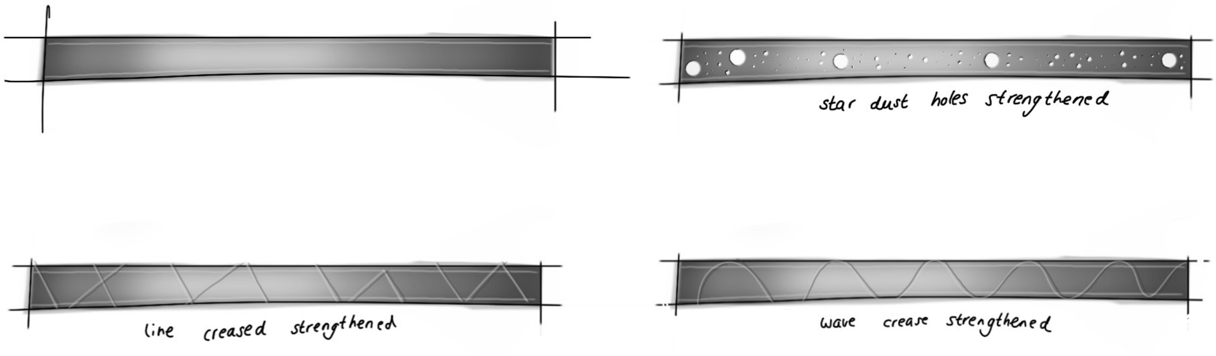
1 part only

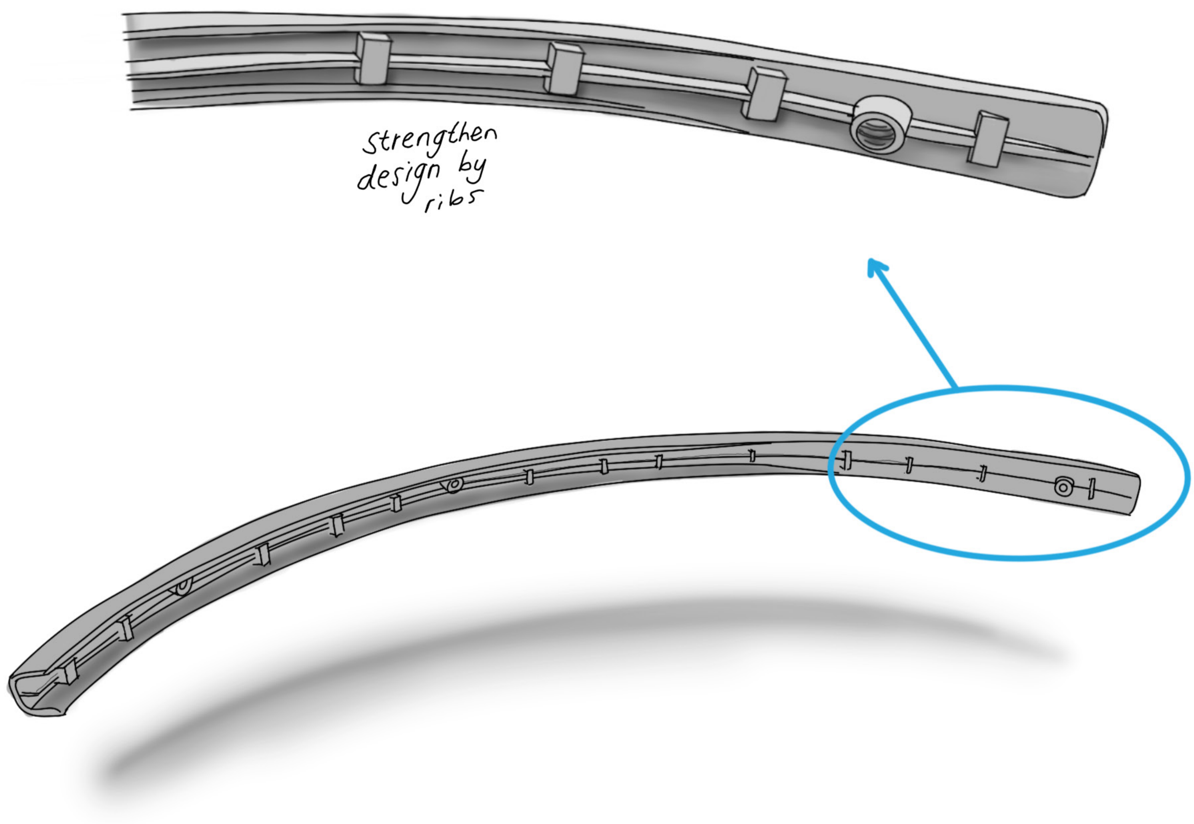


This mindmap displays the aspects that can have an influence on the purchase costs of products. Targeting these aspects can help in reducing these costs. However, purchase cost is not directly or only design related. Replacing the production method by AM could already lead to reaching the goal by by realizing multiple elements mentioned in the mindmap as learned in the literature study.

The collage of pictures used for inspiration serve in showing various possible ways in the enhancing strength of components. These pictures have nothing to do with reducing purchase cost but focus on the design side for ideation. We know that the business class cabin bumper recuringly fails on the same area. The products used as inspiration source are enhancing thin surfaces by adding ribs or curving the flat surfaces which even could lead into interesting results as in the water bottle. These techniques could be used on the bumper design without influencing the overall look.

Redesign phase





CAD phase

The redesign mainly focused on enhancing strengting and fix the recurring fail.

The outside is kept completely original.

The weak point where the U-profile end up is enforced with thicker horizontal and vetical ribs.

The bumper normally has a metal coating. This post-process should likewise applied on the redesign to maintain the same business class cabin appearance.

FEM analysis

DINED is an anthropometric database, which results in limited information about the applicable forces and is more focused on body dimension. Due to lack of information about the impact force of the trolley, which results into breaking the bumper and therefore becomes the biggest culprit of the current problem according to Tolga Inan, Engineer Repair Lab at KLM (11-7-2019), another assumption has been made. Instead of the impact force, is the pulling force of the trolley into the Zodiac business class bumper with one hand been selected as the most suitable maximum use scenario.

P95 male with an age between 20-30 are chosen as the target audience for the analysis to really create a use scenario with maximum forces. This group is the strongest compared to older men or all women. P95 is the methodology based on simulating potential scenarios with Monte Carlo simulations, where the P stands for Percentile *([Terminology explained], 2016).* Thus, does P95 in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

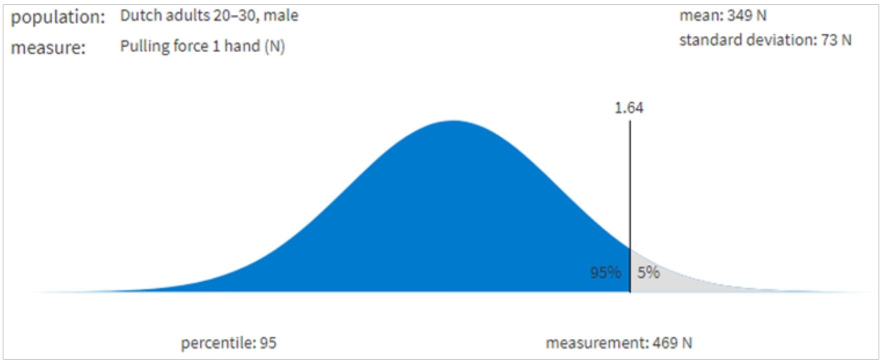


Figure 44. Result of DINED pulling force with one hand P95 male, 20-30 age.

Material choice

Because suitable AM cabin materials such as Ultem9085 and PA2241FR, described in paragraph "6.3 Selecting All Plastic AM processes", were not available in the FEM analysis software, a different material was required to choose. The choice fell on PAEK plastic, due to the fact this material being family with the Ultem9085 and therefore become the closest to reality. The material properties of PAEK plastic according to Fusion360 software, version 2.0.6045, are as following.

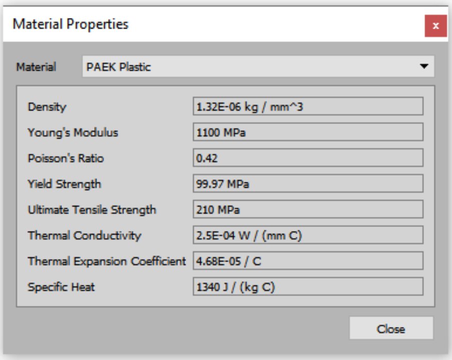
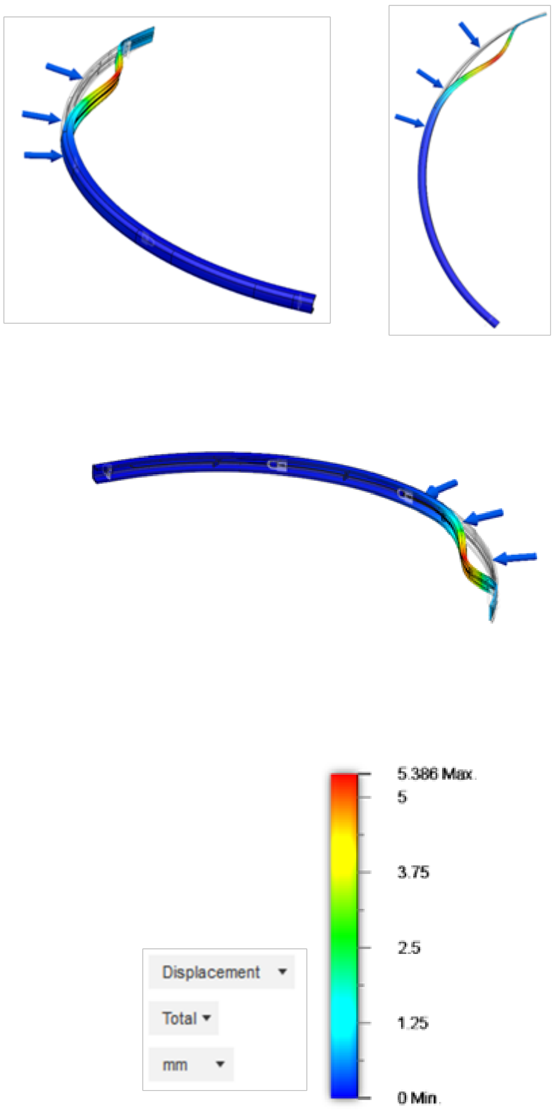


Figure 45. Material proposition of PAEK from software Fusion360.

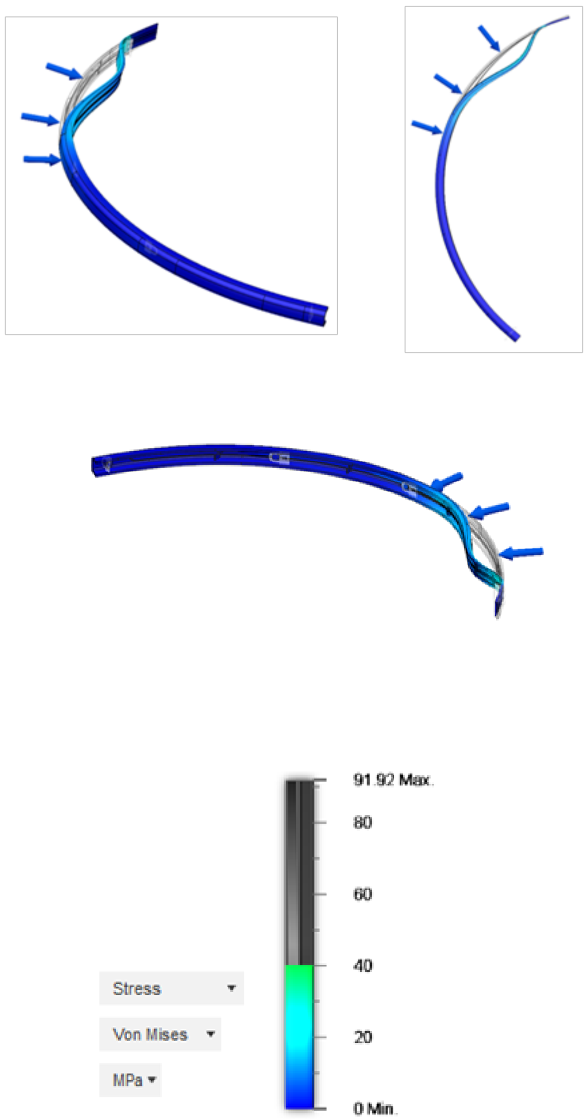
Results FEM

Yield strength is the is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation *(J.S. Kalra, 2019).* The total force is placed at 3 points around the weakest point of the original part. This allows to test the strength of the weakest point. When this point is strong enough, would the other parts certainly pass the test. In the scenario where a 3 point distributed force of 469N is applied on the surface of the business class bumper, is the recorded maximum stress in the material 40MPa. While the yield strength of the material is 99MPa. This means that the part will deform elastically and return to its original shape without any problem. This result tells us that the business class bumper has successfully passed the test and with this demonstrates to be sufficiently strong.

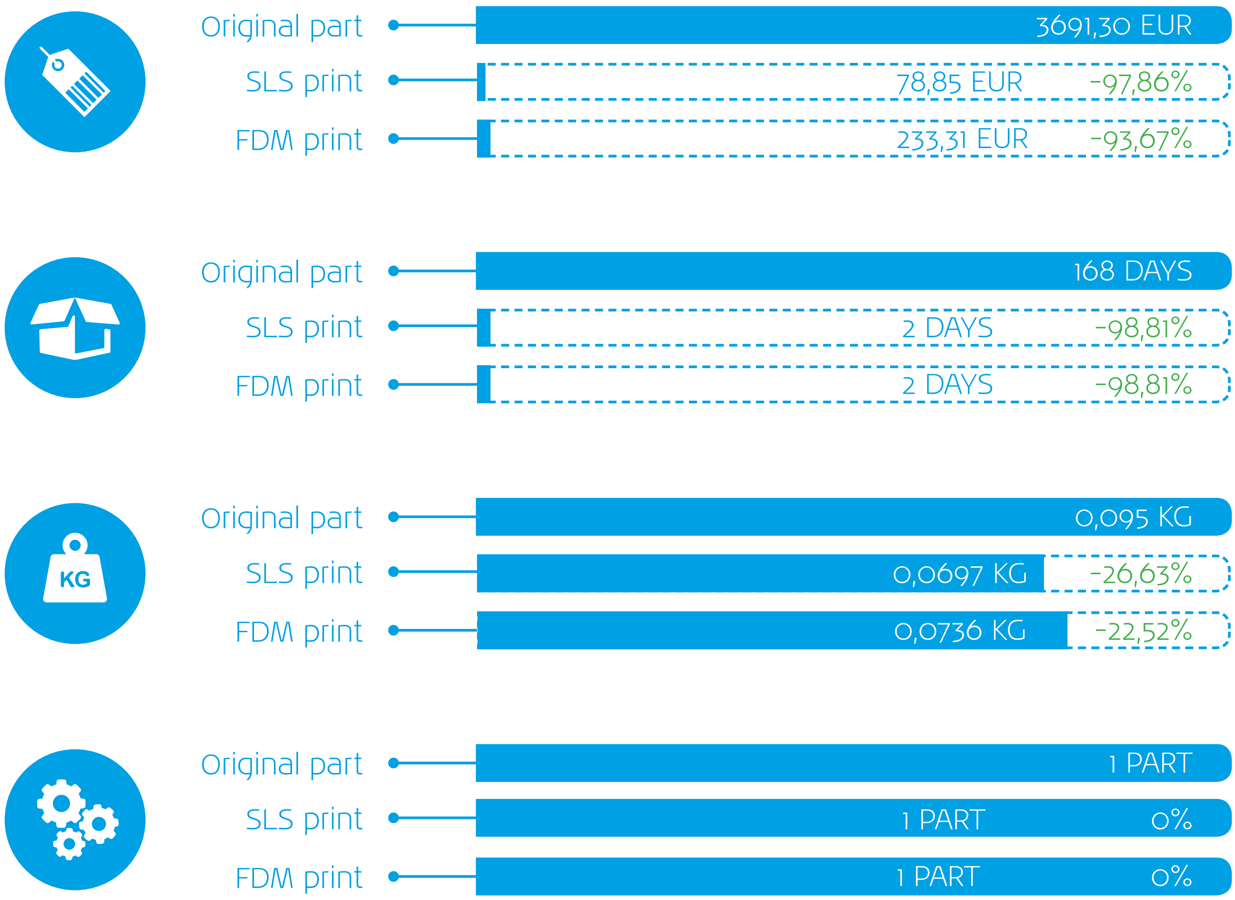
Displacement (in mm)



Stress (in MPa)



Compare results



Is it printable?

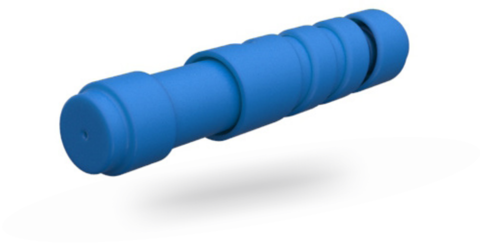
Aesthetic quality	Flexibility	Strength	Impact resistance	Wear resistance	Chemical resistance	Water-thightness	Air-thightness	Humidity resistance	Temperature resistance
●			●		●				

There is no limiting problem which inhibits printing this component. It has been redesigned by taking wall thickness, minimum feature size, material overhang and post process into account. Aesthetic quality is very important because this part is being used in the business class interior as a bumper and at the same time as a decorative item. Because it is a bumper and currently, due to incorrect design, it constantly breaks down in the same places when impact is made, this is an important aspect. Chemical resistance is important to take into account because these parts will be cleaned. Last, the original bumper has a metal coating, the same post process should be apllies as well.

Unique Selling Points

Zodiac seat armrest
chosen for lead time

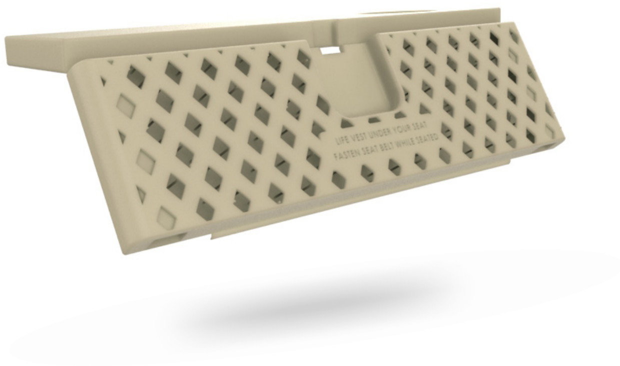
- super fast lead time (-97% reduced)
- lighter design (-27% reduced in weight)
- total of 557 kg potential weight reduction when all will be replaced on fleet (US$1.671.000* annual fuel reduction)
- customizable with logo and KLM color
- ability to color code armrest on seat types for ease of understanding



Lavatory toilet paper holder
chosen for integrating assemblies

- super fast lead time (-98% reduced)
- lighter design (-33% reduced in weight)
- total of 7,19 kg potential weight reduction when all will be replaced on fleet (US$21.570* annual fuel reduction)
- big reduction in purchase price (-74%)
- no assembly needed, print in one go (from 8 to 1)
- ability to customize color according to lavatory design

**fuel price has been calculated according to Revees P. (2012) 1 kg reduction = US$3000 saving on fuel annually.*



Recaro bi-fold seat table
chosen for reduce weight

- super fast lead time (-96% reduced)

caution, the hinge and click mechanism are still missing in the weight

- lighter design (-9% reduced in weight)
- total of 501 kg potential weight reduction when all will be replaced on fleet (US$1.503.000* annual fuel reduction)
- tablet/phone holder added to increase customer satisfaction
- integrated emergency text added which can't fade away, reduces labor and increases employee satisfaction

Boeing window shades
chosen for customization

- lighter design (-23% reduced in weight)
- total of 153 kg potential weight reduction when all will be replaced on fleet (US$459.000* annual fuel reduction)
- reduction in purchase price (-23%)
- no assembly needed, print in one go (from 3 to 1)
- subtile branding with wow-factor

Zodiac Business Class cabin bumper
chosen for reduce purchase price

- super fast lead time (-98% reduced)

caution, the price and weight are calculated without post-process of metal coating

- lighter design (-24% reduced in weight)
- total of 5,52 kg potential weight reduction when all will be replaced on fleet (US$16.500* annual fuel reduction)
- reduction in purchase price (-95%)
- fixing recurring fail issues due to bad design

8.7 Selecting one concept

After the 5 different concepts have been worked out and sufficient knowledge and results have been achieved to evaluate them, the next step has arrived. In this step, a choice will be made between the concepts on the most promising to further develop. The selection procedure has not been made on gut feeling. The previously constructed criteria list for the trade-off table using weighted objective method in paragraph §7.4 Selecting parts has been used. The weighted objective method is an evaluation method used to compare concepts on various criteria with a specific weight assigned according to its degree of importance. (Roozenburg and Eekels, 1998).

Figure 46. displays the eventual criteria's in the trade-off table which were developed with an organized workshop together with KLM experts based on the previously concluded benefit - consequence combinations which AM could provide KLM back in §5.2 Elaboration of benefits AM offer aviation. To remember the details, it is recommended to re-read paragraph §7.4 Selecting parts.

The result of the trade-off table shows us that the Zodiac seat armrest the greatest potential offers, by being scored as the best on the enlisted criteria. This concept has been selected for the benefit of "reducing lead time" that AM may offer. For this reason, it is especially important that the new Zodiac seat armrest focuses on reaching its goal on the reduction of lead time. In addition, the redesigned part should be made printable, strong enough for use and meets all the requirements that will be listed in the following paragraph §9.2 List of requirements.

All other benefits that AM offers such as integrating assemblies, reducing weight, customization and reducing purchase costs are side concerns and not the main objective for this component. Because the whole idea of this project approach and the research question was to find the possibilities additive manufacturing offer in aircraft part production. For this reason, among the 5 benefits of AM found 1 specific component has been chosen. These components are chosen on the basis of their current problem that can possibly be remedied with the advantage of AM for which they have been chosen. For this reason are all other benefits that AM offers such as integrating assemblies, reducing weight, customization and reducing purchase costs are side concerns and not the main objective for this component.

		1. Faster lead time		2. Integrate assemblies		3. Reduce weight		4. Customizaztion		5. Reduce pruchase cost	
Weighing scores requirements	**Average weighted score**	Zodiac seat armrest (P/N F0479566)	SCORE	Lavatory toilet paper holder (P/N 0FS3500A04G01)	SCORE	Recaro bi-fold table (P/N 0FS3500A04G01)	SCORE	Boeing window shades (P/N 411W1602-6A)	SCORE	Zodiac Business class cabin bumbers (P/N F0494959)	SCORE
Faster leadtime	4,00	5	20	5	20	5	20	2	8	5	20
Integrating assemblies	3,50	2	7	5	17,5	5	17,5	4	14	1	3,5
Reduce weight	4,00	4	16	2	8	3	12	2	8	3	12
Increase product life cycle	4,25	4	17	1	4,25	3	12,75	2	8,5	4	17
Opportunity of complex geometry	2,63	1	2,625	5	13,125	5	13,125	1	2,625	1	2,625
Customization	3,63	4	14,5	2	7,25	3	10,875	5	18,125	1	3,625
Increase employee satisfaction	2,75	0	0	0	0	0	0	0	0	0	0
Increase customer satisfaction	4,38	0	0	0	0	3	13,125	0	0	0	0
Fix recurring fail issues	4,00	5	20	1	4	2	8	4	16	4	16
Reduce purchase costs	4,38	1	4,375	5	21,875	-2	-8,75	2	8,75	5	21,875
Reduce supplier dependency	4,00	5	20	1	4	5	20	4	16	5	20
Increase buy-to-fly ratio (waste material reduce)	2,75	0	0	0	0	0	0	0	0	0	0
Reduce labor time	3,75	4	15	2	7,5	5	18,75	0	0	5	18,75
Reduce TAT (Turn Around Time)	4,13	0	0	0	0	0	0	0	0	0	0
Reduce fuel consumption	4,00	5	20	2	8	5	20	4	16	2	8
Attractiveness for KLM (Marketing potential of AM)	4,63	3	13,875	2	9,25	3	13,875	3	13,875	1	4,625
Possible implementation speed	4,25	4	17	5	21,25	2	8,5	5	21,25	4	17
		TOTAL	**187,375**		**146**		**179,75**		**151,125**		**165**

Figure 46. Results of trade-off table filled in for the 5 developed concepts.

8.8 Conclusion

The selection of part numbers/specific parts for the previously created list of suitable parts with the developed route has lead to the list displayed in figure 46.

AM benefit = Selected component
Faster lead time = Seat armrest
Integrating assemblies* = Toilet paper holder*
Reduce weight = Bi-fold seat tables
Customization = Window shades
Reduce purchase costs = Business class Cabin bumpers

A viable system has been created with the prepared formulas, assumptions and methods to test on printability and strength. These will help during future development processes similar to this project. The comparison aspects and tests can by this mean be determined easily and quickly for a redesigned concept model before fully developing/producing the part. Thus can be said that the hard job of inventing the wheel is completed for future use.

The main target during development of the 5 concepts was the AM benefit this part was selected for. While other advantages of AM are side concerns. One thing is certain, there can be lots gained even with the side issues. For this reason are they certainly very important, but have no value if the main benefit is insufficiently or can't be achieved.

Executing the same trade-off table developed in the previous chapter together with KLM experts. Helped the selection procedure becoming more objective as well as better grounded. Filling in and rating all developed concepts with the enlisted criteria result into the conclusion that the Zodiac seat armrest provides the greatest potential.

AM benefits	Selected component
Faster lead time	Seat armrest

Part number	Aircraft type
F0479566	777 & 787 fleets

Figure 47. Results of second trade-off table filled in best concept to develop in the final phase.

Now that the part with the greatest potential has been chosen, the final phase can be entered. Whereby the part will be further optimized and finalized.


KLM
D10
WM
KLM

9. Final phase

The final phase has started at the point that the Zodiac seat armrest has been selected as the most promising concept. This paragraph is devoted to the elaboration of the final design. This will be done on the basis of optimizing the previous concept CAD model and the knowledge associated with this FEM analysis. After the CAD model has been optimized and redesigned, it will be re-analyzed with the FEM method as well as checked for printability. During the entire development phase of the final CAD design, the list of requirements drawn up will be taken into account.

In case the results of the analysis and printability check are sufficient, the prototype of the final model will be produced with FDM. According to the website of Printzkart3D (2018) is FDM one of the best AM methods when a single part is needed to test the design fast. This prototype will be used to validate the fit of the design in the assembly and check the modeled dimensions in reality. With the validation, information will be collected about possible adjustments to the model. With this, the final CAD model will be fine tuned and, if necessary, printed out again to validate the changes.

The moment the prototype fits and the dimensions are correct, will the CAD model be finalized and sent to the third party POA holder, Materialize. They will produce the final model according to the established requirements. With the component being produced in final form in terms of material, technology and post-process, will the real comparison aspects be obtained which could be used to validate the determined comparison aspects on accuracy. Lastly, this last part will once again be tested for suitability in the aircraft cabin.

Chapter structure

The method used for the chapter is explained in §9.1. Next is an elaborate list of requirements set up for the redesign of the armrest in §9.2. Next are all design choices during the optimization process of the armrest explained in §9.3. In paragraph §9.4 is the strength of the optimized armrest analyzed and in §9.5 is it tested on printability. Consequently are the 4 comparison aspect determined and compared with the original part and the prior concept armrest in §9.6. After the CAD model is finished, is this part tested on fit and correctness of the dimensions with a prototype. The design is iterated until everything would be perfect in §9.7. Next is the new armrest produced in its final SLS form in §9.8. Whereby the prior determined comparison aspects are validated. The importance and investigation whether the new armrest makes a chance to succeed is treated in §9.9. Finally, is the conclusion of the chapter is taken care of in §9.10.

9.1 Method

The list of requirements is set and refined with two KLM experts specialized in the areas of seats and airworthiness. While the design choices to optimize the new armrest are done mainly based on gained knowledge during the prior process steps. However, web research through Google was needed to collect data to choose between various screw thread options.

The strength of the optimized new armrest is performed with the use of FEM software. To bring the execution of this analysis as close as possible to reality, the specific AM process and material are selected. This selection is done by the prior determined comparison aspects for the armrest during the concept phase. Testing on printability and determination of the comparison aspects is executed exactly in the same way as in the concept phase. These steps may seem like double work, but the optimized armrest must still be seen and treated as a new component in connection with the changes. After finishing all design steps, the fit and dimensions of the redesigned armrest are validated in 2 iteration steps. These iterations are done by creating tangible prototypes with which can be tested in the real world and real use of context. All comparison aspects for the redesigned products are determined until now. After finalizing the armrest design, is the armrest produced in its eventual real manner. This result is used to validate the real comparison aspects with the prior determinations. At last, the final armrest is researched whether it meets previously set requirements to make a statement if this part has a chance of obtaining a certification. 7 experts actively on this topic were consulted to make a substantiated statement.

9.2 List of requirements

A list of requirements state the important criteria a design should meet in order to call it successful. The criteria enlisted as requirements should be concrete and testable. For example, change: 'The product should be as cheap as possible' into: 'The product should have a maximum production price of €50'. This list has been refined with the help of Cor de Zeeuw (30-7-2019), KLM cabin engineer specialized in seats and Peter Dol (9-8-2019), KLM head of airworthiness.

1. Function

1.1 The product should replace the current seat armrest where part number F0479566 is installed.
1.2 The product should close the entire armrest at the top.
1.3 The product should provide arm support while sitting in the seat.

2. Use

2.1 The product should be resistant to KLM cleaning chemicals used in the cabin.
2.2 The product should be watertight.
2.3 The product should withstand salty water.
2.4 The product should withstand UV.
2.5 The product should be approved in terms of appearance and comfort by Fleet Services (Customer Experience).

3. Product specifications

3.1 The product should weigh less than 0,15 kg in total.
3.2 The product should fit the current seat armrest where part number F0479566 is installed.
3.3 The product must show the same color in the event of damage.

4. Materials

4.1 The product should withstand flammability requirements FAR 25.853 (ref CS25-583(a)).

5. Production

5.1 The production cost should be less than €150.
5.2 The post-process costs together with the production should be less than €165.
5.3 The product should have a lead time less than 5 days for production and post-processing.

6. Safety

6.1 The product should pass function & installation requirements (ref CS25-1301(d)).
6.2 The product should pass general – design and construction (ref CS25-601)).
6.3 The product should pass all related ETSO-C127B criteria.

9.3 Design choices

This section provides an overview of the design choices made during the optimization of the concept CAD model to the final CAD model.

Exterior

The entire exterior of the Zodiac armrest has been kept original, this is the side which is in sight of the passengers. This means that the original part has been copied. Although different patterns and customization options have been explored (Appendix I.), these will not be applied at this stage. Because the focus of the component and for which it was chosen is, lead time. Like previously explained, the project has been arranged the way the main benefit a component is targeting should be reached mainly. Together by redesigning the part to make it printable, strong enough for use and meeting all the enlisted requirements. All other possible applicable benefits which can be applied on this component are in this case side issues.

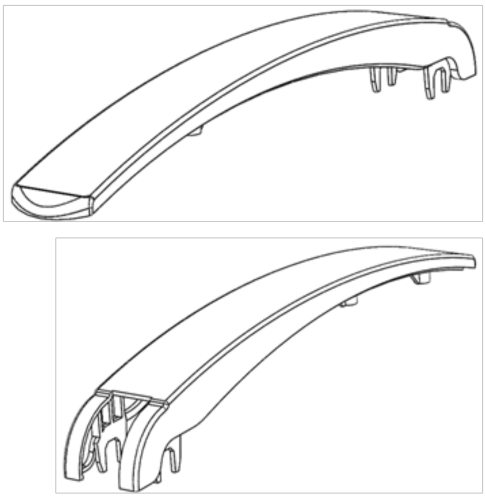


Figure 48. Design choice representation of optimized armrest for exterior.

Wall thickness

The wall thickness of the complete part has been reduced to 2 mm. The choice here is not directly related to the benefits of AM. However, the benefit of no need for ribs has been applied here, more can be read in the next section. The wall thickness of the part can possibly be even reduced more and simultaneously reinforced with a complex honeycomb structure. With this, the possibilities AM offers would be used more optimal. Nevertheless, the choice of not doing this due to stay safe, read more about this at the end of the section.

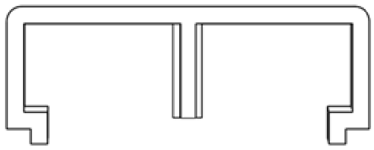


Figure 49. Design choice representation of optimized armrest for wall thickness.

Ribs

The rib structure that is characteristic of injection molded parts has been completely removed. Ribs are used to increase the strength of the part without increasing wall thickness. Walls that are too thick can sink, warp or result in other defects in injection molded parts ([Ribs can enhance your injection molded part], 2018). AM as a technique does not come with the same defects and therefore does not need to use ribs. However are ribs still an effective form to increase strength, so the final part without ribs should be investigated whether is strong enough during extreme use.

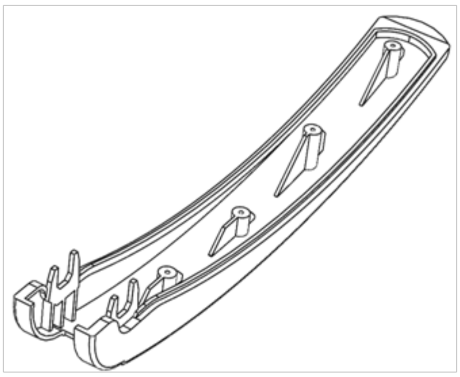


Figure 50. Design choice representation of optimized armrest for internal ribs.

However is the use of ribs kept for the screw pins. This is used as a safe option to enhance the strength of these pins against torque in case the armrest will be over tightened.

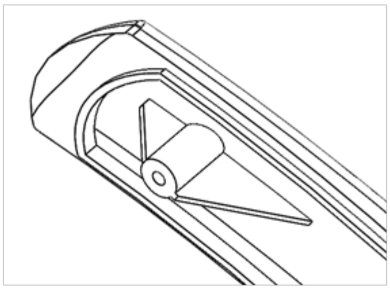


Figure 51. Design choice representation of optimized armrest for screw pin ribs

Ribs are used on the u-shaped clips on the back of the armrest. These ribs replace the solid form used now, and will with this serve possible to reduce weight.

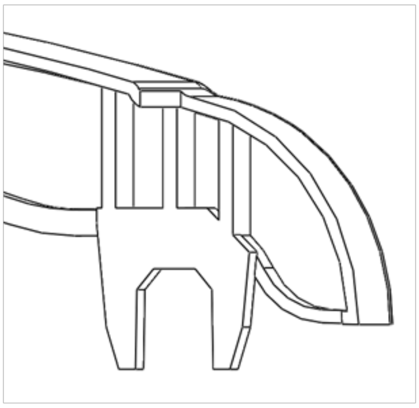


Figure 52. Design choice representation of optimized armrest ribs for u-shaped clips.

Screw pins / thread

The current Zodiac armrest uses brass inserts that are "melted in" after the production of the part. The process of melting in the thread insets is called the heat staking process. This provides the extra labor and assembly time and will preferably be avoided because AM offers the possibility to directly print threads. The different options are investigate to make a considered choice. A research was found, which test 3 AM thread options and compare these on pull force and torque; printed thread, tapped thread and thread insert.

Figure 53. Design choice of optimized armrest thread. From left to right: printed thread, tapped thread and brass thread insert.

The results show that the brass thread insert is the strongest in both situations. ([Threaded Inserts in 3D Prints - How strong are they?], 2019). The research also advises to use of inserts when the connections are tightened multiple times but more regularly, due to plastic threads are wearing out more quickly than the inserts.

The use of thread inserts is selected for its strongest connection for prolonged use. Now, it is important to research whether the inserts can be used for parts produced on both FDM and SLS. When a web search is done with the keywords "fdm brass insert" and "sls brass insert", sufficient examples are found which explain the use of this application. Furthermore, in forums found through these search terms can be read about the successful experiences of users inserting these brass threads in both FDM and SLS printed parts. This gives sufficient confidence about its possible use.

Next are the screw pins prepared for the use of these brass insert according to the design guideline provided by 3DSYSTEMS ([Brass Insert Design Guide for SLS Parts], 2015). The current threads used on the Zodiac armrest are 4 mm, logically is this dimension kept. The provided design guideline is using Tappex multisert brass inserts. The hole diameter for M4 bolds should be 5,6mm, while the minimum wall thickness should be 3 mm. The minimum length of the pin should be 5,6 mm.

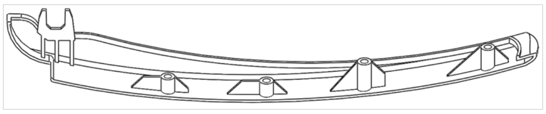


Figure 54. Design choice representation of optimized armrest for thread insert design.

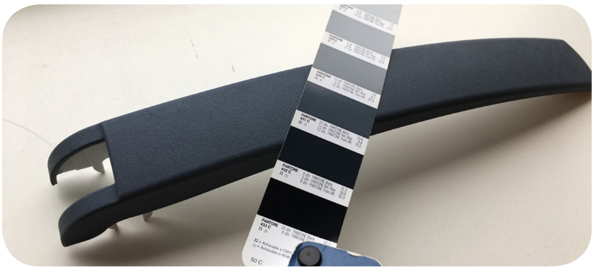


Figure 55. Determination of the original armrest color with a color range.

Conservative design

The choices made during the optimization process of the final model for the Zodiac armrest are fairly conservative. AM offers more possibilities in producing complex forms. This approach has been done due to the limited time reserved for this project. This limitation has made sure to go for the safe option. Being conservative is unfortunately at the expense of the "full" use of AM, but increases the chance of successfully performing the function.

Color choice

The choice for the color has been made to match the color of the original Zodiac armrest. This is done on the basis of a colors range (Figure 55). In this way, it will be ensured not to be required to replace the original armrests all at the same time. Which prevents a large investment, and hence could reduce the risk of deterrence in KLM's management. The original Zodiac armrest can be replaced 1 by 1 in case of breakage.

9.4 FEM analysis

Although a FEM analysis has already been performed on the Zodiac armrest in the concept development phase to test the strength, it is also very important to do this in the final phase. This may look like double work, but it is not. Because the design of the armrest concept is optimized in this phase and thus adjusted. An adjustment to the component can lead to a product that can behave differently under the influence of physical situations. It is therefore necessary to re-analyze the component on strength as a whole new part.

In addition to the adjustments of the design, a choice in AM process and thus material is now made in the final phase. This choice influences the FEM analysis.

AM process choice

The choice is based on the previously determined comparison aspects for both FDM and SLS for the armrest. The main advantage of AM for which the Zodiac seat armrest has been chosen is lead time and thus the most important aspect to base the selection on. The original armrest has a delivery time of 83 days, because the current part often breaks and therefore needs to be replaced, this causes problems. With the assumption made in the concept development phase, the lead time will be reduced to 2 days independent of the AM process. This means that the goal of reducing lead time will be achieved. For this reason, it is necessary to look at the other comparison aspects to make a choice. The results in the determined purchase price for SLS and FDM (figure 56.) shows that the purchase price of FDM can be more than 154% more expensive than the original part while the SLS is almost 14% cheaper.

It is still important to be aware that the lead time assumption for FDM and SLS of 2 days can change in reality. This also applies to the determined purchase price. For this reason, first of all it is very important to understand that there is always a trade off balance between lead time and purchase price. An example scenario is outlined in the table to explain such a situation. It may therefore be that a higher purchase price could be acceptable when lead time is more important. Or in contrast, the lead time is good enough and therefore a lower purchase price is favorable. For this reason, good consideration must be given to which criteria are the most important and why. In the scenario of the table, SLS is half the price of FDM while the lead time is twice as long. In both cases, the current lead time of 83 days will be improved, but it must still be considered which of the 2 AM processes fits better in such a situation.

	FDM	SLS
Real lead time	€100	€50
Real purchase price	1 day	3 days

Figure 57. Example scenario to explain the importance of the comparison aspects.

Figure 56. Results of the determined comparison aspect of the previous concept CAD model of the Zodiac seat armrest.

Eventually is the AM process, SLS chosen. This is due to having a lower purchase price and offering better printer specifications than FDM with regard to smaller details and thus aesthetics ([paragraph §8.4, test on printabiliy]).

Material choice

With the choice of SLS, the choice of materials is reduced to a certain number. As we have read in paragraph §6.3 Selecting all Plastic AM processes that more than 1 SLS material is suitable according to the FAR material requirements of the aircraft cabin.

> The known and best suitable material currently used in aviation is PA2241FR. This is also the material that is used for the current printed and certified KLM part, the tulip soap holder.
>
> **Tolga Inan** (20-3-2019)
> engineer repair lab @ KLM
>
> **Rik Steenkist** (18-3-2019)
> manager cabin engineering @ KLM

For this reason, the existing knowledge and experience of KLM experts with this material, no further search will take place. Meaning that PA2241FR is selected for use. No in-depth investigation of other materials is partly caused in connection with the limited time of the project.

To increase the reliability of the new FEM analysis results it is necessary to take the chosen material specifications into account. Unfortunately does PA2241FR not exist in the material library of the FEM analysis software, Fusion360 version 2.0.6045. Thus is this material created base of material datasheets provided by the manufacturer EOS and user of the material, Materialise, in the following sources: ([Material datasheet PA2241FR EOS], 2013), ([Material datasheet (provisonal) PA2241FR], 2011) and ([PA2241FR Materialise], n.d.).

This results in the following material properties.

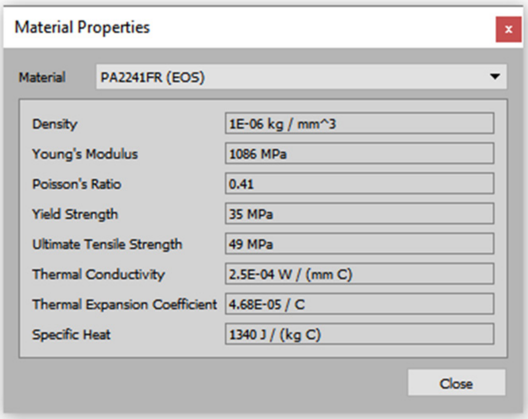


Figure 58. Material properties of PA2241FR.

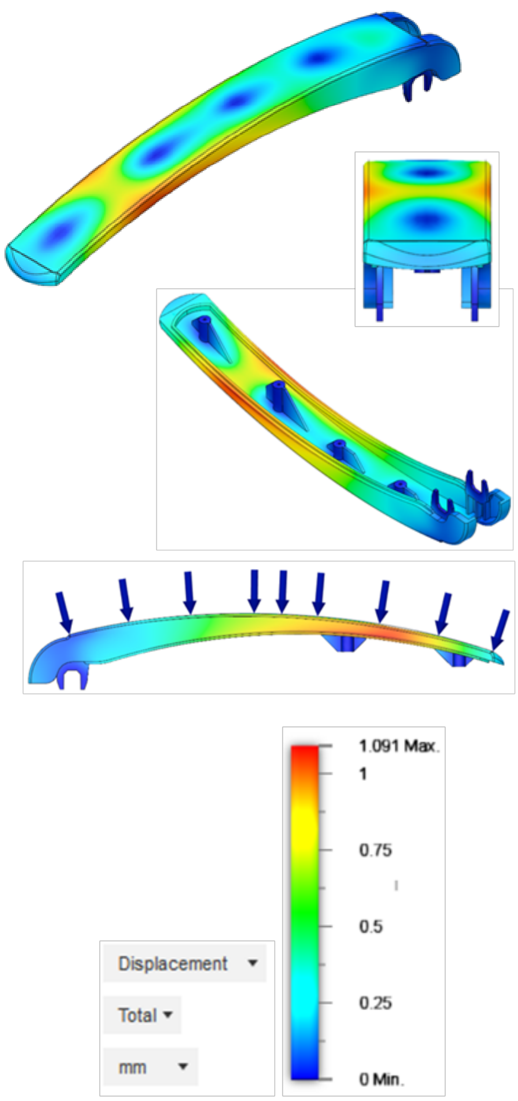
FEM analysis execution

The same forces from the maximum usage scenario in the concept development phase have been used. The exertion of force by pushing with two hands on the Zodiac armrest while standing up. P95 male with an age between 20-30 has been selected, they are the youngest and strongest of the target group and exert a maximum force of 710N. The P of P95 stands for Percentile ([Terminology explained], 2016) and in this case mean that at least a 95% of the target group actually exceed the estimated maximum force. If the component is strong enough to withstand this strength of the strongest 95% from the target group, it proves that it can certainly withstand almost any situation.

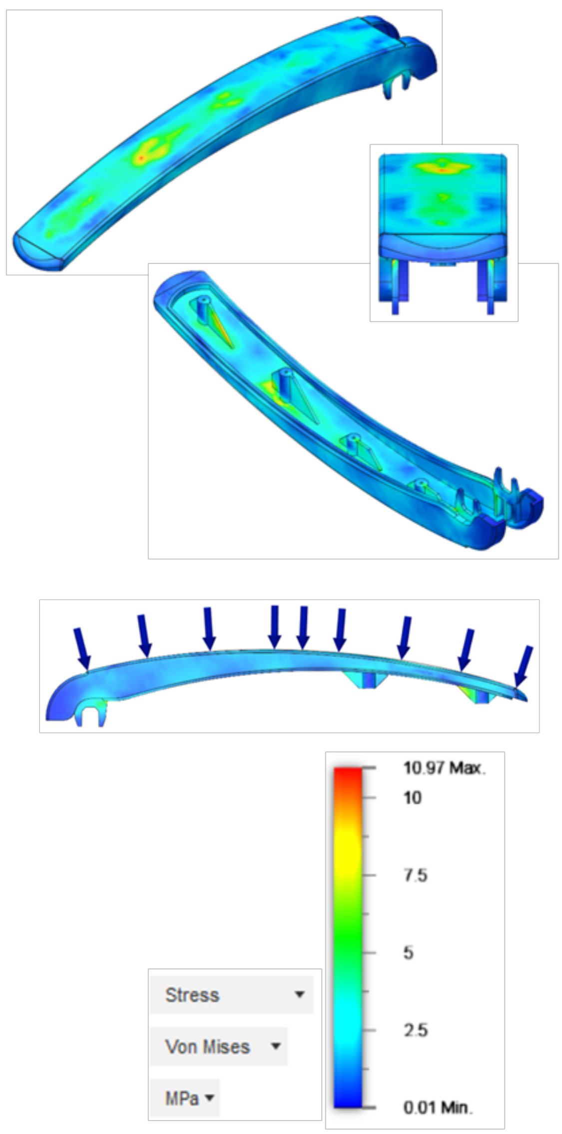
In the defined scenario is the force of 710N gradually distributed on the top surface of the armrest. The model is clamped on the 4 screw pins and the 2 u-shaped clips on the back. The recorded maximum stress in the material in this scenario is just below 11MPa. While the yield strength of the material is 35MPa. Yield strength is the minimum stress under which a material deforms permanently, it could also be defined as the maximum stress a material can withstand without permanent deformation (J.S. Kalra, 2019). This means that the part will deform elastically and return to its original shape without any problem. During the application of this force, the maximum displacement will be just around 1mm. This result tells us that the final design of the armrest produced from PA2241FR has successfully passed the test and with this demonstrates to be sufficiently strong.

The result of the FEM analysis is very promising. In the current maximum usage scenario, the DINED force of 710 N is used. After the analysis results, another possible scenario in the aircraft cabin is imagined which will exert a larger force on the armrest. In this scenario will a passenger sit on the armrest with their entire weight. Due to the larger force in this scenario and the reality of happening, it is necessary to perform a new FEM analysis to exclude whether the armrest is strong enough for this situation.

Displacement (in mm)



Stress (in MPa)



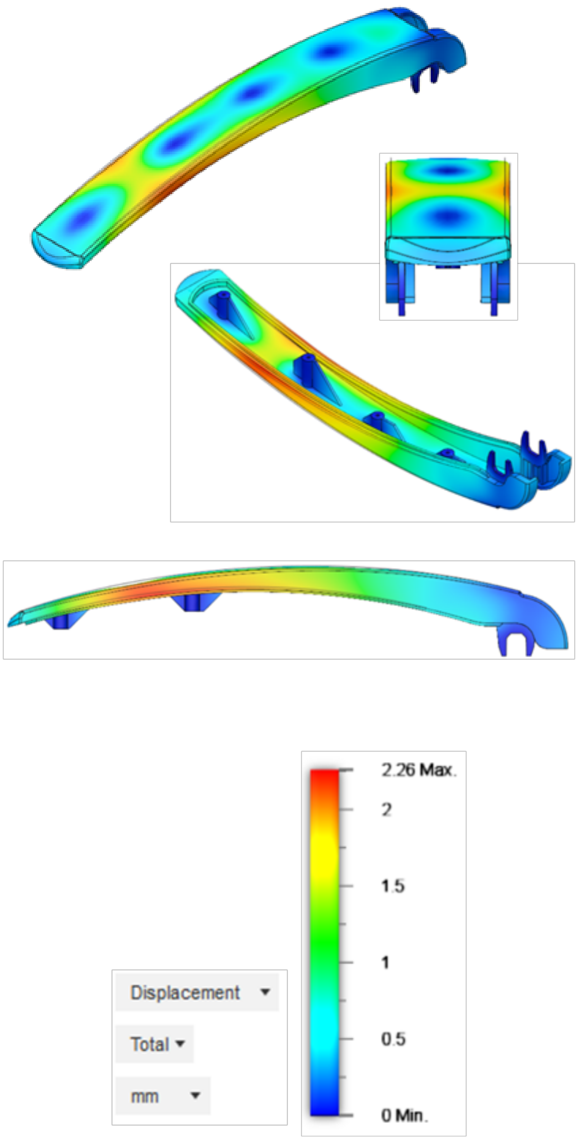
Extra extreme scenario

An extreme has been chosen in which a person weighing 150 kg sits on the armrest. To make this information usable for the analysis, should the weight be converted to the Newton force (on earth). This is done with by multiplying the weight of 150 kg * 9.81 (gravity on earth), resulting in 1471 N.

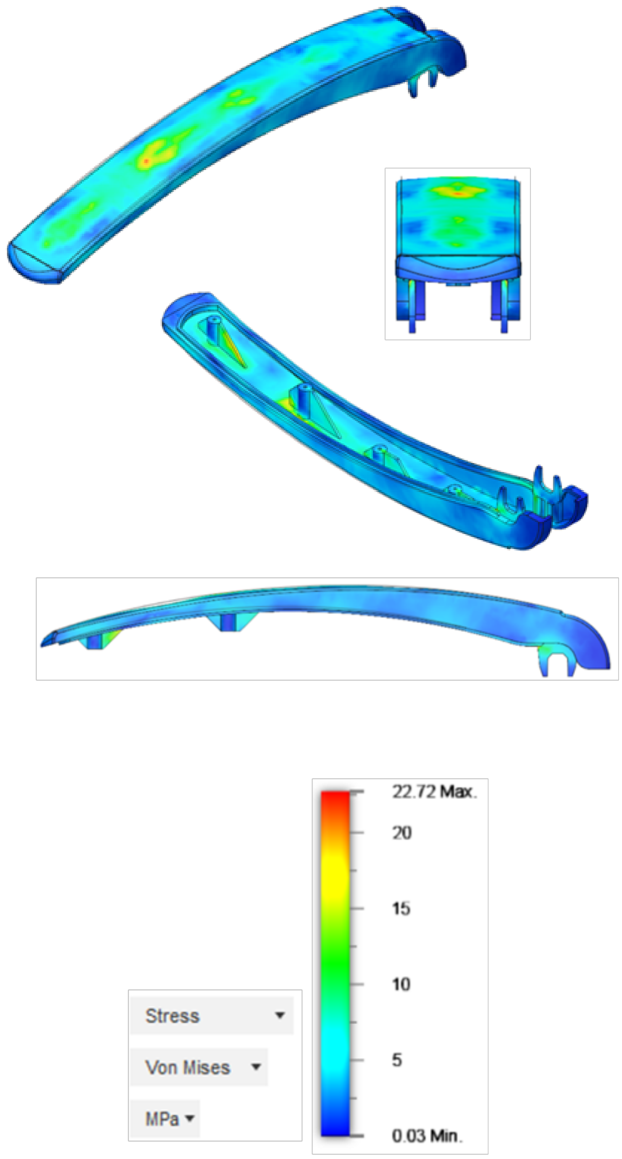
Furthermore, the force is gradually distributed on the top surface of the armrest and the model is clamped on the 4 screw pins and the 2 u-shaped clips on the back. These settings resulted in the following FEM analysis.

The recorded maximum stress in the material in the new maximum use scenario is just below 23MPa. While the yield strength of the material is 35MPa. This still means that the part will deform elastically and return to its original shape without any problem. During the application of this force, the maximum displacement will be around 2mm. Although the results are higher, they are still below the limit where the armrest permanently deforms or even breaks. Which ensures good expectations about the new armrest with PA2241FR on sufficient strength in extreme scenario's.

Displacement (in mm)



Stress (in MPa)



9.5 Test on printability

The importance of testing for printability has been explained in detail in paragraph §8.4. Printability has to do with 2 conditions, the function requirements of the component and printer specifications. The approach developed In paragraph §8.4 starts with determining the function requirements of the component and find the linked printer specifications. To remember the details, it is recommended to re-read paragraph §8.4.

Determined function requirements of the redesigned Zodiac armrest to print are:
1. Aesthetic quality;
2. Chemical resistance;
3. Waterthightness;

Aesthetic quality is very important, due to the fact the armrest being the part which is in the immediate vicinity where a passenger spends most of his journey on the plane. This signifies possible prolonged and extensive use and because the part being in sight amplifies the importance of its aesthetic quality. The importance will even increase when customization will be applied to the design. Both the functions of chemical resistance and waterthightness are important due to the armrest being exposed to the KLM cleaning chemicals used in the cabin, passenger sweat (salty water) and possible passenger drinks waste.

The 3 determined function requirements are linked to the following printer specifications:
1. Material overhang angle;
2. Minimum features;
3. Tolerance / Accuracy;
4. Post process;
5. Material;

The 5 printer specifications for SLS are listed below. These specifications can also be seen as design guidelines, due to this reason they were actually used during the optimization of the concept CAD model to the final CAD model.

	SLS (plastic)
Material overhang angle	no support needed
Minimum features	0,8 mm
Tolerance / Accuracy	±0,3%
Post process	Powder removal, Vibro polish, Dyeing, Spray paint, Lacquering, Watertightness, Metal coating
Material	PA2241FR

Figure 59. Results of linked printer specifications to needed part function requirements of the armrest.

9.6 Comparison aspects

The 4 comparison aspects ensuring the possibility to easily compare new concept models with the original parts will also serve to compare final redesign models with the previous concept models. This comparison will serve to show whether an improvement or deterioration has been achieved with the final design.

The volume of the final zodiac seat armrest CAD model will be used to determine the weight and price with the previously constructed formulas. The prior made assumption for 2 days will be used for the lead time, whereby the quantity of parts can be counted in the final CAD model.

	Final zodiac seat armrest
Volume	88792 mm3

Figure 60. CAD model volume of the final optimized seat armrest redesign.

By reason of SLS being chosen as the AM process for the final zodiac seat armrest, as explained in paragraph §8.8.2 FEM analysis, only the comparison aspects for SLS will be calculated. The determined results for the final zodiac seat armrest are as follows.

Zodiac seat armrest	**Original part**	**Final SLS**	**Final %**
Price	€186,90	€134,57	-28,00
Leadtime	83 days	2 days	-97,59
Weight	0,186 kg	0,119 kg	-36,02
Assembly	6 parts	5 parts	-16,67

Figure 61. Comparison table between original armrest and determined aspects from final CAD model.

When the results of the final zodiac seat armrest are compared with the previous concept results, we see an improvement in the results. This means that the optimization of the design was actually successful.

Zodiac seat armrest	**Concept SLS**	**Final SLS**	**%**
Price	€161,05	€134,57	-16,44
Leadtime	2 days	2 days	0
Weight	0,142 kg	0,119 kg	-16,20
Assembly	5 part	5 parts	0

Figure 62. Comparison table between the determined aspects of the concept and final CAD model.

In case all current Zodiac armrest will be replaced by the final zodiac seat armrest redesign, will result in a potential of 955 kg weight reduction in the complete fleet of KLM. Which results in a potential fuel cost reduction of $2.865.000 on an annual base (Revees P., 2012). The potential possibility of achieving this large fuel cost reduction, which is a consequence of the weight reduction benefit of AM. This result shows how important the consequences can be of the benefits that AM can offer and that this should not be ignored. This contributes to the need as described in paragraph §3.4 Literature gap and the effort made in paragraph §5.2 Elaboration of benefits AM offer aviation to map these out.

9.7 FDM prototype

The strength analysis and the determination of comparison aspects based on the CAD model are executed before developing a prototype. In any given time during the process of optimizing and finalizing a computer aided design, it is important to check its precision of dimensions and real fit on the assembly (figure 63.). The best way to do this is by creating a tangible prototype which can be tested in the real world and real use of context. However, this iteration process could lead to adjustments and changes in the CAD model which could affect the result of the strength analysis and the determined comparison aspects. Nevertheless, the choice in the order of execution was deliberately made due to the changes in the model are expected to be small and hence will not have (a major) influence on the strength nor volume of the part.

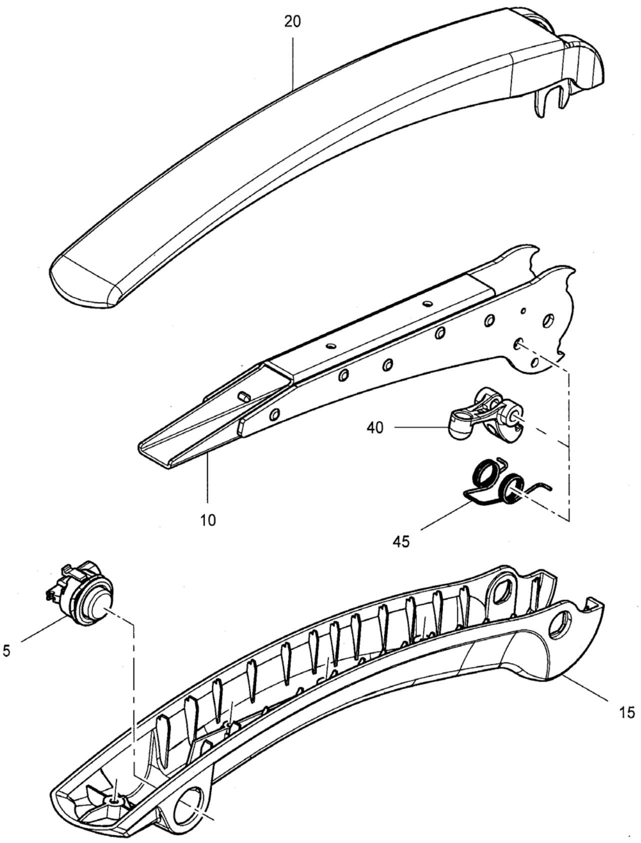


Figure 63. Assembly of the original Zodiac seat armrest.

Prototype 1

The first prototype was deliberately produced in 2 parts. This is done to offer flexibility to the length of the prototype. If this length dimension was fixed and the prototype was not correct in this dimension and therefore did not fit, this would mean that other dimensions such as width, fitting of the u-shaped hook or the alignment of the screw holes could not be tested.

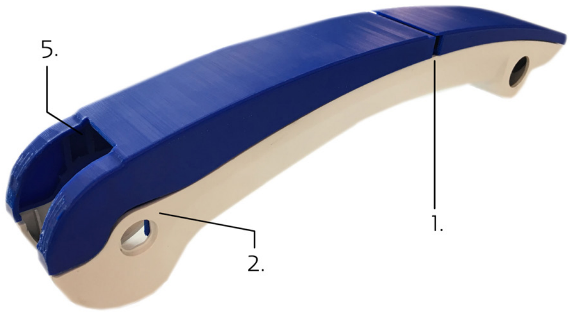


Figure 64. Picture of first prototype and the issues which needs to be fixed.

Figure 65. Picture of first prototype tested on fit and dimensions in the 787-9 cabin.

The research with the prototype led to the following results. There are some points where the CAD model needs to be improved, these are as follows:

1. The length dimension must be extended by 8,5 mm from the center of the armrest;
2. The curves must be adjusted based on the curves of part 15 in the assembly drawing;
3. All length sizes of the screw pins must be shortened by 2 mm;
4. The alignment of the rear 2 screw pins must be aligned with part 15 in the assembly drawing;
5. The recess at the rear of the armrest part 20 must add 2 mm on all sides;

After this iteration of the model, a second prototype will be printed to test fitability in context.

Prototype 2

The result of the second prototype was already almost perfect, 4 of the 5 improvement points were perfectly corrected. Only point 2 of the previous list, the curves at the back of the armrest contained a minor gap. The result of the second prototype shows a perfect fit, except for point 2. After filling in the minor gap, the CAD model will be final and ready to be printed in SLS.

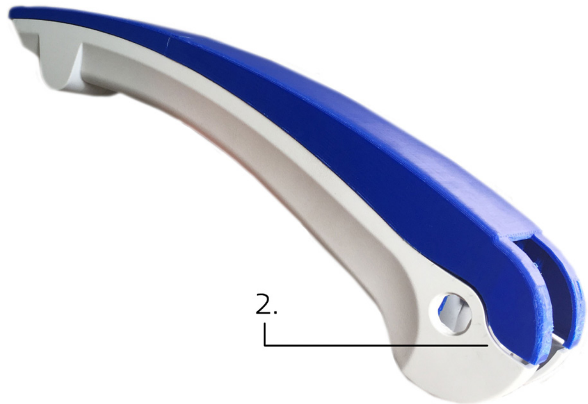


Figure 66. Picture of second prototype with minor gap at the back.

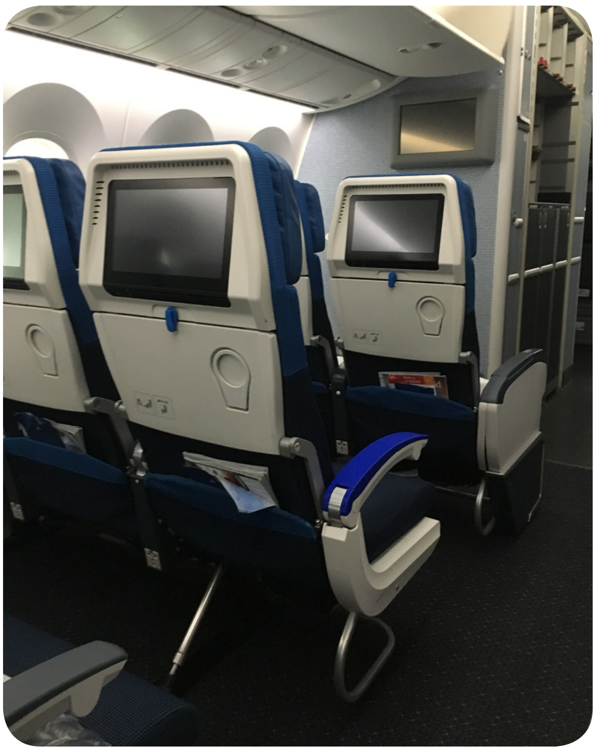


Figure 67. Picture of second prototype fitting like a glove tested in the 787-9 cabin.

9.8 SLS final product

After the new armrest design has been optimized, tested on fit and dimensions and has been finalized, it can ultimately be produced in the chosen real manner. This means that quotation has been placed at Materialise for the production with SLS in the material PA2241FR. The expert at Materialise, Daniel Hoogstraate account manager for the Netherlands, has been contacted to discuss the needs. He responded by explaining that the part would be resistant to KLM cleaning chemicals due to its nylon based material and watertightness can be achieved, just by having a polished finish by tumbling and color dying. Due to the dye being sucked in by ±0.5 mm the part would this protect from salty water and UV. However, should these steps be tested and adjusted by trial and error.

Additionally, the expert at Parts on Demand, Eric van Es, explained that the water repulsion can be achieved by color dying and shot peening the part. He adds that SLS material has generally absorbent content of 2%. With color dyeing, this will be reduced to 0.1% and shot peening would make it water repellent. Shot peening also ensures that the surface becomes smoother, which facilitates cleaning. This would in all probability decrease the chance of the part getting dirty from the combination of sweat and skin flakes. Thanks to Daniel's and Eric's expertise in his area, could his advice be accepted.

Nevertheless, I advise to carry out a long-term investigation in context and thereby implement the possible changes if necessary. Given the limited time span of the project, the research can't be carried out during this project which would have been preferable. Unfortunately, this requires advice on the next steps about the armrest. My advice would be to replace 1 entire row of armrests, 3 or 4 pieces, with the redesigned armrest and every month for 6 months in a row check on changes. The intensive use by passengers in the real environment will ensure sufficient findings to decide whether the advice of Daniel and Eric should be accepted fully or adjusted for the upcoming armrest replacements.

The investigation could prevent a large investment in a still not fully optimal product, likewise chosen in paragraph §9.3 Design choices by not to replace the original armrests all at the same time. Both actions could serve to reducing the risk of deterrence in KLM's management.

Validating the determined comparison aspects

With the new armrest being produced in the eventual real specifications, could this SLS printed part be used to validate the previously determined comparison aspects with the eventual real aspects.

The price per piece has been calculated from the quotation requested for batch production of 350 pieces at an on demand printing company. This is done due to the fact these companies are charging fixed start-up, model checking and labor costs etc. for each project. In case only 1 component is produced, these fixed costs become percentage wise unnecessarily high as a result of not being able to spread them over to multiple products which will normally happen. The reason for the number of 350 parts is because this corresponds to an entire replacement of 1 aircraft. The lead time has also been calculated in the same way. This results in the following outcomes.

Zodiac seat armrest	**Original part**	**Final CAD model determinations**	**Final SLS armrest print**
Price	€186,90	€134,57	€ 116,94*
Leadtime	83 days	2 days	2 days
Weight	0,186 kg	0,119 kg	0,077 kg
Assembly	6 parts	5 parts	5 parts

Figure 68. Comparison table between original armrest, determined aspects of CAD model and the final printed armrest.

Zodiac seat armrest	**Original part**	**Final SLS armrest print**	**Final %**
Price	€186,90	€ 116,94*	-37,43
Leadtime	83 days	2 days	-97,59
Weight	0,186 kg	0,077 kg	-58,60
Assembly	6 parts	5 parts	-16,67

Figure 69. Comparison table between original armrest and final printed SLS armrest.

The provided price by Materialise for a batch of 350 pieces is the piece without certification. According to Daniel Hoogstraate, is it impossible to calculate this price in advance and only possible when the part actually enters the certification route. Which means that the given price per piece cannot be applied for a certified piece. However, the total price would stay under the set price of €165 in the requirements.

The delivery time including post process per piece for a quote of 350 parts is difficult to determine. For this reason, the 2-day assumption can be retained.

Finally, the weight of the part turned out much better than was previously determined. In case all current armrest will be replaced on the 777 and 787 fleet by the final seat armrest redesign, will result in 1055 kg weight reduction in the complete fleet of KLM. Which results in a potential fuel cost reduction of $4.665.000 on an annual base (Revees P., 2012).

9.9 Will it succeed?

After all the previous steps in design, test and maturation in the process, we have now fully completed the development of the new part and printability has been proven. However, this does not mean that the part is ready. It is now especially important that the developed component actually meets previously set requirements and a statement is made whether this part has a chance of obtaining a certification. This certification should declare the part being airworthy and therefore authorized to fly.

First of all, we know that the airplane seat is an (E)TSO product. Let's remember what this means. A European Technical Standard Order (ETSO) product is certified in both design and production. Normally are products certified on the level of installation on an aircraft. Because (E)TSO parts are theoretically installable in any aircraft with its special status, they don't carry inherent installation eligibility. ([FAA TSO & TSOA Explained], 2018).

To be able to make a substantiated statement, 7 experts actively on this topic were consulted. All have been shown the list of requirements and has the issue whether or not having a chance of success at KLM and obtaining certification for this redesign has been asked. The conversations and discussions with the experts led to the following interesting findings and statements.

> During the certification procedure of the tulip-shaped soap bottle holder is EASA contacted for a review. EASA commented on the request that in the case of replacing a non-critical cabin part, the following 2 issues are the most important valid for the new developed part. First, in case the new part will be damaged or broken, the part must not have sharp edges with which passengers can hurt themselves (ref CS.601). Second, the new part as a whole must be proven it meets the flammability requirements (ref CS25-583). Both criteria were easily achieved with the tulip-shaped soap bottle holder. The results from these test could be used for the armrest as well.
>
> **Peter Dol**
> head of airworthiness @ KLM

> Normally, in case of modifying an (E)TSO product should the OEM of the product must be informed and asked for permission. However did EASA make an exception to this. (E)TSO products can be modified without permission but only at airplane level. This will make the product lose its POOL part functionality. Furthermore, a sticker must be affixed to a specific area of the seat indicating the modification. This is mandatory for the traceability of changes.
>
> **Kees Jongbloed**
> cabin engineer lead team seats @ KLM

> The ETSO criteria apply to the entire seat, with all its components. Whenever the manual specifically about the ETSO criteria valid on the seat, in this case ETSO-C127B criteria, contains nothing specifically about the armrest, it means that the armrest can be seen as an (indirect) exception. This allows KLM to carry out the armrest modification with its DOA certificate on airplane level. However, this still means that the complete seat will lose its (E)TSO certificate and hence its POOL part functionality.
>
> **Jan van de Maat**
> certification manager @ KLM

> When the ETSO criteria manual about the seat is investigated, we can't find any specific information about the armrest. Herewith we can assume that the armrest has an exception. The chance of success is very high for this redesigned armrest to be certified. However, in this case of losing the ETSO for the seats should asked for permission from the operator KLM. Looking back to the past, we can see several examples where similar situations which results in losing the ETSO certificate on seats have been carried out by KLM.
>
> **Rik Steenkist**
> manager cabin engineering @ KLM

> Products are only (E)TSO certified on the parts which are critical for the function and execute the real work. In the case of the armrest, the metal construction in the armrest is covered by this certification and is the redesigned part just a cover. For this reason, Delta itself also makes certified modifications to these cover parts.
>
> **Geoff Pettis**
> manager cabin engineering @ Delta

> The material PA2241FR is certified for the use in the aircraft cabin, this is idem the same material used for the already 3D printed and certified tulip-shaped soap bottle holder of KLM. This part is resistant to KLM cleaning chemicals and watertight, just by having a polished finish by tumbling and color dying. Due to the dye being sucked in by ±0.5 mm the part would this protect from salty water and UV. However, should these steps be tested and adjusted by trial and error.
>
> **Daniel Hoogstraate**
> account manager for the Netherlands @ Materialise

> Products printed with SLS are of themselves waterthight. However, this material they do absorb moisture. The standard absorbent content is 2% generally for SLS printed parts. When the part is color dyed, this content is reduced to 0.1% but still means that the part would not water repellent. Additionally, when the part subsequently undergoes another post-process called shot peening it certainly can be accepted as water repellent. Shot peening also ensures that the surface becomes smoother, which facilitates cleaning. This would in all probability decrease the chance of the part getting dirty from the combination of sweat and skin flakes.
>
> **Eric van Es**
> sales engineer @ Parts on Demand

We can conclude from the discussions with the experts in the field that the most important thing is that the operator (KLM) accepts the new part and thus the expiry of the ETSO certificate. We know that this has happened before for seats, which generates sufficient confidence. Furthermore, the component must be proven for flammability and the moment of breaking will have sharp edges. This will most likely be easily proven because the armrest will be produced with the same technology and material as the tulip-shaped soap bottle holder. There is even the possibility that the results from the bottle holder can be reused without a new test for the armrest. All in all, from the results together prove to meet previously set requirements and provide enough confidence to conclude that the new armrest will get certified (eventually) and thus will succeed.

9.10 Conclusion

The choices made the during optimization process of the final model for the Zodiac armrest are fairly conservative. The limited time reserved for the project ensured to choose for the safe option. Without a doubt, the component is developed for AM. But the advantages AM offers in terms of production possibilities are not optimally exploited. From this, it can be concluded that the part can be optimized even further than the current state of the redesign.

Although, the current state of the redesign is the armrest further optimized compared to the state in the concept phase. This final optimization has therefore a larger influence on the reduction of the weight and purchase price of the armrest when compared to the original part.

Furthermore, the material and specific AM process have been selected for the final armrest. This has become SLS printing with PA2241FR. Which has been used in the new established FEM analysis. The further optimized final armrest redesign has successfully passed the even increased maximum use test. In this scenario is person weighing 150 kg sitting on the armrest. This means that the previously used force for the FEM analysis is increased from 710N to 1471N.

With the final redesigned armrest being produced in the eventual real specifications, could this SLS printed part be used to validate the previously determined comparison aspects with the eventual real aspects. This resulted in the following table.

Zodiac seat armrest	**Original part**	**Final CAD model determinations**	**Final SLS armrest print**
Price	€186,90	€134,57	€ 116,94
Leadtime	83 days	2 days	2 days
Weight	0,186 kg	0,119 kg	0,077 kg
Assembly	6 parts	5 parts	5 parts

Figure 70. Comparison table between original armrest, determined aspects of CAD model and the final printed armrest.

We can see a much better result than was previously determined with the CAD model and formulas. This shows that these are not accurate enough, but operate more to be quick and dirty. In the end, it is less interesting because the final results of the real aspects are not above the determined numbers. However, the provided price by Materialise is the piece without a certification yet. However, the total price would stay under the set price of €165 in the requirements. Besides, the weight of the part turned out much better. In case all current armrest will be replaced on the 777 and 787 fleets, will result into a potential fuel cost reduction of $4.665.000 on an annual base (Revees P., 2012).

We can conclude from the conversations and discussions held with 7 experts from the field of 3D printing, certification and engineering in the aviation. That the results together prove the armrest meet previously set requirements and provide enough confidence to conclude that the new armrest will get certified and thus succeeded. The most important thing is that the operator (KLM) accepts the new part and expiry of the ETSO certificate. And the component must be proven for flammability and the moment of breaking will have sharp edges. We know that this has happened before, which generates sufficient confidence.

All in all, the results from the discussions held with 7 experts together with the real comparison aspects of the SLS printed part shows that the project has led to an amazing and successful result.

10. Thesis Conclusion

At this point, we reached the end of the project where the implementing of 3D printers to produce airworthy aircraft cabin parts is researched. The information presented in the project is used to explain the results and their implication on the main research question for the overall conclusion of this thesis research.

The main research question of this project is: What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production and in what way can suitable parts be selected and redesigned?

This main question actually exists out of three smaller parts:
1. What possibilities does Additive Manufacturing (AM) offer in airworthy aircraft part production?
2. In what way can suitable parts be selected for airworthy AM parts?
3. In what way can suitable parts be redesigned for airworthy AM parts?

The complete thesis process is the answer on the main research question.

The various studies done through the entire thesis have led to the collection of knowledge on which choices in the process are based. Experts from the field were consulted throughout the entire process to validate or strengthen the choices made. Various methods have been applied and have resulted in successful outcomes. A long list of suitable components has been prepared in 3 different ways. Together with the standard criteria composed that suitable components must meet and these 3 ways of finding components are constructed for the reuse by KLM.

New methods, formulas and routes have been created and can be standardized for the viability of the process for the future of KLM with the implementation of AM. A very comprehensive and objective criteria list has been drawn up for the trade-off table with which selected parts can be easily and quickly filtered for their provided potential size.

The determination of comparison aspects are constructed for the price, delivery time, weight and number of parts with which a redesign can be compared with the original part without having to be produced. A test for printability and the steps in strength testing of a redesign have been carried out in detail and form an important basis for the process.

The entire thesis process has led to the selection and final development of the Zodiac seat armrest. This component was initially chosen for the lead time problem with which the part had to contend and possibly could be remedied with AM. The main problem is well solved, the lead time has been reduced from 83 days to just 2 days. Likewise, are other aspects of the component also been improved. The purchase price is reduced by 37%, from € 186,90 to € 116,94. While the weight is reduced by 58%, from 0,186 kg to 0,077 kg. This weight reduction has consequences for annual fuel consumption. When all 14.262 armrests will be replaced with the redesign, this will lead to $4.665.000 in fuel savings on an annual basis (Revees P., 2012).

After all the previous steps in design, test and maturation in the development process of the seat armrest, should the part be investigated whether it could get certified to fly. The conversations and discussions held with 7 experts from the field of 3D printing, certification and engineering in the aviation provide enough confidence to conclude that the new armrest will get certified and thus succeeded. The most important thing is that the operator (KLM) accepts the new part and expiry of the ETSO certificate. And the component must be proven for flammability and the moment of breaking will have sharp edges. We know that this has happened before, which generates sufficient confidence.

All in all, it can be concluded that the complete project process has led to successful results and sufficient answers to the main research question.

11. Recommendations

The project is of course not yet fully completed. For this reason I want to express my recommendations for the continuation of this process and the future of AM in aviation.

1. Long-term research must be done on the comfort of the new armrest in use. The current part has a rubber-like top layer. The printed redesign will only consist of hard plastic. We do know, however, that arm rests currently exist and are being used that also only consist of hard plastic. Nevertheless, the comfort test is recommended.

2. In addition, it is also recommended to test the part with the post-process prepared in this project for wear, changes and becoming dirty due to use. And in this way, if necessary, look for alternative post-processes.

3. Furthermore, a general cabin test must be performed by central engineering and an Engineering Approval must be drawn up for the component.

4. The current design of the redesign is done very conservatively for AM, due to the limited time of the project. It is advised to accommodate more explorative design for AM with thinner wall thickness and this with more complex honeycomb structures.

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Appendix A

The total of 47 article relevant to the topic of research are found. All of them are clustered into categories. Each of the abstract and introduction of these articles are read. When these contained 3 out of 5 the following AIQS, the article was completely read and analyzed:

AIQS1: Benefits AM offer aviation
AIQS2: Differences and types of AM techniques
AIQS3: Criteria to asses different AM techniques on usability in aviation
AIQS4: Future potential, gaps and needs of AM in aviation
AIQS5: Current use of AM in aviation

Code	Title	Author
AU1	Additive manufacturing for lightweight aviation parts	Gürbuz, C.
AU2	Additive manufacturing of titanium alloy for aircraft components	Uhlmann, E., Kersting, R., Klein, T.B., Cruz, M.F., Borille, A.V.
AU3	High performance metal additive manufacturing technology applied in aviation field	Lin, X., Huang, W.
AU4	Additively manufactured components for structural applications in aircraft interior – Two case studies	Oltmann, J., Seemann, R., Spallek, J., Krause, D.
AU5	The Application of Additive Manufacturing to the 2018 SAE Aero Design Challenge	Blake, N.D., Waters, C., Esau, S., Kizito, J.
AU6	Aircraft structure technology of additive manufacturing	Wang, X., Cui, H., Xu, P., Bi, S.
AU7	Integrating additive manufacturing and repair strategies of aeroengine components in the computational multidisciplinary engineering design process	Handawi, K.A., Lawand, L., Andersson, P., Isaksson, O., Kokkolaras, M.
AU8	Three-dimensional printing of "green" fuels for low-cost small spacecraft propulsion systems	Whitmore, S.A.
AU9	Additive Design and Manufacturing of Jet Engine Parts	Han, P.
AU10	Airbus approach for F&DT stress justification of Additive Manufacturing parts	Mardaras, J., Emile, P., Santgerma, A.
AU11	3D printing resilient thermoplastic aircraft ducting	Koehler, F.B., Benedict, M., Price, P., Holshouser, C.
AU12	Aerospace applications of laser additive manufacturing	R. Liu, Z. Wang, T. Sparks, F. Liou, J. Newkirk
AU13	Additive manufacturing for Aerospace	G.J. Schiller
AU14	Aviation finds that extra dimension: 3D manufacturing at 2015 Paris Air Show	Brookes, K.J.A.

AU15	Three-dimensional scanning system design and its application in a small aircraft shaped pieces precision measurement and the application of damage repair	Fa-jun, D.
AU16	3D printing technology and the latest application in the aviation area	Zhou, F., Lin, G.M., Zhang, W.G., Shang, M.
AU17	Application of additive technologies in the production of aircraft engine parts	A.V. Agapovichev, A.V. Balaykin, V.G. Smelov, A.V. Agapovichev

Code	AIQS1	AIQS2	AIQS3	AIQS4	AIQS5	Completely read and analyze?
AU1	YES	NO	NO	NO	YES	NO
AU2	YES	NO	YES	NO	YES	YES
AU3	NO	YES	NO	NO	YES	NO
AU4	YES	NO	NO	NO	YES	NO
AU5	YES	NO	NO	NO	NO	NO
AU6	YES	NO	NO	NO	NO	NO
AU7	YES	NO	NO	YES	NO	NO
AU8	YES	NO	NO	NO	NO	NO
AU9	YES	NO	NO	YES	YES	YES
AU10	YES	NO	YES	YES	NO	YES
AU11	YES	NO	NO	YES	YES	YES *(but no access to complete paper)*
AU12	YES	YES	YES	YES	YES	YES
AU13	YES	YES	NO	YES	YES	YES
AU14	NO	YES	NO	NO	YES	NO
AU15	NO	NO	NO	NO	NO	NO
AU16	YES	YES	NO	NO	YES	YES
AU17	YES	NO	NO	NO	YES	NO

Code	Title	Author
RS1	3D printing and its effect on outsourcing: A study of the Indian aircraft industry	Manda, V.R., Kampurath, V., Msrk, C.
RS2	Exploration of Additive Manufacturing for HTS Cable Components for Electric Aircrafts	Cheetham, P., Nowell, R., Al-Taie, A., Graber, L., Pamidi, S.
RS3	Numeric simulation of aircraft engine parts additive manufacturing process	Maksimov, P., Smetannlkov, O., Dubrovskaya, A., Dongauzer, K., Bushuev, L.
RS4	Energy savings through additive manufacturing: an analysis of selective laser sintering for automotive and aircraft	Hettesheimer, T., Hirzel, S., Roß, H.B.

	components	
RS5	Demonstration and characterization of novel additive manufacturing approaches for aerospace RF applications	Waller, D., French, D., Valentin-Hernandez, E.
RS6	Analysis of an Additive Manufacturing Process for an Unmanned Aerial Vehicle	Dalewski, R., Gumowski, K., Barczak, T., Godek, J.
RS7	Evaluating Eco-Efficiency of 3D Printing in the Aeronautic Industry	Mami, F., Revéret, J.-P., Fallaha, S., Margni, M.
RS8	Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components	Huang, R., Riddle, M., Graziano, D., (...), Cresko, J., Masanet, E.
RS9	Additive manufacturing in aerospace: Examples and research outlook	B. Lyons
RS10	3D printing adds up for aviation	Newell, J.
RS11	A comparison between 3D Printing and Milling process for a Spar Cap Fitting (wing-fuselage) of UAV Aircraft	C.G. Ferro, A. Mazza, D. Belmonte, C. Seclì, P. Maggiore

Code	**AIQS1**	**AIQS2**	**AIQS3**	**AIQS4**	**AIQS5**	**Completely read and analyze?**
RS1	YES	YES	NO	YES	YES	YES
RS2	NO	NO	NO	YES	NO	NO
RS3	NO	NO	NO	NO	NO	NO
RS4	YES	NO	NO	NO	YES	NO
RS5	YES	NO	NO	YES	NO	NO
RS6	NO	YES	YES	NO	NO	NO
RS7	YES	NO	NO	YES	NO	NO
RS8	YES	YES	NO	YES	NO	YES
RS9	YES	NO	YES	YES	YES	YES
RS10	YES	NO	NO	NO	NO	NO
RS11	YES	NO	NO	NO	YES	NO

Code	**Title**	**Author**
PS1	Material-design-process selection methodology for aircraft structural components: application to additive vs subtractive manufacturing processes	Hodonou, C., Balazinski, M., Brochu, M., Mascle, C.
PS2	Design and evaluation of an additively manufactured aircraft heat exchanger	Saltzman, D., Bichnevicius, M., Lynch, S., (...), Dickman, C., Martukanitz, R.
PS3	Development, test, and evaluation of additively manufactured flight critical aircraft components	Kasprzak, J.M., Lass, A.B., Miller, C.E.

PS4	Process monitoring of additive manufacturing by using optical tomography	G. Zenzinger, J. Bamberg, A. Ladewig, T. Hess, B. Henkel, W. Satzger
PS5	3D printed parts for quick turnaround aircraft projects and legacy issues	Rehmanjan, U.H.

Code	AIQS1	AIQS2	AIQS3	AIQS4	AIQS5	Completely read and analyze?
PS1	YES	NO	YES	YES	NO	YES
PS2	YES	NO	NO	YES	NO	NO
PS3	NO	NO	NO	YES	YES	NO
PS4	NO	NO	NO	NO	NO	NO
PS5	YES	NO	YES	YES	YES	YES *(plastic cabin part)*

Code	Title	Author
RM1	Metal additive manufacturing in aircraft: Current applications, opportunities and challenges	Zhang, X., Liang, E.
RM2	Additive manufacturing's impact and future in the aviation industry	Wagner, S.M., Walton, R.O.
RM3	The present and future of additive manufacturing in the aerospace sector: A review of important aspects	A. Uriondo, M. Esperon-Miguez, S. Perinpanayagam
RM4	Current trends of additive manufacturing in the aerospace industry	L.J. Kumar, C.G.K. Nair
RM5	Additive manufacturing for aerospace flight applications	A. A. Shapiro, J. P. Borgonia, Q. N. Chen, R. P. Dillon, B. McEnerney, R. Polit-Casillas and L. Soloway
RM6	AM and aerospace: an ideal combination	L. Nickels
RM7	3D printing in aerospace and its long-term sustainability	S.C. Joshi, A.A. Sheikh
RM8	Additive manufacturing trends in aerospace	J. Hiemenz

Code	AIQS1	AIQS2	AIQS3	AIQS4	AIQS5	Completely read and analyze?
RM1	YES	YES	NO	YES	YES	YES
RM2	NO	NO	NO	YES	YES	NO
RM3	YES	YES	YES	YES	NO	YES
RM4	YES	YES	NO	NO	YES	YES
RM5	YES	YES	YES	YES	NO	YES
RM6	YES	NO	NO	NO	YES	NO
RM7	YES	YES	NO	YES	YES	YES
RM8	YES	NO	NO	NO	YES	NO

Code	Title	Author
SC1	An additive manufacturing spare part inventory model for an aviation use case	Togwe, T., Eveleigh, T.J., Tanju, B.
SC2	Impact of additive manufacturing on aircraft supply chain performance: A system dynamics approach	Wang, X., Cui, H., Xu, P., Bi, S.
SC3	An aerospace business case on additive layer manufacturing technologies in aerospace and defense supply chain	Kemsaram, N., Maley, K.K.
SC4	Additive manufacturing in the spare parts supply chain: hub configuration and technology maturity	H. Khajavi, S., Holmström, J., Partanen, J.
SC5	The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis	P. Liu, S.H. Huang, A. Mokasdar, H. Zhou, L. Hou
SC6	How additive manufacturing improves product lifecycle management and supply chain management in the aviation sector?	Romero, A., Vieira, D.R.

Code	AIQS1	AIQS2	AIQS3	AIQS4	AIQS5	Completely read and analyze?
SC1	YES	NO	NO	YES	NO	NO
SC2	YES	NO	NO	YES	NO	NO
SC3	YES	NO	NO	NO	NO	NO
SC4	YES	YES	NO	NO	NO	NO
SC5	YES	NO	NO	YES	NO	NO
SC6	NO	NO	NO	YES	NO	NO

Appendix B

Appendix B displays the important notes about the 5 AIQs each fully read article contained.

Code / Title / Author / Year	RS1 / 3D printing and its effect on outsourcing: A study of the Indian aircraft industry / Manda, V.R., Kampurath, V., Msrk, C. / 2018
AIQ1	Less waste reduction during production / less scrap material Timely production (time to market) Lightweight Small cycle time Complex geometry production Mass customization Improve strength-to-weight ratio No tooling needed for production with AM Integrate assemblies to 1 part Reduce assembly time and costs In-process manufacturing quality assurance Economical single quantity/ one-off production Local manufacturing Replace expensive spare part inventory Freedom in design
AIQ2	SLM is one of the leading methods of 3d printing for aviation
AIQ3	-
AIQ4	Reduce AM costs of current raw materials and machinery Increase the slow speed of AM production for large-scale-production Increase en ensure quality of results of printed parts Limited and small production size Increase choice for materials Increase precision in printing
AIQ5	Production of tools for ease of assembly or helps accelerating production Fan blade edge (Metal) Titanium nacelle hinge bracket (Metal)
Extra note	1. Outsourcing AM allows airline management to focus attention on the core business of attracting and satisfying passengers , while at the same time it releases capital and reduces the cost of support services. (Ghobrial, 2005) 2. Engineers traditionally could design anything by considering the possibilities and limitations of various machining process, which compromised designs on optimization (Dimitrov et al. 2006)

Code / Title / Author / Year	RS8 / Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components / Huang, R., Riddle, M., Graziano, D., Warren J., Das S., Nimbalkar S., Cresko, J., Masanet, E. / 2016
AIQ1	Improve material efficiency Reduce life-cycle impact

	Greater engineering functionality Lightweight design Cost effective design Reduce "cradle-to-gate" environmental footprint No tools needed Energy savings due to reduced material Reduced fuel usage lighter weight
AIQ2	SLM (Selective Laser Melting) DMLS (Direct Metal Laser Sintering) EBM (Electron Beam Melting)
AIQ3	-
AIQ4	Issues with geometric repeatability, residual stresses and high surface roughness also present barriers in applications that require high dimensional precision, surface quality and fatigue resistance
AIQ5	Flight deck monitor arms (Plastic) Seat buckles (Metal) Various hinges and brackets (Metal)
Extra note	1. Aviation is currently the second largest consumer transport fuels globally (IEA, 2010) 2. Lighter weight aircraft are a critical strategy for reducing societal energy use and GHG emissions (Immarigeon et al., 1995) 3. Each 100 kg reduction in the weight of an aircraft is estimated to save 0.45 – 0.67 TJ of fuel per year (Lufthansa Group, 2011; Helms and Lambrecht, 2006; American Airlines, 2007)

Code / Title / Author / Year	RS9 / Additive manufacturing in aerospace: Examples and research outlook / B. Lyons / 2012
AIQ1	No tooling needed during production Reduced costs Reduced time to market Complex design Lightweight Nonporous design Thin walled part production Integrated systems production Life-cycle production flexibility
AIQ2	SLS
AIQ3	Consistency in material and production process properties Weight of part is often deciding factor in choosing material and process Material performances: strengths, fatigue resistance, creep resistance, use temperature, - survival temperature, flammability, smoke release, toxicity, chemical sensitivity, - radiation sensitivity, appearance, process suitability and cost

	Build with repeatable mechanical properties, even temp. distribution across build area
AIQ4	Need of flame-retardant polyamides Software tools for generation and predictive analysis of complex structures for AM
AIQ5	AM for fast development of metal castings and long-fiber-reinforced components
Extra note	-

Code / Title / Author / Year	PS1 / Material-design-process selection methodology for aircraft structural components: application to additive vs subtractive manufacturing processes / Hodonou, C., Balazinski, M., Brochu, M., Mascle, C. / 2019
AIQ1	Topology optimization design Complex shapes Lightweight design
AIQ2	-
AIQ3	First select needed material to select machine. Machines will ranked by AHP using criteria: - Material variety - Surface quality - Post-finishing operations - Precision - Resistance to impact - Flexural strength - Prototype costs - Post cure
AIQ4	Research of integrating manufacturing process during material-design-process selection
AIQ5	-
Extra note	1. Material waste resulting from machining aircraft components cause economic and environmental problems by Babu et al. (2016) 2. Although SLM components is 7 times more expensive than machined part, it remains competitive considering functional and economic criteria Hodonou et al. (2019)

Code / Title / Author / Year	PS5 / 3D printed parts for quick turnaround aircraft projects and legacy issues / Rehmanjan, U.H. / 2012
AIQ1	Ability of update part design number of times fast, easy and cheap Fast product to market No tooling needed Multiple different parts produced at same time in 1 run Reduce stock of spare parts
AIQ2	-
AIQ3	Aircraft interiors applications is compliance with flammability requirements (FAR 25.853)
AIQ4	Study strength characteristics of plastic 3D printed parts Need for software which can predict how printed part will behave in various conditions Develop "in process quality control" to ensure process quality consistency Develop regulations to manufacture parts everywhere in world and be certified - when its according to material and presets it requires
AIQ5	AM is used for aircraft cabin modifications - New part designs

	- Support parts / system legacy issues Blanking plate armrest instead of PCU Airbus produces 1000+ AM parts for A350XWB
Extra note	1. The whole aircraft cabin needs at least 1 and often 2 upgrades during useful life with negative reviews affecting the aircraft seats most. (Rehmanjan, U.H., 2012) 2. Non critical parts needs to be able to certified with just compatibility to flammability requirements, this approach would save the aviation industry significantly. (Rehmanjan, U.H., 2012)

Code / Title / Author / Year	AU2 / Additive manufacturing of titanium alloy for aircraft components / Uhlmann, E., Kersting, R., Klein, T.B., Cruz, M.F., Borille, A.V. / 2015
AIQ1	Topology optimized component designs Resultant material properties Complex parts Lightweight parts (decrease fuel consumption and emission levels) Integrate functions No multi-channel processing
AIQ2	SLM (Selective Laser Melting) - Titanium (TiAl6V4)
AIQ3	Part density properties Part micro hardness properties Part Surface roughness properties Part tensile and fatigue properties Layer thickness effects High porosity issues
AIQ4	Develop material qualification parameters Develop optimized AM process parameters Develop mechanical properties for AM Develop finishing technologies for AM parts Develop and define quality control
AIQ5	Light-weight engine components (Metal) Light-weight structural aircraft parts (Metal) Structural aerospace applications (Metal)
Extra note	-

Code / Title / Author / Year	AU9 / Additive Design and Manufacturing of Jet Engine Parts / Han, P. / 2017
AIQ1	Gradient materials Micro-structures Part consistency Complex and sophisticated parts (in particular internal shapes) Reduce costs Efficiency in material use Lightweight parts No multi-channel processing Integrate assemblies Optimize design making it efficient and reliable Reduce time to market of parts
AIQ2	-
AIQ3	-
AIQ4	Change in designing thinking of parts by engineers Develop methods, tools, criteria and standards to analyze AM part microstructures Develop standard procedure bridging material props. with structure build

	from this
AIQ5	Turbo fan jet engine (Metal) Fuel nozzle jet engine (Metal) High-pressure turbine nozzle jet engine (Metal) High-pressure turbine blade (Metal)
Extra note	AM allows system design directly according to end-user requirements AM allows no need to compromise on design due to manufacturing infeasibility

Code / Title / Author / Year	AU10 / Airbus approach for F&DT stress justification of Additive Manufacturing parts / Mardaras, J., Emile, P., Santgerma, A. / 2017
AIQ1	Geometry optimized parts Topology optimized parts Complex parts Efficient use of material Simple and quick part production Reduced production costs
AIQ2	-
AIQ3	Airbus certification standards for AM parts in - Material properties - Fabrication methods - Material design values - Damage tolerance and fatigue evaluation of structures - Knowledge in defects and part shapes
AIQ4	Development need of surface improvement techniques Development need of refined damage tolerance approach
AIQ5	Currently are standard part design kept and directly produced with AM
Extra note	-

Code / Title / Author / Year	AU12 / Aerospace applications of laser additive manufacturing / R. Liu, Z. Wang, T. Sparks, F. Liou, J. Newkirk / 2017
AIQ1	Complex geometry Integrating functions to parts High buy-to-fly ratio, sustainable use of materials Economic for small production runs Mass customization (tailor to own needs) No need for tooling for AM Quick turnaround times Reduced inventory of parts Lightweight parts, improved fuel and emissions Integrate assemblies to 1 part Fast lead time

	Topology optimization
AIQ2	AM can classified by energy source, feedstock stat or method of feed material DED (Direct Energy Deposition) - Melting materials as it being deposited - Metal powders or wires - Focused energy source (laser, electron beam or arc) which locally melt feedstock Hybrid AM of laser and milling is 10x faster than powder bed process PBF (Powder Bed Fusion) - Spreads powder layer and selectively melt powder with focused energy source - Accuracy of +-0.05mm
AIQ3	-
AIQ4	Need for design guidelines for aerospace component for AM Develop new CAD system which overcomes the limitations of parametric of AM Need for database for standards material characteristics about properties Develop process control to predictable, repeatable an consistent uniform fabrication - in process monitoring Develop software predicting material properties, surface roughness and fatigue
AIQ5	AM for rapid prototyping, rapid tooling, direct part manufacturing and repair Forward fuselage area of F-18 with SLS Turbine housing of stainless steel (Metal) Helicopter engine combustion chamber (Metal) Metal fuel nozzle of GE (Metal) Bracket connector forA350 XWB (Metal) A320 door hinge cores and casting Examples: gear cases and covers, fuel tanks, transmission housings, engine part and structural hinges Piper tooling for hydroforming part (Tooling) Bell helicopter ploycarboante wiring conduits (Plastic - FDM) NASA developed a gas turbine (Plastic - FDM) Compressor inlet guide vanes and acoustic liners (Plastic - FDM) High pressure CMC turbine nozzle segments (Plastic - Binderjet) Bearing housing from a gas turbine engine (Repair) High pressure compressor front drums Rolls-Royce BR715 engines (Repair)
Extra note	1. The hybrid process provides greater build capabilities in accuracy and surface quality for freeform fabrication, which was successfully applied to build and repair functional metallic part (Xue and Islam, 2006)

Code / Title /	AU13 / Additive manufacturing for Aerospace / G.J. Schiller / 2015

Author / Year	
AIQ1	Designer are not constrained by the ability to manufacture a component Low cost production Produce singular units Produce complex parts Integrate assemblies, reduce part count and connections points - Improve reliability Tailor to own needs Integrate functions to increase part functionality Minimizing weight, cuts fuel consumption Topology optimization No tooling needed Reduced assembly labor Reduced costs for tooling production - Faster turn times - Tailor to own needs (Ergonomic needs) - Faster labor with better fit tooling Local manufacturing
AIQ2	Bed systems - Powder or liquid materials - DMLS and SLS - Limitations are smaller size of print bed Fed systems - Materials are fed into head in powder or filament form - LENS and FDM - Limitations are capability of finished products Hybrid systems - Combine of bed or fed systems together with milling machine capabilities - Best finished product after production on single machine
AIQ3	Material consistency and quality In-situ process monitoring (ex. sensor monitoring of melt pool for metal AM)
AIQ4	More need of capable alloys for AM Material need of consistency and quality Industry standards are lacking for AM use for aviation - Factors of safety for design are determined on a case-by-case basis - Methods for test and inspection are missing More materials for AM suitable for aviation Build size needs to be increased of AM Design and analysis tools (software) for AM is needed
AIQ5	Designers use AM to redesign existing applications GE fuel nozzle of jet engine (Metal) Lockheed Martin connection brackets (Metal) Environmental control system ducts (Plastic) Protective covers (Plastic) Cockpit parts (Plastic) NASA Marshall engine propulsion injector plate (Metal)

	Liquid oxygen flange for United Launch Alliance Launch Vehicles (Metal) Environmental control system ducts for United Launch Alliance Launch Vehicles (Plastic)
Extra note	1. "If you can design, AM can produce it" (Schiller, G.J., 2015) 2. Reduced weight with AM cut fuel consumption and thus reduces long term costs (Smarttech, 2014) 3. Reliability and durability is driven up by integrating assemblies due to consolidating what was 20 parts ton 1 (General Electric, 2013) 4. Reduces buy-to-fly ratio with AM, which is amount of material being used to produce a part, ensure cost reduction on component level. (Schiller, G.J., 2015) Current ducts are composed primarly of multiple fiberglass pieces with metal attach fittings 5. Activity aids sharing of data and developing much needed industry standards. (Schiller, G.J., 2015)

Code / Title / Author / Year	AU16 / 3D printing technology and the latest application in the aviation area / Zhou, F., Lin, G.M., Zhang, W.G., Shang, M. / 2014
AIQ1	One machine for all Quickly and accurately production Complex shapes No traditional tools, jigs and no multi-channel processing Form freedom Reduce processing cycle (Fast time to market) Manufacturing speed Cost reduction Shorten developing cycle
AIQ2	FDM (Fused Deposition Modeling) 3DP (3Demension Printer) SLA (Stereo Lithography Apparatus) SLS (Selected Laser Sintering) - Nickel chromium alloy LOM (Laminated Object Manufacturing) EBM (Electron Beam Melting) - Titanium alloy Plasma Arc Resistance Welding
AIQ3	Increase scope of materials Improve precision of AM
AIQ4	-
AIQ5	Form validation Direct product manufacturing - Whole structure of UAV called SULSA, from wings, control surface and doors - Multiple F-35 titanium parts

	- Chinese military titanium aircraft parts Precision investment casting
Extra note	-

Code / Title / Author / Year	RM1 / Metal additive manufacturing in aircraft: Current applications, opportunities and challenges / Zhang, X., Liang, E. / 2019
AIQ1	Integrated assemblies Lightweight design Cost reduction Shorten developing period for new components Increases economical efficiency and ECO performance Customization of part (tailor for own needs)
AIQ2	Metal Additive Manufacturing - SLM (Selected Laser Melting) - WAAM (Wire-Arcing Additive Manufacturing) - EBM (Electron Beam Melting) - RPD (Rapid Plasma Deposition)
AIQ3	SAE developed standards for AM metals - AMS7000, AMS 7001, AMS 7002, AMS 7003 Stability of mechanical properties
AIQ4	Security level of AM components need to be developed Stability in mechanical properties of materials for AM needs to be developed AM certification standards Need of roadmap for non-standardized AM situations Need of new materials and AM processes Develop stability of anisotropy nature of AM which influences mechanical performances Need for conclusion on inspection methods or acceptance standards of defected parts AM process need more testing items to get certified other than tensile and fatigue, like - compress, rupture, shear, bearing, impact and creep
AIQ5	Prototyping Mass production Quick repair FAA approved structural part for B787 (Metal) FAA approved GE9X high-bypass turbofan aircraft engine fuel nozzle (Metal)
Extra note	1. RPD is believed to have better mechanical performance and less defects than other AM processes (Martina F., 2012)

Code / Title / Author / Year	RM5 / Additive manufacturing for aerospace flight applications / A. A. Shapiro, J. P. Borgonia, Q. N. Chen, R. P. Dillon, B. McEnerney, R. Polit-Casillas and L. Soloway. / 2016

AIQ1	Lightweight parts In situ (local) production Integrate assemblies In situ (local) material utilization New design opportunities Fast prototyping Tool development Resolve mismatch issues by multiple material production Highly complex parts Cost reduction Reduce manufacturing time
AIQ2	SLM (Selective Laser Melting) EBM (Electron Beam Melting) - Both powder bed methods LENS (Laser Engineered Net Shaping) - Powder supplied and melted in laser head - Can accommodate multiple materials SLS and EBM often produce parts with significant porosity
AIQ3	Material selection parameters Processing and post-processing parameters Part qualification process Source material heavily influences resulting part Source material grain size, porosity, sintering degree affects - toughness, hardness, yield strength and surface finish Print 5 sample coupons to test them instead of part on tensile, fatigue and others Tracking by powder certification, heat treatment certification and build logs Automated surface finish is ideal for repeatability
AIQ4	Development of statical process control and qualification procedures Need of detailed (open) database for accurate statical process control Determine types of test appropriate and amount of coupons Determine sensitivity of materials to process parameters for each material and machine Continue developing (metallic and ceramic) materials Develop design for AM to maximum benefit Develop machine, material, process and post-process qualifying steps
AIQ5	Rocket nozzles from gradient material of titanium to niobium (Metal) Ceramic waveguide dielectrics Embedded circuitry within structural elements Sensors and windows embedded into spacecraft structures Eurostar E3000 satellite topology optimized aluminum bracket (Metal) Lightweight optimized steel node (Metal) Antenna support for Sentnel-1 Eath-observation satellite (Metal) Several flight hardware parts for Lockheed Martin planes (Metal)
Extra note	Future lies in not simply applying AM to existing parts but design with additive in mind

Code / Title / Author / Year	RM3 / The present and future of additive manufacturing in the aerospace sector: A review of important aspects / A. Uriondo, M. Esperon-Miguez, S. Perinpanayagam / 2015
AIQ1	Low volume production Customization of parts (Tailor to own needs) Sustainable products High level of complexity of parts No tooling needed for production Economical small production batches Possibility of quick design changes Short product to market time Complex geometries Simpler supply chain Lower inventories Shorter lead times
AIQ2	EBM, SLM, WAAM, MD, FDM, LMD, Photo-polymerization, Ink-jet printing Powder bed fusion systems control powder fusion to specific regions in each layer - SLM and LMD use high power lasers MD process melt material as it being put down - EBM uses an electron beam - WAAM uses a plasma arc Comparing electron and laser beam melting - EBM can only use metals while SLM can process plastic and ceramics as well - EBM defocusing electron beam heats the powder bed before placing the next layer while SLM uses infrared heaters to maintain the temperature of the powder bed consistent during whole process - SLM crates smaller grain size - Fatigue life of SLM parts are higher than EBM SLM achieves elevated density during process with higher porosity close to surface Residual stresses are the most significant problems in MD processes Laser cladding (MD) produces the highest surface roughness
AIQ3	Accuracy of process and material properties Monitoring process variables
AIQ4	Need for industry specifications and standards for process and alloys Develop integrated process to monitor process and quality of production Need of qualification methods for produced parts Develop non-destructive techniques capable of detecting defects Need for design guidelines for AM for aviation Develop software predict microstructure characteristics, mechanical and elec. properties Need for material development for better surface finish and better fatigue props.

	Need for test methods for raw materials characteristics Standardization of testing final parts
AIQ5	Production and repair of metal aircraft parts Air-cooling ducts (Plastic)
Extra note	1. SLM, EBM, LMD and WAAM are considered the 4 most applicable for the aerospace industry , because they can produce almost fully dense components without any post-process with mechanical and electrochemical properties comparable to other traditional methods. (Uriondo A., et al. 2015) 2. Effects of fatigue life are surface defects (highest), surface roughness (high) and porosity level (low) of the part being produced. Surface roughness depends on the scan strategy, position of the part in build platform, hatch space or velocity. (Uriondo A., et al. 2015)

Code / Title / Author / Year	RM7 / 3D printing in aerospace and its long-term sustainability / S.C. Joshi, A.A. Sheikh / 2017
AIQ1	Part customization (tailor to own needs) Complex and integricate components Manufacturing time reduction Reduced material wastage Reduced costs Freedom of part design Integrate assemblies Reduced of supply chain management Recycle material used Reduced environmental impact Lightweight parts Reduced resource and energy requirements Reduced down time of aircrafts Reduced inventory Service aircraft after stop of spare part production
AIQ2	AM can classified in two classes - Physical state of the raw material - Manner in which the matter is fused Commonly applied processes in aviation are SLS, SLM, EBM and WAAM
AIQ3	Inspection for every batch, testing on tensile and flexural properties - You need to show AM high quality and repeatability of process
AIQ4	Need to improve material properties Develop safety standards for AM in aerospace Fix issues in printing patterns, porosity built-up and uneven print flow
AIQ5	Metal aircraft bracket EBM is used to repair turbine blades Bell helicopter parts (Plastic - SLS) Titanium A320 nacelle hinge bracket (Metal - SLS) In turbine blades (Metal - SLS) Copper rocker engine parts (Metal - SLM)

	Liquid-propellant rocker engines (Metal - SLM) Fuel pump (Metal - SLS) Liquid oxygen and gaseous hydrogen injectors (Metal - SLS) Support struts on the air intake door (Plastic - SLS) Protective covers for cockpit radios (Plastic - SLS) Protective guards for power take-off shafts (Plastic) Front bearing housing Rolls-Royce Trent XWB-97 engines (Metal) Support structures for cabin crew seats on A310 (Plastic - FDM)
Extra note	1. The most attractive potential is for fuel savings due to even more lighter parts manufactured through 3D printing for aerospace industry. (Gebler M., et al. 2014) 2. Every kilogram reduced in weight saves the annual fuel expenses by US$3000. (Reeves P. 2012) 3. Products obtained through WAAM are of extremely high quality and are even better than those produced by normal welding procedures. (Hibbert L. 2014) 4. FSAM process improved the mechanical properties compared to conventional methods. FSAM could be used for fabrication of stiffeners/stingers, wing spars and longerons in skin panels. (Palanivel S. et al, 2015) 5. Need to improve material properties by adding nanoparticles this can improve mechanical properties, enhance electrical and thermal conductivity, decrease sintering temperature and can have an impact on the dimensional accuracy. (Ivanova O.S. et al, 2013)

Code / Title / Author / Year	RM4 / Current trends of additive manufacturing in the aerospace industry / L.J. Kumar, C.G.K. Nair / 2017
AIQ1	High complex part Lightweight designs Reduced waste material / Maximum utilizing materials Reduced lead time Flexibility in material composition Able to process higher temperature materials Integrate assemblies into 1 part (Structural stronger and more reliable) Fast design changes Reduced time to market of components No tools required Design optimization Recycle waste materials
AIQ2	LMD, Laser Cusing, DMLS, SLS, SLM
AIQ3	-
AIQ4	-
AIQ5	AM is used prototyping, making moulds/tools , direct manufacturing and repair in aviation GE leap engine fuel nozzle (Cobalt chrome - SLS) SAFRAN guide vanes for silver-crest business jet engine (Metal)

	SAFRAN manifold for Vinci rocket engines + hydrogen turbo pump (Metal) NASA rocket injector part for J-2X engines (Metal - SLS) A350 XWB cabin bracket connector (Titanium - SLS) Rolls-Royce Trent XWB-97 engine front bearing housing (Titanium - EBM) Pratt and Whitney compressor stators + sync ring brackets for PW1500G engines (Metal) HAL high pressure rotor blades + nozzle guide vanes + combustion chamber + HPC stator stage 5 assembly + vane IGV blades + HPC stage 5 blades + Gearbox assembly (Metal) Comac C919 structural wing span (Metal - Laser Cladding Cell)
Extra note	1. The aerospace industry is demands stronger, lighter and more durable components. (Kumar L.J. et al 2017) 2. AM enables integrating assemblies into single piece manufacturing without joint, which enhances structurally strength and reliability. (Kumar L.J. et al 2017)

Code / Title / Author / Year	**Reference** / Additive manufacturing process selection based on parts' selection criteria/ Cauê G. Mançanares, Eduardo de S. Zancul, Juliana Cavalcante da Silva,Paulo A. Cauchick Miguel / 2015
AIQ1	Complex part production Small batch size Short time to market Easy part design changes
AIQ2	SLA, TDP, SLS, FDM, DMLS, CJP, MJP are all assessed on *(check paper for results)* - Variety of materials - Surface quality - Post-finish - Accuracy - Resistance to impact - Flexural strength - Prototype cost - Post cure
AIQ3	Material plays an overwhelming role in the selection of AM technique
AIQ4	Develop decision-making support system based on rationale and machine database
AIQ5	-
Extra note	1. Importance of each of the criteria the different AM techniques are assessed varies from one specific production case to another, according to the user's needs for the part (Mançanares et al, 2015)

Appendix C

Appendix C displays the exact list of KLM experts, names and function, who are interviewed.

Peter Dol – Head of Airworthiness
Taco Vingerhoed – Director Commercial Operations of E&M
Arlette van der Veer – Projectleader intergrating AM in KLM

Ian Breed – Project leader POA
Rik Steenkist – Team leader Cabin Engineering (Helps Ian in POA project)

Tolga Inan – Cabin Engineer of Central Repair Lab
Ebubekir Yildiz - Cabin Engineer of Central Repair Lab
Robber Bakker – Head of Central Repair Lab
Tim van den B urg – Intern mapping repair routes

Buddy Zuijderduijn – Head of shop R6 (= Cabin parts Repair)

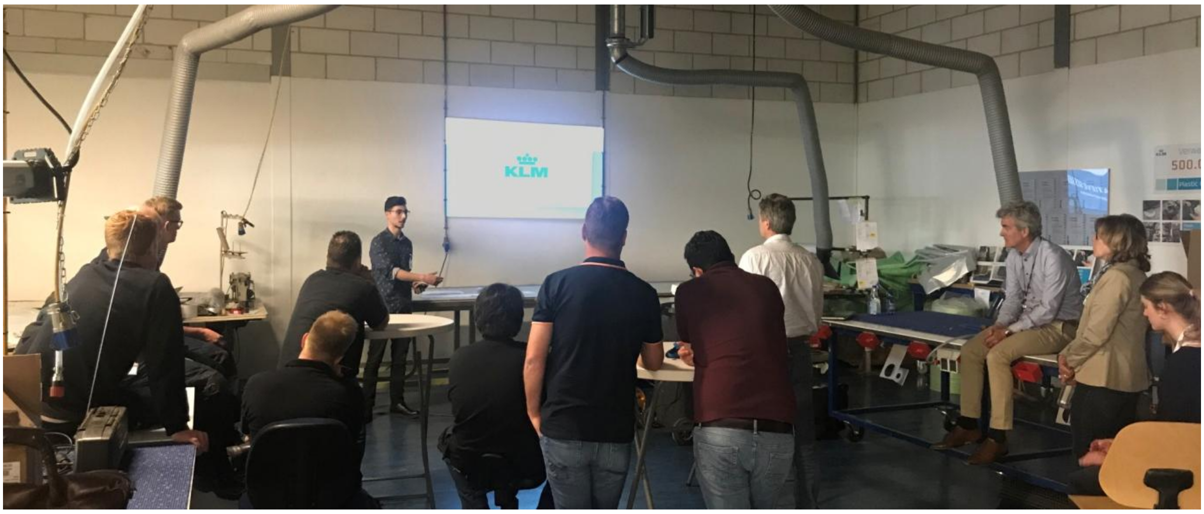
Armand Keet – Head of Checkpoint Charlie (Department of Unservicable parts)

Ferry Domingues – Data analist SAP (plant 3000)
Björn Meijer – Data analist SAP (plant 2000)

Appendix D

Appendix D explains the exectued activities during the project to construct the suitable parts list for AM.

Workshop I



The main goal of the workshop was to end up with a list of potential parts which would help reduce maintenance cost at KLM E&M. Additional purpose was to share knowledge about 3D printing for aviation in a centralized manner. Unfortunately, that does not happen at the moment. There are several departments throughout E&M that are doing their own research on this technique and possibilities for their department specific. All keep this information to themselves, so that everyone tries to reinvent the wheel. This is unnecessary competition makes innovation more difficult, if not discouraged.

The workshop was done together with 12 participants from the direct field of E&M.

1. Cabin repair shop - Daily contact with parts
    a. Buddy Zuijderduijn (Shop leader cabin repair)
    b. Levi Veugelers (Cabin repair engineer)
    c. Joey Middelbos (Cabin repair engineer)
    d. Mathijs de Vries (Cabin repair engineer)
    e. Fons Jansen (Cabin repair engineer)
    f. Eric van Slooten (Cabin repair engineer)

2. Cabin engineering - Medium contact with parts
    a. Rik Steenkist (Manager cabin engineering)
    b. Ebu Yildiz (Cabin engineer of central repair lab)

3. U/S depot - Daily contact with parts
    a. Armand Keet (Head of unserviceable parts depot)

4. Organizational function – No contact with parts

a. Taco Vingerhoed (Director commercial operations of E&M)
b. Wilma van den Oever (Manager of change office at E&M)
c. Arlette van der Veer (Innovation manager at E&M)

To get the group looser, I briefly introduced myself, my job and experience but also told something personal to break the ice. Then the program was briefly discussed, after which a short introduction round took place so that everyone would get to know each other and to break through the awkwardness for the next steps of brainstorming. After being loosened is the workshop started with a presentation by myself.

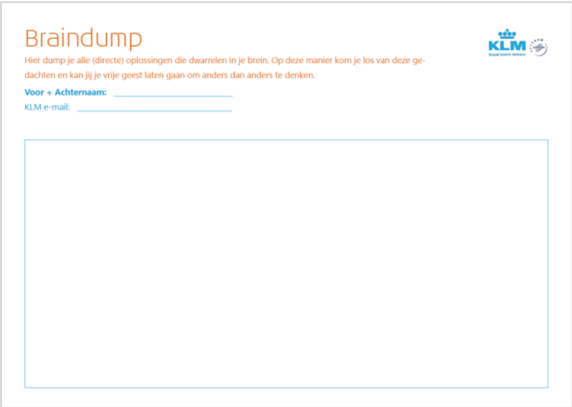
1. The purpose of the day was told first as the most important thing to remind of. Subsequently, the possibilities and limitations of KLM with this technology regarding the DOA and POA were discussed. This has been told so that everyone is sufficiently aware of the expertise that I have about this topic which will prevent participants from forming a possible bias so that they will label ideas in advance with not possible during the brainstorm.
2. Hereafter, the list of benefits of AM in aviation was told to trigger participants on which types of solutions they could think of and which parts could be tackled with these benefits.
3. At last, to demonstrate once again that KLM has been busy with AM for a while and already has 1 certified component, it has been told what KLM has done so far with regard to this technique. Furthermore, this will help to give courage to those who had a bias about the possibilities of this technique, that printing and certifying is actually possible.

After everyone has been informed about the possibilities and in this way has been given a kind of steam course in this technique to be able to think more easily in solutions, it is time for the creative sessions to start.

Three different creative sessions were held, each with a different function. For each of the sessions was a slide prepared showing the rules for the specific session and the list of benefits of AM in the aviation industry. This list will support in helping to find solutions and the possible areas they can think of.

Creative session 1 – Mind mapping

It was decided to start with the mind mapping technique. This ensures participants to easily put what they have in mind on paper. The "list of requirements" were used to delineate in freedom of usefulness. The purpose of this techniques is to search for solutions, step-by-step. Often when participants already have a solution in mind, makes it difficult for them to think step-by-step what is actually what we want. A "Brain Dump" works well in these situations. This is a section where you can write direct solutions and come loose from this idea while you also know that this will not be forgotten. The template below has been used.



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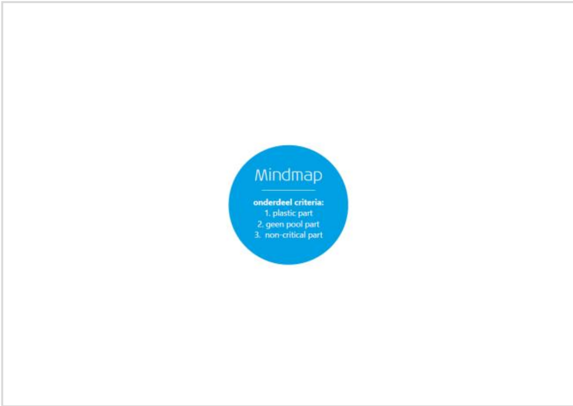


back page

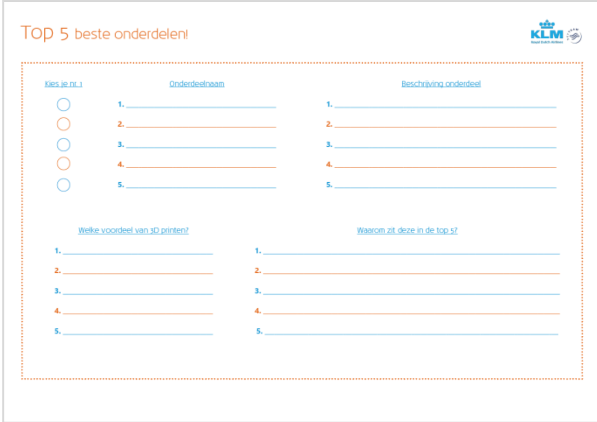
The outcome of this technique helps to understand which areas participants are thinking about mostly when it comes to potential parts to be produced with a 3D printer within the list of requirements and the benefits of this technique.

Creative session 2 – Battle for the top

The second sessions is held in a group context. All participants are divided into groups of three people.
All groups must set up a list of top 5 components. They can make use of their individual ideas they had during session 1. Group context ensure discussion and battle which ideas are worthy to be in the top. This interaction can simultaneously spark new ideas within the group and with the different views on the topic.

To give the feeling that it is really important, it was decided to use peer pressure. This is done in the way that the groups had to present their number 1 and explain why it was chosen at the end of the session. Through this peer pressure, groups naturally want to present something good that they are proud of. This could also increase the quality of the ideas. The template below has been used during this session.

front page



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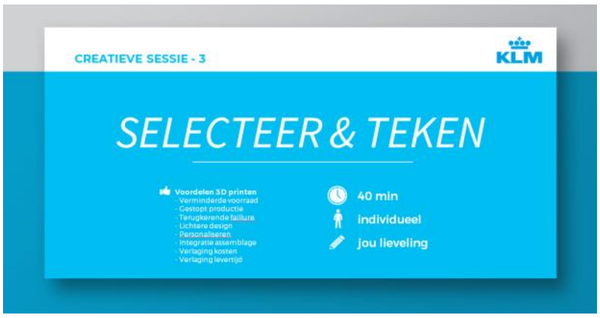
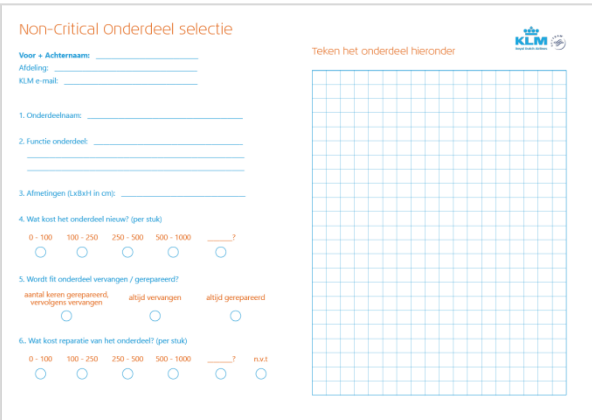
The outcome here is more qualitative than quantitative. Each written potential part needs to be explain in terms of name, function and type of 3D print benefit it covers. Additionally, the outcomes in specified parts will validate which area of the aircraft participants saw the most potential for 3D printed parts. Finally, the product category can be derived with the results and the most potential category can be found.



Creative session 3 – Select & Draw

The final session is again individual and focuses on the details of previously written or thought ideas. This is literally the last step where participants provide details like dimensions, price, reparability and repair cost of the part they were thinking of. Additionally, simply drawing the part will help me understand the appearance of it. Everyone can now freely provide information about the parts which maybe did not reached the top



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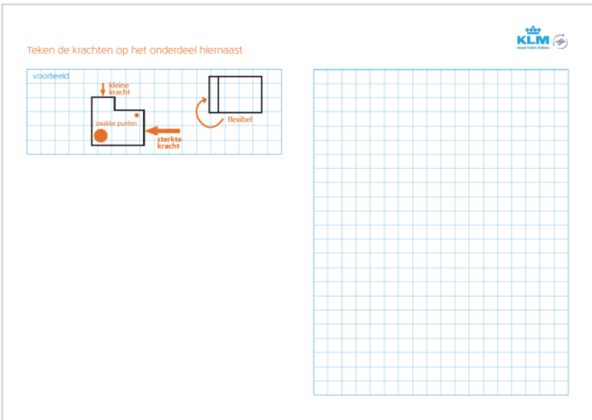

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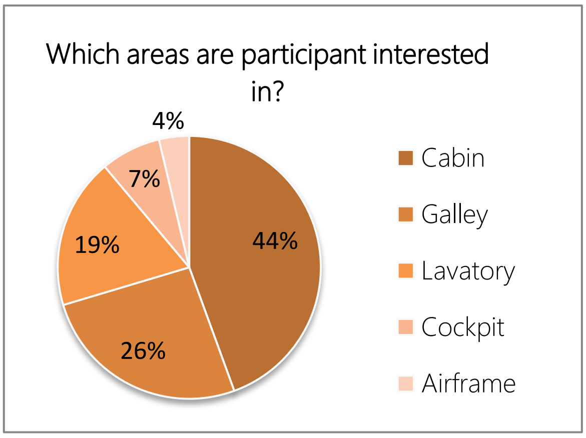
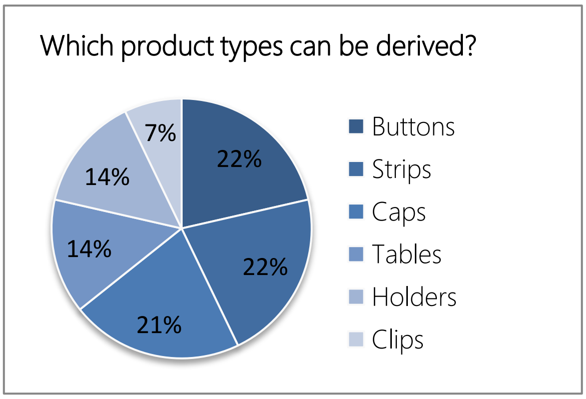
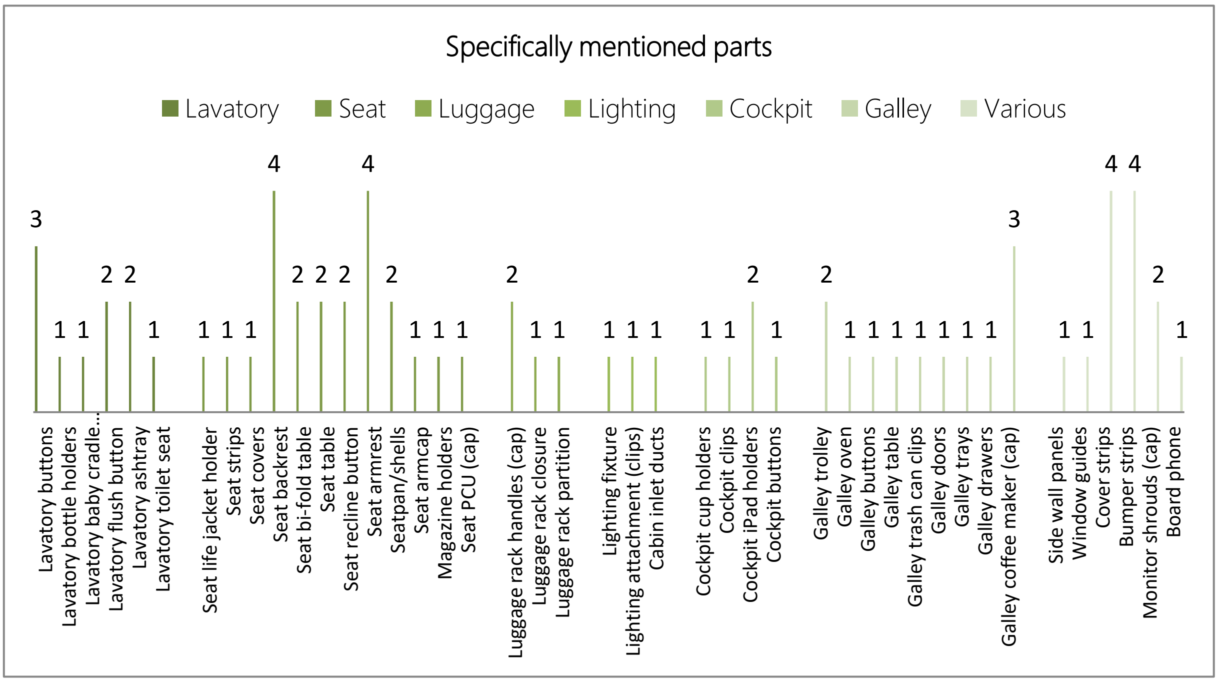
Executing the 3 creative sessions successfully resulted in the following findings.



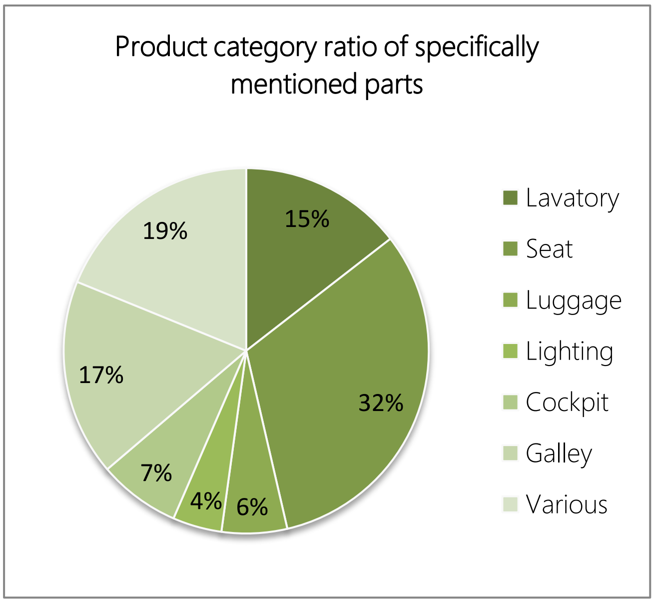
With the fact that the vast majority of participants work with the cabin, it is more than logical that this is the area of greatest interest. Following are the two main areas, the galley and lavatory. This is of course interesting because this is again a sub category of the cabin. This first result is still far too general to draw conclusions.



Recurring product types can be derived, from all written potential parts throughout the day. The results illustrated in the diagram are by no means all types various components fall, yet these are the most common and striking. The results show a reflection of the type of components the participants think to get the most out of it with this technology. It looks like the interest of participants currently see the use of AM mostly for smaller and simpler components.



The table of specifically mentioned parts, like the title explains, the total and amount of times specifically mentioned parts by the participants illustrated. This could also be seen as the general view of the participants in which product area they see potential of using AM.



A much more detailed representation of this interest can be given with the diagram derived from the previous table. It displays the amount of times a part is mentioned from a certain product category.

The results show clearly the leader from this workshop being the seat area with a score of 32%. This result should probably have a reason, unfortunately this cannot deduced immediately. But because a large proportion of the participants were cabin repair engineers and input about seats mainly came from them, a hypothesis can be made that these parts presumably fail often and are listed by them for this reason. A speculative reason why these components fail more often is because they come the most into direct contact with passengers. One thing is certain, this area needs to be investigated extra carefully.

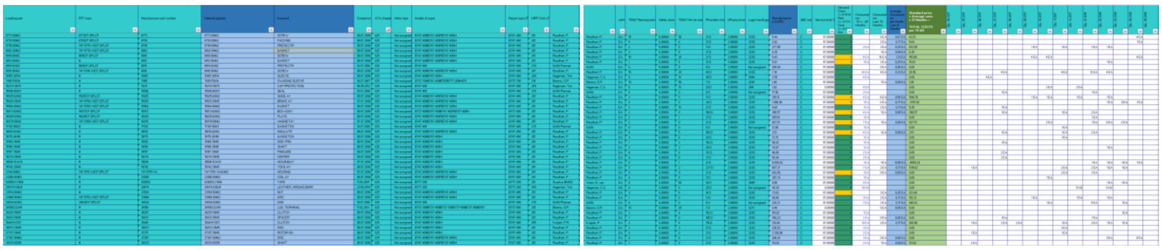
SAP raw data Excel

KLM uses an administration system called SAP. The SAP system can simply be interpreted as a stock system where all parts are entered based on price, quantity, aircraft type, part number, etc.. In this way use maintenance engineers to check if the required parts are available and order them from colleagues in the stock department.

Together with Ferry Domingues, data analyst SAP, we have made a printout with real parts from SAP. As can be imagined, this administration system consists of millions of components. To specify and maximize the usability of the list are several filters used such as:

ATA25 = To filter only on cabin parts;
P2000 = To filter only on plant 2000 which contains the Component & Services department;
P3000 = To filter only on plant 3000 which contains the Hangar department;
HERB002 = To filter only on consumable parts, these are thrown away after use;

This resulted in long and still hard to understand excel sheets. The following snapshot is just 1/50th of the complete list.



First of all, I have removed the columns that are not relevant to this project. Subsequently, summarizable information is reduced to 1 column which has led to the following "clean" excel sheet. Here too the snapshot is only part of the entire excel sheet.

Models & types	Manufacturer part number	Keyword	Standard price in EURO		Average Consumption per Month Last 12 Months	Standard price x Average cons. x 12 Months = TOTAL COSTS per YEAR	
B787-9	F0495917	SHAFT	€	653,97	94,25 EA	€	739.640,07
B747-400/B747-400M/B777-200/B787-9	S015767	AERTRIM LHR sht 60'X96" New design	€	1.027,33	51,08 YD	€	629.753,29
B777-200/B777-300	130-00-231-20	SEATPAN ASSY	€	200,00	226,50 EA	€	543.600,00
B777-200/B777-300	130-00-231-21	SEATPAN ASSY	€	200,00	148,17 EA	€	355.600,00
B777-200/B787-9	20419266	ACTUATOR MECHANICAL	€	70,34	378,58 EA	€	319.554,62
A330-300/B737-700/B737-800/B737-900/B747-400/B787-9	20402760	N2-LOK ACTUATOR	€	258,94	86,67 EA	€	269.297,60
A330-200/A330-300/B777-200	S016873	PEOPLE WITH LINES LAMINATE WITH PSA ADH	€	723,97	27,58 YD	€	239.634,07
A330-200/B737-900/B747-400/B777-200/MD11	S8068	SCHNELLER PANFLOOR/855P/WITH GRIT 60X130	€	639,84	27,92 SH	€	214.346,40
B787-9	F0494734	OTTOMAN CUSHION LAT	€	4.303,80	3,08 EA	€	159.240,60
B747-400M	1047450	TAPIJT BREED 200 CM	€	59,98	220,48 M	€	158.691,49
B787-9	F0494736	OTTOMAN CUSHION LAT	€	4.113,40	3,08 EA	€	152.195,80
B777-200	130-00-225-00	LIFE VEST POUCH VERTICAL	€	68,00	184,25 EA	€	150.348,00
B777-200/B777-300	470-00-731-05	DRESS COVER BOTTOM CUSHION	€	23,57	405,00 EA	€	114.550,20
B787-9	F0479566	ARMCAP STD	€	186,90	50,50 EA	€	113.261,40
B777-200/B777-300	130-00-231-26	SEATPAN ASSY	€	200,00	47,00 EA	€	112.800,00
B787-9	ATSA021003A0232	SHROUD ASSY	€	4.791,82	1,92 EA	€	110.211,86
B787-9	F344688	TRACK FITTING, AFT	€	3.369,35	2,50 EA	€	101.080,50
B777-200/B777-300	470-00-730-05	DRESS COVER BOTTOM CUSHION	€	23,57	350,67 EA	€	99.182,56
B737-700/B737-800/B737-900	379-00-701-01	BACKREST COVER	€	29,65	246,83 EA	€	87.823,30
B777-200	130-00-630-16	BOTTOM CUSHION 480 STD	€	158,55	42,50 EA	€	80.860,50
A330-200/A330-300/B737-700/B737-800/B737-900/B747-400	717001015	CARPET WIDTH 200 CM	€	57,32	114,96 M	€	79.072,94
B777-300	470-00-701-03	BACKREST COVER	€	98,39	65,00 EA	€	76.744,20
B737-800/B737-900	139-00-631-35	SEAT - FOAM	€	51,00	122,67 EA	€	75.072,00
B787-9	F0494719	EXTRUSION TRIM, FOOTWELL LH	€	3.692,30	1,67 EA	€	73.846,00
B737-800/MD11	219002-5A	HINGE	€	84,44	64,08 IN	€	64.934,36
B777-200	130-00-630-12	BOTTOM CUSHION 490 STD	€	158,55	33,08 EA	€	62.944,35
B787-9	F0494732	OTTOMAN CUSHION CENTER	€	1.669,50	3,00 EA	€	60.102,00
B787-9	F0494733	OTTOMAN CUSHION CENTER	€	1.669,50	3,00 EA	€	60.102,00
B787-9	F0524525	ARMREST BUTTON AND CABLE ASSY	€	2.488,19	1,92 EA	€	57.228,37
B777-200/B777-300	S018986	HOUSING DECOR	€	968,94	4,83 SH	€	56.198,52
B777-200	1022878	CARPET BREED 220 CM	€	55,66	77,93 M	€	52.053,23

After this I went to Armand Keet, head of unserviceable parts depot, to look together at the list to select suitable parts for this project. Unfortunately, the specific material of parts are not entered in SAP which makes selection more difficult. Because of this we estimated the part material with the expertise of Armand by reading the short description written under "keyword". In this way we selected all plastic parts that had an annual cost of € 10.000,- . The main focus here was still on finding the most expensive parts in terms of high purchase costs and high consumption in order to reduce costs as much as possible. This resulted in the following last excel list.

Models & types	Manufacturer part number	Keyword	Standard price in EURO		Average Consumption per Month Last 12 Months	Standard price x Average cons. x 12 Months = TOTAL COSTS per YEAR	
B787-9	F0479566	ARMCAP STD	€	186,90	50,50 EA	€	113.261,40
B777-200/B777-300	130-00-231-26	SEATPAN ASSY	€	200,00	47,00 EA	€	112.800,00
B787-9	F0494719	EXTRUSION TRIM, FOOTWELL LH	€	3.692,30	1,67 EA	€	73.846,00
B777-200	130-00-361-00NP	PANEL ARMREST ASSY	€	202,49	18,33 EA	€	44.547,80
B747-400/MD11	139-00-306-16FS	ARMCAP STD	€	49,43	63,42 EA	€	37.616,23
B787-9	F0494959	BUMPER, TRIM INSTALLATION	€	3.691,30	0,75 EA	€	33.221,70
B777-200/B787-9	0FS3500A04G01	HOLDER	€	243,06	10,75 EA	€	31.354,74
B787-9	F0486569	STOP	€	100,00	25,00 EA	€	30.000,00
B777-200	130-00-361-01NP	PANEL ARMREST ASSY	€	202,49	11,58 EA	€	28.146,11
A330-200/A330-300/B737-800/B737-900/B777-200/B777-300/B787-9	0FV9600A01G01	ASHTRAY	€	88,98	18,83 EA	€	20.109,48
B777-200	130-00-361-03NP	PANEL ARMREST ASSY	€	202,49	8,25 EA	€	20.046,51
B777-200	130-00-351-98NN	ARMCAP ASSY	€	263,39	6,08 EA	€	19.227,47
B787-9	F0479684	GLASS HOLDER ASSY	€	29,00	39,08 EA	€	13.601,00
B787-9	F0494951	LATCH ASSY, VIDEO MONITOR	€	1.759,60	0,58 EA	€	12.317,20
B777-200/B787-8/B787-9	AAHT014000A0003	ASH TRAY	€	114,31	8,75 EA	€	12.002,55

As a final step, Armand used this list to find out in the KLM system and repair manuals with the part number what this part actually is and whether the estimation of material is correct.

Workshop II

As the project began to take shape, it was decided to no longer just focus on trying to reduce the costs for KLM E&M by implementing AM, but to explore and look for the way and possibilities of what AM could bring for KLM. As a result, it was decided to create a vision for KLM in which the benefits of AM, as described in paragraph "Elaboration of Benefits AM offer Aviation" are worked out by redesigning a selected part for each benefit. This will provide a better picture of the possibilities that AM can offer KLM. With this change in approach the project fits perfectly with the main objective and main research question again.

Due to the success of the first workshop and experience with some experts, a few were again invited to the second workshop. But due to the change in approach and direction of the project, some new and more suitable experts have been invited. The total group consisted of 7 participants from the direct field of E&M.

1. Cabin repair shop - Daily contact with parts
    a. Buddy Zuijderduijn (Shop leader cabin repair)

2. Line maintenance - Daily contact with parts
    a. René Smit (CMM line maintenance lead)
    b. Joost Jansen (CMM line maintenance lead)
    c. Kim Prins (Production Engineer)

3. Cabin engineering - Medium contact with parts
    a. Rik Steenkist (Manager cabin engineering)
    b. Gerard van der Tol (Senior cabin engineer)

4. Organizational function – No contact with parts
    a. Taco Vingerhoed (Director commercial operations of E&M)

The approach of this workshop was very different from the first workshop. Here is a list of different benefits that AM offers, which are then formulated into very specific assignments where the benefit is subtly incorporated. In this way, participants will not immediately think of the applicability of AM but will (unnoticed) find components that fit a certain benefit. This list of benefits together with the formulated assignments looks like following.

Benefits	1. Consequence	2. Consequence	3. Consequence	1. Formulated assignment	2. Formulated assignment
1. Faster leadtime	Cost reduction by small/no inventory of spare parts	Cost reduction by faster turnaround times of		Which plastic cabin parts have a high consumption and have a	Which plastic cabin parts are in the warehouse for at least 4-8 weeks

		aircrafts		delivery time of at least 3 weeks?	before they are used?
2. Integrate assemblies	Cost reduction by reduce fuel consumption due to reduced weight	Cost reduction by reduced labor time due to reduced assembly time (labor costs)	Cost reduction by reduced labor time due to reduced part maintenance (labor + part costs)	Which plastic cabin parts are produced with more than 3 consecutive steps?	Which plastic cabin (sub) assemblies consist of at least 3 components?
3. Reduce weight	Cost reduction by reduced fuel consumption			Which plastic cabin parts come back more than 10 times in the plane?	
4. Customization	Increase customer satisfaction	Fix recurring fail issues		Which plastic cabin parts in the cabin are used by passengers immediately?	
5. Reduce purchase costs	Reduced supplier dependency	Reduced waste material during production (increased buy-to-fly ratio)		Which plastic cabin parts are replaced with every maintenance?	

Each formulated assignment is elaborated on a page which are illustrated below. All assignments were distributed as one complete package to the participants, with whom the brainstorming session was then carried out for each assignment. I started by reading the assignment question out loud, after which everyone first had a moment to ask questions if there were uncertainties. After this, the group was given 5 minutes to silently express their thoughts on the paper and then 15 minutes of to jointly discuss the assignments. After completion of the assignment we went to the next assignment until every was dealt with.

Braindump

Hier dump je alle (directe) oplossingen die dwarrelen in je brein. Op deze manier kom je los van deze gedachten en kan jij je vrije geest laten gaan om anders dan anders te denken.

1. Welke kunststof cabine onderdelen hebben een hoogverbruik en hebben een levertijd van minimaal 3 weken?

2. Welke kunststof cabine onderdelen worden geproduceerd met meer dan 3 opeenvolgende stappen?

zoals draaien, frezen, gaten boren, etc.

3. Welke kunststof cabine (sub)assemblies bestaan uit minimaal 3 onderdelen?

4. Welke kunststof cabine onderdelen komen tot meer dan 10x terug in het vliegtuig?

5. Welke kunststof cabine onderdelen liggen minimaal 4-8 weken in het magazijn voordat ze worden gebruikt?

6. Welke kunststof cabine onderdelen in de cabine worden per direct gebruikt door passagiers?

7. Welke kunststof cabine onderdelen worden bij iedere onderhoudsbeurt vervangen?

Appendix E

Appendix E displays the results of the prior activities executed to find suitable parts for AM. All found parts are listed here according to the AM benefit it is linked to.

Components list from workshop I + SAP + workshop II

1. Faster leadtime

1. **Ashtray**
   a. Fact: ashtray in the toilet of a 747 was broken and had to be replaced, this lead to a 4 hour delay in order to by its absence.
2. **Suspension point of baggage bins**
   a. When a suspension point is broken and the luggage bin does not close, an airplane does not go away.
3. **MOB sills**
   a. Are seals linking the side panels of the B787 with the floor panels. There is no inventory of these but gets broke a lot due to passengers hitting it with their shoes or baggage. (Currently engaged in working with new vendor for these parts).
4. **Galley corner strips**
   a. Cover strips of galley patricians. There is no inventory only repair is option due to Boeing having long lead times. These are covering sharp edges in the galley and need to be covered. Passengers can hurt themselves or break their clothing. Now, KLM is covering them with ugly white tape which is not up to the representation standards of KLM.
5. **Front row furnishing of Zodiac business class strips in B787**
   a. These have a lead time of minimum 6+ weeks and break really easy due to galley trolleys hitting them. They are very fragile and cost $7000 per strip. We are currently improvising a lot to be able to do it ourselves and be less supplier dependant. Especially it being business class, a nice representation is very important.
   b. This part can also be used for customization
6. **Galley table stop and profile B787**
   a. The galley table in the B787 slides in and out of the galley. This is pushed hard by the stewardesses so that the stops and profile by bending and breaking. Because of this you cannot get this table out and you cannot use it. These parts are very difficult to repair and because they are hidden behind the galley equipment.
7. **Flush button lavatory B787 + B777**
   a. Flush button cover in the toilet is pressed too hard by passengers causing them to tear through. It is only cover plates and are difficult to obtain, these often break down.
   b. This part can also be used for high purchase costs

8. **Shoe covers of B.E. business class in the B777 + A330**
    a. These are the covers on the rear of the seats where the passengers can put their feet on. To carry out maintenance on the chair mechanism or to replace the carpet, these covers must always be detached. Because of this they often break down and delivery is very difficult.
    b. This part can also be used for integrate assembly or customization
9. **Baggage bin internal covers A330**
    a. These parts disappear because they are pushed by luggage that is pushed into the bins. These are very difficult to obtain.
10. **Ventilation grilles**
    a. These parts are slow movers and are often 1 or 2 in stock while they do not often fail. Because the delivery time is so long, they are kept in stock, but sometimes it takes months unnecessary space.
11. **Seat armrest of B737**
    a. These break a lot and are not supplied by Boeing.
    b. This part can also be used for integrate assembly or customization

<u>2. Integrate assemblies ((1)reduce weight + (2)increase product life cycle)</u>

1. **Handicap handrail toilet B787, B777 + A330**
2. **Toilet shrouds B777 + A330**
    a. These already consist of fewer parts with the B787, but the B777 and A330 still have separate parts. The toilet seat, toilet valve, dampers, seat pen, etc.
3. **Harex galley trolley guide**
    a. These consist of several parts and often fail because they are completely hollow for the weight. But these guide bumpers are just to absorb the energy from the trolleys. You can strengthen this and produce it in one go with AM.
4. **Toilet paper holder**
5. **Socket cover in lavatory**

<u>3. Reduce weight (complex geometry)</u>

1. **Galley countertops**
    a. Are really heavy and never in stock. These damage unnecessary due to incorrect use. An example is that heavy parts such as the coffeemaker are pulled out into the upper cupboards which make a hole in the countertop with its corner being smashed into it. The countertop is made of aluminum and corrodes by the acids of food and drinks that are prepared on it.
        i. *When it will consist of* lighter and separate printed parts, it can last longer, provide weight reduction and be easily maintained when it is broken.

2. **Galley locks**
    a. These are (red) metal locks in the galley to hold the trolleys in place during take-off and landing. There are always multiple of these in each plane.
3. **Curtain rails**
    a. These are metal and are present in every galley.
4. **Seat tables**
    a. Everything related to seats is most common in an airplane. Tables are the parts where something can still be gained in terms of weight.

4. Customization (small batch production)

1. **Passenger seats**
    a. Arm rest
    b. Tables
        i. Table holder knob
    c. Entertainment
        i. Shroud
        ii. Remote
    d. Lecture holder
2. **Lavatory**
    a. Flush button
    b. Toilet paper roll holder
    c. Baby cradle
    d. Valve of waste bin
3. **Baggage bin**
4. **Window shades**
    a. These always break in the corners and delivery takes a long time. These shades can be strengthened in these weaknesses and at the same time nice KLM patterns can be made which can be seen when this shade is closed and the sun is shining.

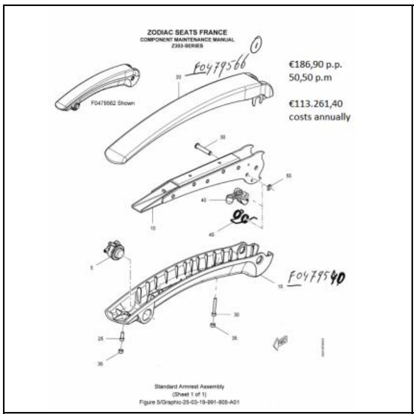
5. Reduce purchase costs

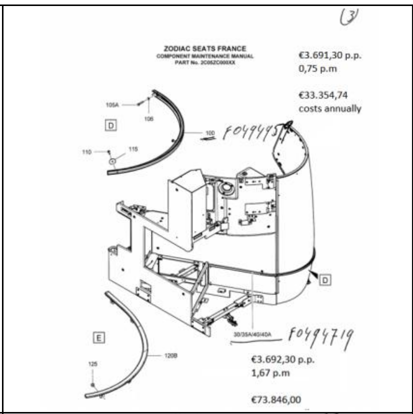
1. **Table holder knob**
    a. When a table cannot close, it is blocked and not sold. This is because a passenger could not get away in an emergency situation. Every chair also costs money and causes a loss if it cannot be used. If the table cannot close on the aisle, it immediately blocks 3 chairs.
2. **Cabin attendant armrest**
    a. These must be repaired or replaced within 10 days. If that does not happen, the entire device cannot go away and that is very expensive.
3. **Bi-fold table B777**
    a. These break down very often, these break down 6032 times a year due to incorrect design. They each cost € 342,38 and in this way amount to **€2.065.236** costs on an annual basis. KLM currently has a guarantee on this

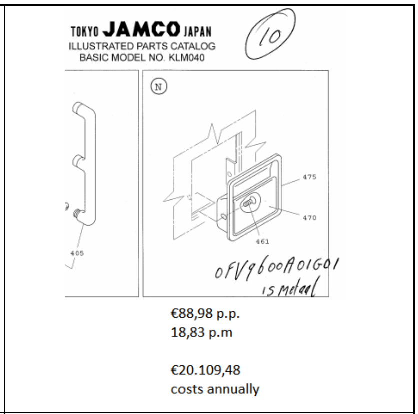
table and they are reimbursed "for free" by Recaro, but this will soon end according to Armand Keet. It is of course not entirely free because delivery time is a problem and ultimately employees have to work for both repair of these tables through the delivery time and for the warranty procedure, this naturally also costs a lot.

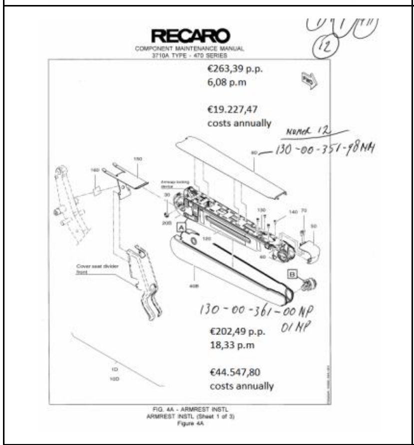
b. This part can also be used for customization

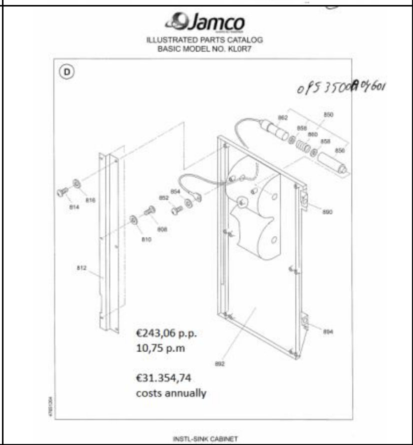
Everything below is from the Excel sheets derived from SAP for component price and annual use.

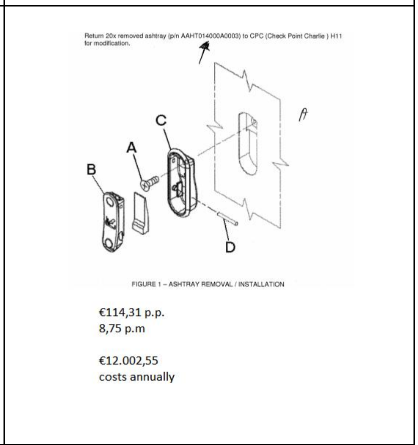


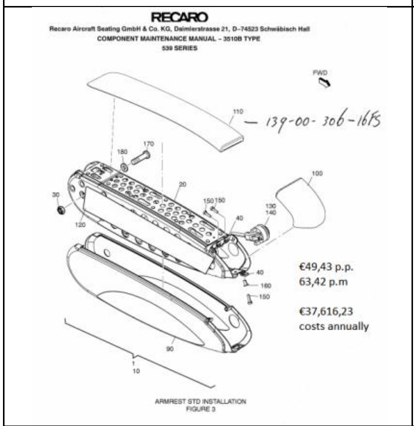


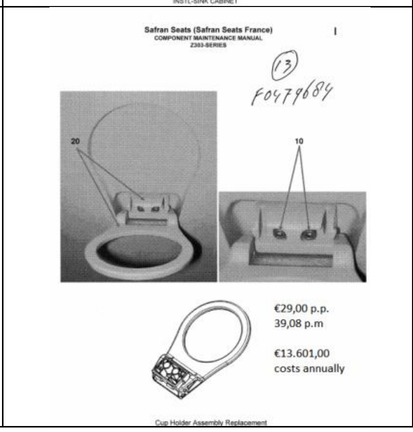












Appendix F

Appendix F describes the construction of an elaborate trade-off table using the weighted objective method and the knowledge of KLM experts. Besides, it describes the steps in how the entire parts list is assessed with the trade-off table. It eventually shows the results of the complete approach.

Part selection process

For the selection procedure is the overall parts list been tested against criteria. This method is called the weighted objective method. An workshop is organized for the purpose of set this method up together. Doing this together with KLM experts will serve to make this procedure not only more objective but also grounded.

The workshop has been conducted with Taco Vingerhoed, Arlette van der Veer and Fehmihan Kamber. Together they have drawn up the list of criteria on the basis of the previously concluded benefit - consequence combinations of AM back in paragraph "Elaboration of Benefits AM offer Aviation". Some of the criteria feel very similar but differ sufficiently to take them separately. After the total list of criteria been established, are these subsequently rated by the same 8 KLM experts from the direct field of E&M who participated in previous workshops. They are asked to rate the criteria from 1 to 5, which represents the importance of a particular criteria on judge a component with. In this case means 1 very unimportant and 5 very important. The average of all outcomes is taken to determine the weighing score requirements.

Weighing scores requirements	Average weighted score	Taco Vingerhoed	Arlette van der Veer	Rik Steenkisst	Ebu Yildiz	Tolga Inan	Robbert Bakker	Buddy Zuijderduijn	Armand Keet
Faster leadtime	4,00	4	3	4	4	4	5	3	5
Integrating assemblies	3,50	4	4	4	3	3	3	5	2
Reduce weight	4,,00	5	5	2	3	3	4	5	5
Increase product life cycle	4,25	2	4	5	5	5	4	4	5
Opportunity of complex geometry	2,63	3	3	3	1	2	3	4	2
Customization	3,63	5	3	4	3	4	3	3	4
Increase employer satisfaction	2,75	2	2	2	2	2	2	5	5
Increase customer satisfaction	4,38	5	4	4	5	4	3	5	5
Fix recurring fail issues	4,00	2	5	4	3	4	4	5	5
Reduce purchase costs	4,38	3	5	2	5	5	5	5	5
Reduce supplier dependency	4,00	4	4	2	5	4	4	5	4
Increase buy-to-fly ratio (waste material reduce)	2,75	2	3	3	2	2	3	2	5
Reduce labor time	3,75	3	3	3	5	4	4	5	3
Reduce TAT (Turn Around Time)	4,13	5	3	3	4	4	4	5	5
Reduce fuel consumption	4,00	5	2	2	4	5	4	5	5
Attractiveness for KLM (Marketing potential of AM)	4,63	5	3	5	5	5	4	5	5
Possible implementation speed	4,33	4	4	4	5	4	5	3	5

Subsequently, preconditions have been drawn up for each criteria which determine the meaning of the score scale from 1 to 5. This step is performed together during the workshop. Determining the scale ensures the assessment of components becoming less subjective and more determined. This increases the academic level of the assessment. Below you can see how these preconditions scale the score per criteria.

Weighing scores requirements	1	3	5	0
Faster leadtime	Reduces leadtime by 0 - 5 days	Reduces leadtime by 10 - 20 days	Reduces leadtime by 50 or more days	Unknown
Integrating assemblies	Remains the same	Will reduce between 3 - 2 to 1 part	Will reduce between 5 or more to 1 part	Unknown
Reduce weight	Remains the same	Medium opportunity	High opportunity	Unknown
Increase product life cycle	Remains the same	Doubles the product life cycle	Triples the product life cycle	Unknown
Opportunity of complex geometry	Remains the same	Medium opportunity	High opportunity	Unknown
Customization	Remains the same	Medium opportunity	High opportunity	Unknown
Increase employer satisfaction	Remains the same	Medium opportunity	High opportunity	Unknown
Increase customer satisfaction	Remains the same	Medium opportunity	High opportunity	Unknown
Fix recurring fail issues	Remains the same	Some fail issues can be fixed	All issues can be fixed	Unknown
Reduce purchase costs	Remains the same	Reduction 50% of costs	Reduction 75% of costs	Unknown
Reduce supplier dependency	Remains the same	Medium opportunity	High opportunity	Unknown
Increase buy-to-fly ratio (waste material reduce)	Remains the same	Reduction 50% of material	Reduction 75% of material	Unknown
Reduce labor time	Remains the same	Reduction 50% of labor time	Reduction 75% of labor time	Unknown
Reduce TAT (Turn Around Time)	Remains the same	Reduction 50% of TAT	Reduction 75% of TAT	Unknown
Reduce fuel consumption	Remains the same	Medium opportunity	High opportunity	Unknown
Attractiveness for KLM (Marketing potential of AM)	Small opportunity	Medium opportunity	High opportunity	Unknown
Possible implementation speed	Very difficult to implement, more than 12 months	Medium difficult to implement, 6 months	Easy to implement, within 1 month	Unknown

At last is each component assessed on the basis of criteria with the gathered knowledge and information during the organized activities. Considering not enough information being available per component to apply the scale for each criteria, a different solution has been devised. When it's impossible to apply the scale, a zero will be entered in the weighted objective. Which ensures that this criteria is no longer included in the assessment of a component. Performing all steps of the method on the entire components list results in the following outcomes.

For benefit "Faster leadtime" the choice falls on seat armrest.

1. Faster lead time

1.1 Ashtray	SCORE	1.2 Suspension point of baggage bins	SCORE	1.3 MOB sills	SCORE	1.4 Galley corner strips	SCORE	1.5 Front row furnishing	SCORE	1.6 Galley table stop	SCORE	1.7 Flush button	SCORE	1.8 Shoe covers	SCORE	1.9 Baggage bin cover	SCORE	1.10 Ventilation grill	SCORE	1.11 Seat armrest	SCORE
0	0	3	12	0	0	4	16	5	20	1	4	4	16	4	16	4	16	3	12	4	16
1	3,5	3	10,5	0	0	1	3,5	1	3,5	0	0	2	7	4	14	0	0	1	3,5	3	10,5
2	8	1	4	0	0	1	4	1	4	0	0	1	4	0	0	2	8	1	4	5	20
4	17	0	0	0	0	3	12,75	4	17	3	12,75	4	17	3	12,75	1	4,25	3	12,75	2	8,5
1	2,625	1	2,625	0	0	1	2,625	2	5,25	1	2,625	2	5,25	4	10,5	0	0	1	2,625	3	7,875
3	10,875	1	3,625	0	0	0	0	4	14,5	1	3,625	5	18,125	4	14,5	3	10,875	3	10,875	5	18,125
2	5,5	2	5,5	0	0	1	2,75	3	8,25	4	11	3	8,25	2	5,5	2	5,5	1	2,75	1	2,75
1	4,375	1	4,375	0	0	2	8,75	2	8,75	1	4,375	3	13,125	3	13,125	2	8,75	2	8,75	3	13,125
4	16	3	12	0	0	3	12	4	16	3	12	4	16	3	12	0	0	3	12	3	12
0	0	0	0	0	0	0	0	5	21,875	0	0	0	0	0	0	0	0	0	0	3	13,125
4	16	2	8	0	0	3	12	5	20	2	8	3	12	4	16	4	16	4	16	5	20
0	0	0	0	0	0	0	0	1	2,75	0	0	1	2,75	0	0	0	0	0	0	0	0
2	7,5	2	7,5	0	0	2	7,5	3	11,25	4	15	0	0	0	0	0	0	0	0	0	0
3	12,375	2	8,25	0	0	0	0	1	4,125	0	0	2	8,25	3	12,375	0	0	2	8,25	4	16,5
1	4	1	4	0	0	1	4	1	4	1	4	0	0	0	0	0	0	1	4	4	16
1	4,625	1	4,625	0	0	1	4,625	2	9,25	1	4,625	3	13,875	3	13,875	1	4,625	1	4,625	5	23,125
4	17	3	12,75	0	0	4	17	2	8,5	4	17	4	17	3	12,75	5	21,25	3	12,75	2	8,5
TOTAL	**129,375**		**99,75**				**107,5**		**179**		**99**		**158,625**		**153,375**		**95,25**		**114,875**		**206,125**
																				#1	lead time

For benefit "Integrate assemblies" the choice falls on handicap armrail.

2. Integrate assemblies

2.1 Handicap handrail	SCORE	2.2 Toilet Shroud	SCORE	2.3 Galley trolley guide	SCORE	2.4 Toilet paper holder	SCORE	2.5 Socket cover	SCORE
0	0	0	0	1	4	0	0	0	0
4	14	4	14	2	7	4	14	3	10,5
3	12	2	8	0	0	1	4	2	8
2	8,5	3	12,75	4	17	4	17	1	4,25
0	0	3	7,875	3	7,875	3	7,875	3	7,875
4	14,5	3	10,875	2	7,25	3	10,875	4	14,5
4	11	2	5,5	3	8,25	3	8,25	1	2,75
3	13,125	1	4,375	1	4,375	1	4,375	4	17,5
2	8	3	12	4	16	0	0	2	8
0	0	2	8,75	0	0	4	17,5	2	8,75
3	12	3	12	3	12	4	16	0	0
1	2,75	2	5,5	0	0	1	2,75	0	0
3	11,25	1	3,75	3	11,25	3	11,25	1	3,75
3	12,375	0	0	2	8,25	0	0	0	0
2	8	1	4	1	4	1	4	1	4
3	13,875	1	4,625	1	4,625	3	13,875	3	13,875
4	17	3	12,75	5	21,25	4	17	3	12,75
	158,375		**126,75**		**133,125**		**148,75**		**116,5**
#1	integrate assembly								

For benefit "Reduce weight" the choice falls on seat tables.

3. Reduce weight

3.1 Galley counter top	SCORE	3.2 Galley trolley locks	SCORE	3.3 Curtain rails	SCORE	3.4 Seat tables	SCORE
0	0	3	12	0	0	3	12
2	7	1	3,5	1	3,5	3	10,5
4	16	4	16	2	8	5	20
4	17	0	0	0	0	2	8,5
1	2,625	3	7,875	0	0	5	13,125
3	10,875	2	7,25	1	3,625	5	18,125
2	5,5	0	0	0	0	1	2,75
1	4,375	1	4,375	1	4,375	3	13,125
4	16	1	4	1	4	4	16
3	13,125	5	21,875	2	8,75	4	17,5
3	12	3	12	3	12	4	16
0	0	4	11	1	2,75	1	2,75
3	11,25	1	3,75	0	0	4	15
0	0	2	8,25	0	0	0	0
2	8	3	12	2	8	5	20
4	18,5	2	9,25	1	4,625	5	23,125
3	12,75	3	12,75	5	21,25	3	12,75
	155		**145,875**		**80,875**		**221,25**
						#1	weight reduction

For benefit "Customization" the choice falls on window shades.

4. Customizaztion

4.1 Seats arm rest (F0479566)	SCORE	4.2 Seats tables	SCORE	4.3 Entertainment shroud	SCORE	4.4 Entertainment remote	SCORE	4.5 Lecture holder	SCORE	4.6 flush button	SCORE	4.7 baby cradle	SCORE	4.8 Waste bin valve	SCORE	4.9 Baggage bin handle	SCORE	4.10 Window shades	SCORE
0	0	0	0	0	0	0	0	3	12	0	4	0	0	0	0	2	8	4	16
0		0		3	10,5	1	3,5	2	7	0		3	10,5	1	3,5	2	7	1	3,5
0		0		5	20	4	16	3	12	0		2	8	1	4	4	16	1	4
0		0		4	17	0	0	3	12,75	0		2	8,5	0	0	1	4,25	3	12,75
0		0		2	5,25	3	7,875	0	0	0		5	13,125	2	5,25	2	5,25	3	7,875
0		0		3	10,875	5	18,125	5	18,125	0		5	18,125	5	18,125	5	18,125	5	18,125
0		0		1	2,75	0	0	0	0	0		0	0	0	0	3	8,25	1	2,75
0		0		2	8,75	3	13,125	3	13,125	0		3	13,125	0	0	4	17,5	5	21,875
0		0		3	12	4	16	3	12	0		3	12	2	8	1	4	4	16
0		0		3	13,125	0	0	2	8,75	0		3	13,125	2	8,75	4	17,5	2	8,75
0		0		4	16	4	16	4	16	0		3	12	4	16	0	0	4	16
0		0		0	0	0	0	0	0	0		0	0	0	0	0	0	1	2,75
0		0		0	0	0	0	0	0	0		0	0	0	0	1	3,75	1	3,75
0		0		0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0		0		4	16	3	12	3	12	0		2	8	0	0	4	16	0	0
0		0		3	13,875	3	13,875	3	13,875	0		2	9,25	1	4,625	3	13,875	4	18,5
0		0		4	17	2	8,5	4	17	0		3	12,75	5	21,25	4	17	4	17
					163,125		**125**		**154,625**				**138,5**		**89,5**		**156,5**		**169,625**
																		#1 Customization	

For benefit "Reduce purchase cost" the choice should be falling on the Befold tables, but in this case would the same component worked out twice. This does not seem wise to me. To enrich the vision that we are trying to create for KLM, for one of the two benefits should the second highest scoring component assessed. For the benefit "Reduce weight" the second highes scored parts is the galley counter tops. These appear at maximum 15 times in the biggest airplanes of KLMs fleet, while a seat table appeare even in the smaller narrow body aircraft at least 150 times. For this reason, it seems to me that the chance of reducing weight with even minor adjustments is greater with larger recurring parts like seat tables. Because the choice is made for seat tables and the Befold tables are seat tables can this specific table worked out to reduce weight and probably reduce purchase cost aswell with which you will hit two birds with one stone.
Besides, the second highest scoring component of the benefit "Reduce purchase cost", actually has higher purchasing costs than the befold tables but is consumed less. For this

reason, the annual costs are lower than the tables. Nevertheless, this component fits better for this benifit because it is ultimately about purchasing costs.

In the end, the choice for benefit "Reduce purchase cost" falls on Business class cabin bumpers.

5. Reduce pruchase cost

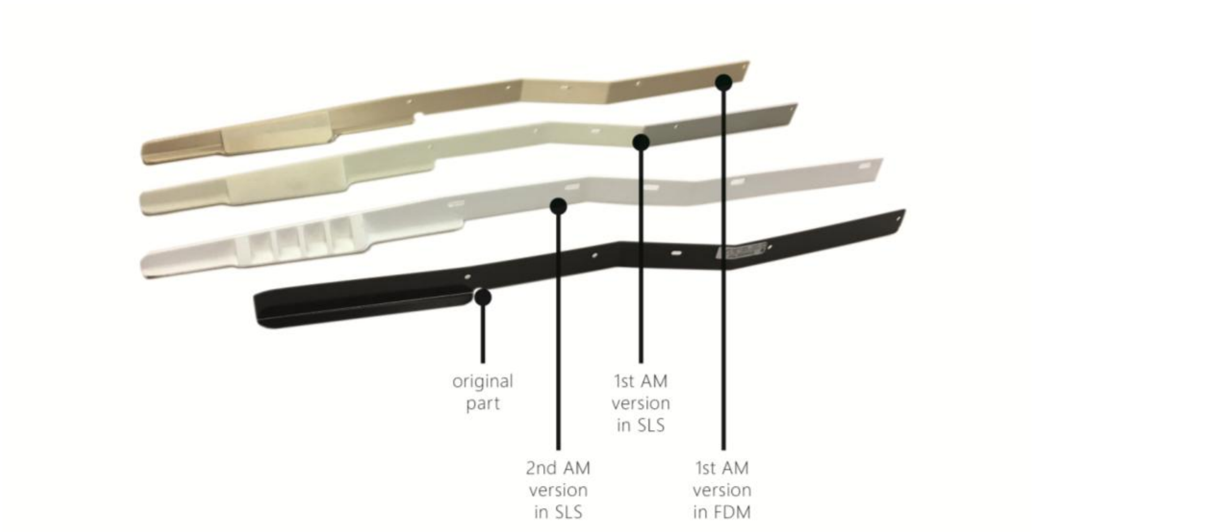
5.1 Table holder knob	SCORE	5.2 Cabin attendent arm rest	SCORE	5.3 Befold table	SCORE	5.4 Business class cabin bumbers	SCORE	5.5 Cup holder	SCORE
2	8	0	0	4	16	5	20	4	16
1	3,5	0		4	14	1	3,5	2	7
3	12	0		5	20	1	4	2	8
1	4,25	0		4	17	4	17	3	12,75
3	7,875	0		5	13,125	3	7,875	2	5,25
5	18,125	0		5	18,125	2	7,25	2	7,25
1	2,75	0		3	8,25	2	5,5	2	5,5
2	8,75	0		4	17,5	2	8,75	2	8,75
1	4	0		4	16	5	20	3	12
3	13,125	0		5	21,875	5	21,875	2	8,75
4	16	0		5	20	5	20	4	16
1	2,75	0		2	5,5	1	2,75	1	2,75
1	3,75	0		4	15	3	11,25	2	7,5
5	20,625	0		3	12,375	4	16,5	1	4,125
4	16	0		4	16	1	4	2	8
3	13,875	0		5	23,125	3	13,875	2	9,25
5	21,25	0		2	8,5	4	17	5	21,25
	176,625				**262,375**		**201,125**		**160,125**
						#1	purchase cost		

Appendix G

Appendix G describes the complete development of the formulas used to determine the comparison aspects for the redesigned CAD models. Besides, it serves as an explanation of the ratio method which is used to develop the formulas with. Lastly, the validation of the created price formula is taken care of.

Weight determination formula

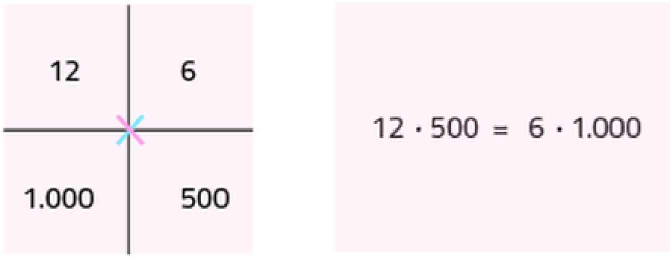
Weight determination of all concepts will be done based on the ratio method. This method creates a ratio with known numbers of parts. In case a new concept is created and has 1 of the 2 numbers, the unknown can be determined. To determine this ratio, the known and factual numbers of an AM printed part developed by Tolga Inan (Engineer Repair Lab at KLM) and produced by Materialise (contracted third party POA holder) are used.



The original part was first redesigned to optimize the design for AM as well as recurring fail issues were fixed. This design was then produced by Materialise in both FDM (Ultem9085) and SLS (PA2241FR). As we know from paragraph "6.3 Selecting All Plastic AM processes" are these 2 of the materials that are suitable for use in the aircraft cabin. Yet another iteration round took place in which the design was optimized for weight. This second version is only printed with SLS. Using the ratio method described above, the missing weight of the second version FDM component can be calculated. This will be illustrated below

	SLS – PA2241FR	**FDM – Ultem9085**
Weight new AM part	0,050 kg	?
Weight old AM part	0,072 kg	0,076 kg

The method is as follows:



When the known value is entered in the ratio method, it should look like this.

0,050 x 0,076 = ? x 0,072
0,0038 = ? x 0,072
? = 0,0038 / 0,072
? = 0,053

For example, we calculated that when printing in FDM with Ultem9085, the second version would have a weight of 0,053 kg.

Moreover, we also derived the volume from the CAD model of the second iteration. In this way together with the known weights for FDM and SLS we can determine the weight of all new concepts by using the volume ratio method and deriving their volumes from CAD.

Volume CAD model new AM part	53761 mm3

With all knowledge about the ratio method and the known numbers, 2 standard formulas can be drawn up which can be used for weight fixing of new concepts.

$$\boldsymbol{concept\ weight\ in\ kg\ SLS\ PA2241FR} = \frac{(0{,}072\ kg * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ mm^3}$$

$$\boldsymbol{concept\ weight\ in\ kg\ FDM\ Ultem9085} = \frac{(0{,}076\ kg * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ mm^3}$$

Price determination formula

To determine the cost price, it was considered to use the online cost calculation that Materialise offers via https://i.materialise.com/en/3dprint. Certain materials can be chosen in this system to calculate the price for these, unfortunately PA2241FR and Ultem9085 were not included in the list. Furthermore, the online calculator calculates the price indication based on a model that needs to be uploaded. This can mean that the model can be stored on the servers of Materialize, which can cause you to lose the rights for this model. For these two reasons, the ratio method is again used to create a formula for price calculation of concepts in the 2 specific materials.

> *Please note that the price calculated with these formulas serve only as an indication and may differ from the price when more quantities are purchased or when production will be done by KLM printers.*

Here too is the same part used in the previous paragraph used to determine the weight formulas. The costs per piece by Materialise is known. These prices, together with the known volume of the CAD model of this part will be used to prepare the formula with the ratio method.

	SLS – PA2241FR	**FDM – Ultem9085**
Price per piece AM part	€70	€244

Volume CAD model new AM part	53761 mm3

The ratio method with the missing cost price per piece for new concepts are as follow.

Ratio method SLS – PA2241FR	
€70 SLS PA2241FR	Cost price per piece concept in €
53761 mm3	Volume concept in mm3

Ratio method FDM – Ultem9085	
€244 FDM Ultem9085	Cost price per piece concept in €
53761 mm3	Volume concept in mm3

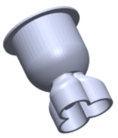
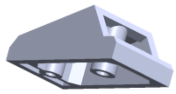
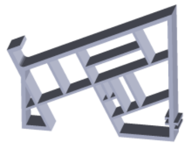
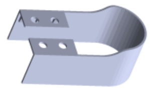
Which finally results in the following 2 formulas.

$$\boldsymbol{concept\ price\ in\ €\ SLS\ PA2241FR} = \frac{(€70 * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ mm^3}$$

$$\boldsymbol{concept\ price\ in\ €\ FDM\ Ultem9085} = \frac{(€244 * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ \ mm^3}$$

Validating the price determination formula

It is found necessary to validate the accuracy of the created formulas to calculate the price for new concepts. These formulas are based on CAD model volume, but as we know is volume of an model not the only aspect on which a price is calculated with. For this reason are the formulas tested with the following 5 models.

Models	Lamp holder 	Suitcase handle 	Laptop stand 	Zipper 	Housing 
Volumes	18069 mm3	7800 mm3	121926 mm3	23954 mm3	27051 mm3

The validation will be done using the online cost calculator Materialise offers via https://i.materialise.com/en/3dprint and compare the results with the outcomes of the formulas. In this way could the difference be calculated and an average difference can be conclude. Important to note are the available materials in the online calculator. For SLS, the option of PA is selected and for FDM is ABS selected due to limited availability of material types. For this reason would the calculator results not be entirely correct either.

	Lamp holder	**Suitcase handle**	**Laptop stand**	**Zipper**	**Housing**
Online calculator SLS	€12,91	€12,75	€109,61	€30,89	€47,63
Formula SLS	€23,50	€10,15	€158,75	€31,19	€35,22
Difference	+82%	-20%	+45%	+1%	-26%
Online calculator FDM	€95,20	€56,00	€366,80	€123,90	€114,80
Formula FDM	€82,01	€35,40	€553,37	€108,72	€122,77
Difference	-14%	-37%	+50%	-12%	+7%

As can be seen in the table, the difference between the results of the formula and the online calculator can vary considerably per component. This shows that the results of the formula are not sufficiently accurate. However, the formula could still be used during this level of concept development to estimate the price. But this is only possible after it has been sharpened slightly by taking the average difference into account.

Average difference SLS	+16,4%
Average difference FDM	-1,2%

$$\boldsymbol{concept\ price\ in\ €\ SLS\ PA2241FR} = \frac{(€70 * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ mm^3} * \mathbf{1,164}$$

$$\boldsymbol{concept\ price\ in\ €\ FDM\ Ultem9085} = \frac{(€244 * \boldsymbol{volume\ concept\ CAD\ in\ mm^3})}{53761\ \ mm^3} * \mathbf{0,988}$$

Appendix H

The CAD model volumes of the redesigned concepts which are used to determine the weight and price for these concepts are listed below.

	Zodiac seat armrest	Lavatory toilet paper holder	Recaro bi-fold seat table	Boeing window shade	Zodiac business class bumper
Volumes	106.259 mm3	20.209 mm3	385.484 mm3	124.841 mm3	52.030 mm3

Zodiac seat armrest	**Original part**	**SLS**	**%**	**FDM**	**%**
Price	€186,90	€161,05	-13,83	€476,48	+154,93
Leadtime	83 days	2 days	-97,59%	2 days	-97,59%
Weight	0,186 kg	0,142 kg	-23,66	0,150 kg	-19,35
Assembly	6 parts	5 part	-16.67	5 part	-16.67

Lavatory toilet paper holder	**Original part**	**SLS**	**%**	**FDM**	**%**
Price	€240,06	€30,62	-87,24	€90,62	-62,25
Leadtime	138 days	2 days	- 98,55	2 days	- 98,55
Weight	0,042 kg	0,027 kg	-35,71	0,029 kg	-30,95
Assembly	8 parts	1 part	-87,50	1 part	-87,50

Recaro bi-fold seat table	**Original part**	**SLS**	**%**	**FDM**	**%**
Price	€342,38	584,24	+70,64	1728,56	+404,86
Leadtime	56 days	2 days	-96,42	2 days	-96,42
Weight	0,584 kg	0,516 kg	-11,64	0,545 kg	-6,67
Assembly	26 parts	1 part	-96,15	1 part	-96,15

Boeing window shade	**Original part**	**SLS**	**%**	**FDM**	**%**
Price	€282,15	€189,20	-32,94	€559,81	+98,40
Leadtime	3 days	2 days	-33,33	2 days	-33,33
Weight	0,218 kg	0,167 kg	-23,39	0,176 kg	-19,27
Assembly	3 parts	1 part	-66,67	1 part	-66,67

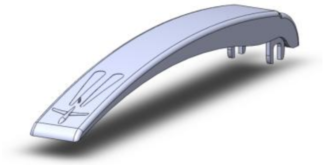
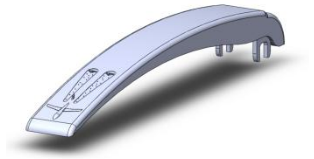
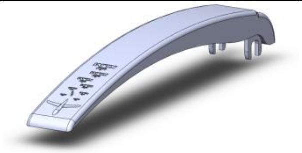
Zodiac BC cabin bumper	**Original part**	**SLS**	**%**	**FDM**	**%**
Price	€3691,30	€78,85	-97,86	€233,31	-93,67
Leadtime	168 days	2 days	-98,81	2 days	-98,81
Weight	0,095 kg	0,0697 kg	-26,63	0,0736 kg	-22,52
Assembly	1 part	1 part	0	1 part	0

Appendix I

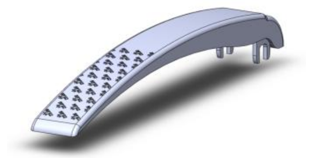
Appendix I shows the different patterns to customize the seat armrest with. A short questionnaire was taken with 3 passengers. The question was simple, which of the 3 version per variations they found the nicest and best fit at KLM.

Pattern research for armrest

Variation 1: Sunk airplane

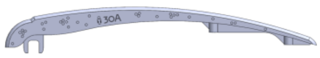
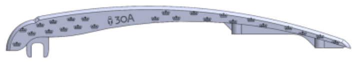
 **Sunk airplane v1**	 **Sunk airplane v2**	 **Sunk airplane v3**
	Participant 1: The whole fits well together, the logo and condens seem to be part of the aircraft **Participant 2:** This version is very nice with the logo, version 1 has nothing to do with KLM and 3 is chaotic which makes it childish. KLM is a serious company. **Participant 3:** This is the nicest and best-suited version for KLM. Simple but classy.	

Variation 2: Front only

 **Front only v1**	 **Front only v2**	 **Front only v3**
		Participant 1: 1 large KLM logo stands out well and the subsequent small crowns provide a nice pattern that looks calm. This is the only serious looking thing that suits KLM.

		Participant 2: This represents the royalness and looks most subtle and classy of all variants. **Participant 3:** Here too, this version is the best fit for KLM because it is classy and simple. Should not be too striking

Variation 3: Side only

 **Side only v1**	 **Side only v2**	 **Side only v3**
	Participant 1: This is a great way to bring the business class pattern back into economy class. This makes for a nice whole on the plane. **Participant 2:** This variant is the nicest because it forms a whole and gives a business class feeling in the economy class. **Participant 3:** Very nice idea, this version will ensure unity within the cabin interior.	

Appendix X

DOA rights of KLM E&M.

EASA
European Aviation Safety Agency

Terms of Approval 21J.012
Issue 10, 17 December 2018

KLM Engineering & Maintenance

Annex A

Scope of work

	TC	STC	major changes	minor changes	major repairs	minor repairs	flight conditions	permit to fly
Large aeroplane								
Avionics								
Autoflight systems		■	■	■	■	■	■	
Communication systems		■	■	■	■	■	■	
Diagnostic and Maintenance systems		■	■	■	■	■	■	
Indicating, Alerting systems		■	■	■	■	■	■	
Navigation systems		■	■	■	■	■	■	
Recording systems		■	■	■	■	■	■	
Surveillance systems		■	■	■	■	■	■	
Cabin								
Cabin interiors		■	■	■	■	■	■	
Cargo compartments		■	■	■	■	■	■	
Electrical cabin systems		■	■	■	■	■	■	
External schemes, placards and markings		■	■	■	■	■	■	
Flight deck interiors		■	■	■	■	■	■	
Electrical Systems								
Electrical generation / distribution systems		■	■	■	■	■	■	
External lighting systems		■	■	■	■	■	■	
Wireless transmission systems		■	■	■	■	■	■	
Environmental Control Systems								
Air conditioning systems				■	■	■	■	
Bleed systems				■	■	■	■	
Ice and Rain protection systems				■	■	■	■	
Oxygen systems				■	■	■	■	
Pressurization systems				■	■	■	■	
Water and waste systems				■	■	■	■	

An agency of the European Union

Page 3 of 4

Hydro-Mechanical Systems				
Flight controls	■	■	■	■
Fuselage doors	■	■	■	■
Hydraulics/Pneumatics systems	■	■	■	■
Landing gear systems	■	■	■	■
Ram air turbine	■	■	■	■
Powerplant and Fuel Systems				
APU installations	■	■	■	■
Fuel systems	■	■	■	■
Powerplant installations	■	■	■	■
Structures				
Control surfaces / Moveables	■	■	■	■
Empennage	■	■	■	■
Engine mounts	■	■	■	■
Fuselage	■	■	■	■
Landing gears	■	■	■	■
Wings	■	■	■	■
Turbine engine				
Propulsion				
Propulsion	■	■	■	■

Legend:

(grey)	Title for product
(light grey)	Title for scope
■	Within scope
	Outside scope

List of products

[not applicable]

Limitations

Limitations common to all products and activities
Development of Operational Suitability Data excludes the OSD constituents SIMD and MCSD

Appendix Y

AM in Aviation

OPERATORS

CHINA EASTERN

Electronic flight bag support
A330, A320 and B737

Print tech. FDM
Partnership: Stratasys
Costs savings 72%
Leadtime 90%

Function: Functional
Material: Plastic
Visibility: Visible

CHINA EASTERN

Business class news paper holders

Print tech. FDM
Partnership: Stratasys
Costs savings 48%
Leadtime 90%

Function: Auxiliary
Material: Plastic
Visibility: Visible

CHINA EASTERN

Door handle covers
B777

Print tech. FDM
Partnership: Stratasys

Function: Auxiliary
Material: Plastic
Visibility: Visible

CHINA EASTERN

Seat signs
B777

Print tech. FDM
Partnership: Stratasys
Costs savings 56%
Leadtime 75%

Function: Auxiliary
Material: Plastic
Visibility: Visible

AIR NEW ZEALAND

Business class cocktail trays

Print tech. FDM
Costs effectiveness
Reduced weight
Reduced leadtime
Reduced inventory

Function: Functional
Material: Plastic
Visibility: Visible

الاتحاد
ETIHAD

LCD shroud
B777

Print tech. FDM
Partnership: DIEHL
Costs effectiveness
Reduced weight 9 - 13%
Reduced leadtime

Function: Auxiliary
Material: Plastic
Visibility: Visible

الاتحاد
ETIHAD

Electronics cap armrest

Print tech. FDM
Partnership: DIEHL
Costs savings 20 - 30%
Retro fit ensure longer use old parts

Function: Auxiliary
Material: Plastic
Visibility: Visible

Emirates

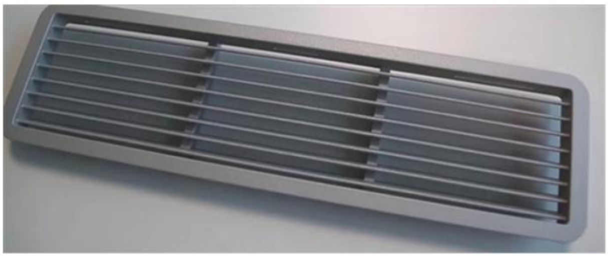
Video monitor shroud

Print tech. SLS
Partnership: 3D Systems
Reduced weight 9 - 13%
Reduced inventory

Function: Auxiliary
Material: Plastic
Visibility: Visible

Emirates

First class air vent grill



Print tech. SLS
Partnership: UUDS
Reduced weight
Strengthened part
Reduced inventory

Function: Auxiliary
Material: Plastic
Visibility: Visible

AIRFRANCE

CAS seat gap cover
A321

Print tech. SLS
Partnership: Materialise
Reduced leadtime
Supllier independancy

Function: Auxiliary
Material: Plastic
Visibility: Visible

AIRFRANCE

Arnic 600 rack ventilation duct

Print tech. SLS
Partnership: Materialise
Reduced leadtime
Supllier independancy

Function: Functional
Material: Plastic
Visibility: Not in sight

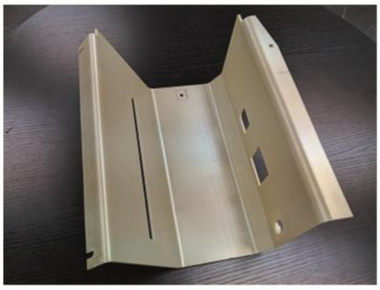
THIRD PART POA HOLDER

WESTERN TOOL & MOLD

Business class headphone cabinet

Print tech. FDM
Partnership: Stratasys
Reduced weight
Supply chain efficiency
Customization

Function: Cosmetic
Material: Plastic
Visibility: Visible

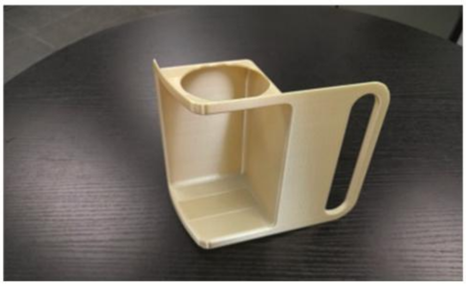


WESTERN TOOL & MOLD

First class lavatory part

Print tech. FDM
Partnership: Stratasys
Reduced weight
Supply chain efficiency
Customization

Function: Cosmetic
Material: Plastic
Visibility: Visible



DIEHL

Curtain comfort header
A350

Print tech. FDM
Reduced lead time
Customization
Simplyfied tooling process

Function: Cosmetic
Material: Plastic
Visibility: Visible

Air ducts for laminar air
Bell Helicopter 429

Print tech. SLS
Reduced lead time
Increased material recyclability
Integrated design reduced parts
Simplyfied tooling process

Function: Technical
Material: Plastic
Visibility: Not in sight

Borescope bosses
A320 neo

Print tech. SLS
Reduced lead time
Reduced weight
Reduced cost
Simplyfied tooling process

Function: Critical
Material: Metal
Visibility: Not in sight

Various air ducts

Print tech. FDM
Reduced lead time
Reduce weight

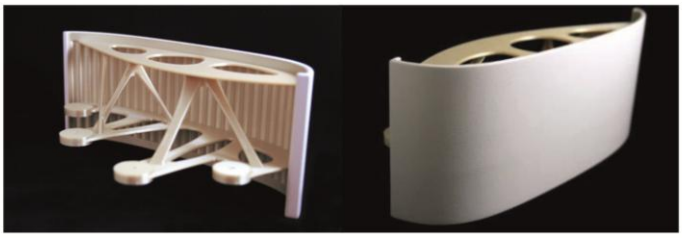
Function: Technical
Material: Plastic
Visibility: Not in sight

AIRBUS

Overhead storage spacer panel
A320

Print tech. FDM
Partnership: Materialise
Cost effective
Reduced weight 15%
Reduced lead time

Function: Cosmetic
Material: Plastic
Visibility: Visible



AIRBUS

Crew seat cover
A310

Print tech. FDM
Partnership: Stratasys
Reduced weight
Reduced lead time

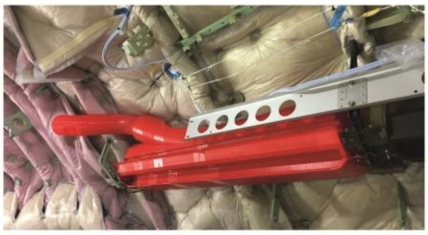
Function: Cosmetic
Material: Plastic
Visibility: Visible

AIRBUS

Air nozzle
A330 neo

Print tech. FDM
Reduced weight
Reduced lead time
Cost effective

Function: Technical
Material: Plastic
Visibility: Not in sight



AIRBUS

Titanium pylon bracket
A350

Print tech. EBW

Function: Critical
Material: Metal
Visibility: Not in sight

AIRBUS

Titanium latch shafts
Helicpoter

Print tech. SLS
Partnership: EOS
Reduced costs 25%
Reduced weight 45%

Function: Technical
Material: Metal
Visibility: Not in sight

BOEING

Structural titanium component
B787

Print tech. Rapid Plasma Deposition
Partnership: Norsk Titanium
Reduced cost
Reduced weight 15%
Reduced lead time

Function: Critical
Material: Metal
Visibility: Not in sight

LIEBHERR

Titanium hydrolic valve block
Airbus A380

Print tech. SLS
Reduced weight 35%
Integrated design reduced parts

Function: Critical
Material: Metal
Visibility: Not in sight

LIEBHERR

Titanium rudder actuator

Print tech. SLS
Reduced weight 60%
Reduced size 30%
Integrated design reduced part

Function: Critical
Material: Metal
Visibility: Not in sights

LIEBHERR

Titanium jet pump

Print tech. SLS

Function: Critical
Material: Metal
Visibility: Not in sight

T25 sensor housing
GE 90-94B engine

Print tech. SLS
Reduced leadtime
Integrated design reduced parts

Function: Critical
Material: Metal
Visibility: Not in sight

Fuel nozzle
LEAP engine

Print tech. SLS
Reduced leadtime
Reduced weight 25%
Integrated design reduced parts 90%

Function: Critical
Material: Metal
Visibility: Not in sight

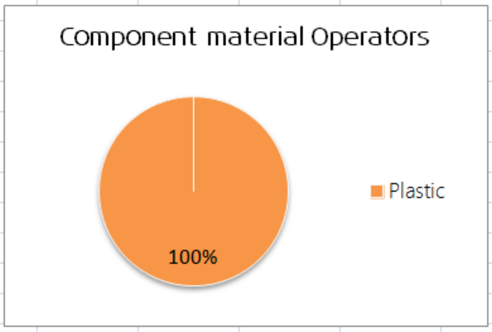
Print tech. SLS
Reduced leadtime
Reduced weight
Integrated design reduced part

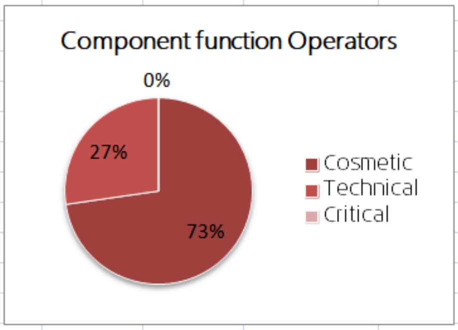
Function: Critical
Material: Metal
Visibility: Not in sight

RESULTS of listed components

OPERATORS
Plastic
11

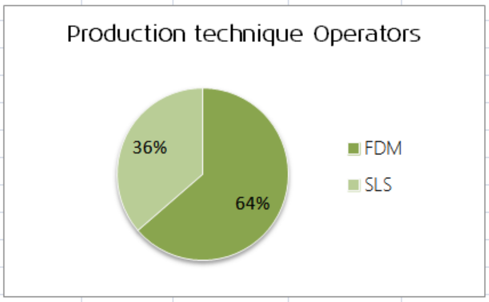
OPERATORS		
Cosmetic	Technical	Critical
8	3	0

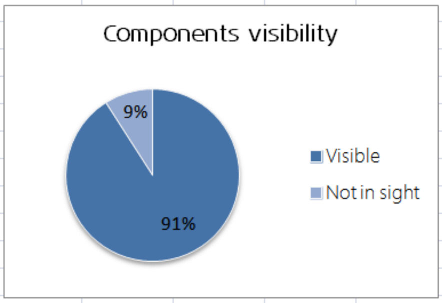




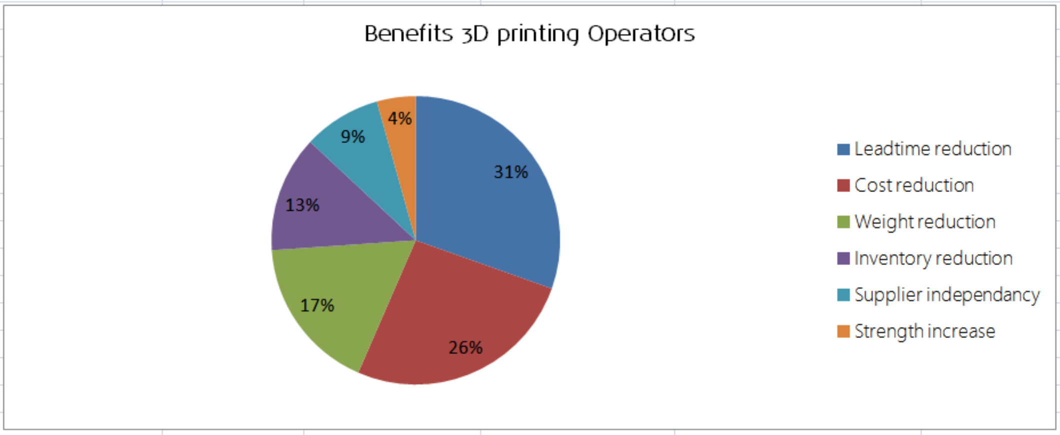
OPERATORS	
FDM	SLS
7	4

OPERATORS	
Visible	Not in sight
10	1





OPERATORS					
Leadtime reduction	Cost reduction	Weight reduction	Inventory reduction	Supplier independancy	Strength increase
7	6	4	3	2	1



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