

Master's Project - Dissertation

MSc Industry 4.0 Advanced Manufacturing

Module Code: ACFA7003

Supervisor: Alan Mumby

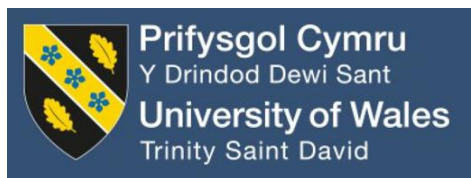
Application of Additive manufacturing in Aircraft interiors

07th March 2024

Student: Vikram Vhanmane

Student ID: 2116969

Email: 2116969@student.uwtsd.ac.uk



Executive Summary

In aircraft interior different materials are used, e.g. steel alloys, aluminium alloys, sheet metal, composites, polymers, leather, fabrics, and foams. Aerospace industry is governed by strict industry regulations. Hence, the materials used need to be regulation compliant, high performance, meeting strength requirement, heat resistant and reliable. Looking at these requirements, it is difficult to use parts produced using additive manufacturing technology for structural applications.

Aerospace industry leaders are already exploring additive manufacturing in different applications. Passenger seat is main aspect of commercial aircraft interior. In first phase, we will try to utilise this disruptive industry 4.0 technology for non-structural elements of passenger seat. Non-structural but aesthetically important vacuum formed, or injection moulded parts are potential areas to experiment AM technology. Another application areas can be overhead bins, lavatories, galleys, and other food equipment.

In aerospace industry some metal or plastic 3D printed parts are successfully used for non-structural applications. In additive manufacturing technology Ultem 9085 CG is certified material for aerospace applications. Fused Filament Fabrication technology is used to produce AM parts using Ultem 9085 CG as feedstock (raw material).

Aircraft Seating aftermarket departments have started exploring opportunities for AM technology implementation where required part quantity is less & AM parts can meet strength requirement for the specified application. Our aim is to meet customer expectations by offering lighter & stronger products using AM technology. Lighter products will be fuel efficient & it will reduce environment impact.

As an Industry 4.0 student, we will try to find out possible areas of additive manufacturing applications in aircraft seating. We will conduct case study research, refer research material available on this subject & take support from design focus group. We will explore options about lightweight & stronger materials suitable for general application. There are many potential areas for AM technology application. In the first phase we will look at the parts which non-structural & not part of structural elements of the seating product.

Acknowledgements

I would like to thank Alan Mumby, lecturer and dissertation tutor for his guidance, support and laughs throughout the last two years of study. He was always available for discussion and knowledge sharing.

I gratefully acknowledge the help and support of the Safran design and manufacturing team during my work on this study.

A special thanks to my mother for her support and words of encouragement. Finally, special thanks to my wife & daughter for putting up with my stress, long working hours, and personal doubt, who supported me constantly.

Declaration Statement

DECLARATION

This work is produced for MSc Industry 4.0 Advanced Manufacturing dissertation purpose. It has not previously been accepted in substance for any educational or commercial purpose. and is not being concurrently submitted in candidature for any other degree.

Signed by:



Date: 07th March 2024

This document is based on my own research & industry experience, except where otherwise stated. All reference sources are acknowledged giving specific references.

Signed by :



Date: 07th March 2024

Contents

Executive Summary	2
Acknowledgements	3
Declaration Statement	4
Abbreviations	8
 Chapter 1 – Introduction	 9-11
1.1 Research Background	9
1.2 Research Methodology	10
1.3 Aims	11
1.4 Objectives	11
1.5 Research Ethics	11
 Chapter 2 – Additive Manufacturing materials	 12-15
2.1 Plastics	12
2.1.1 Thermosets	12
2.1.2 Thermoplastics	13
2.2. Metal	14
2.2.1 Titanium Alloy	14
2.2.2 Special metals	15
2.2.3 Metal Matrix composites	15
 Chapter 3 – Additive Manufacturing Processes	 16-21
3.1 Introduction	16
3.2 Classification	16
3.3 Established Technologies	17
3.4 Process Selection	21
 Chapter 4 – Additive Manufacturing Advantages & Limitations	 22-26
4.1 Advantages	22
4.2 Defects	24
4.2.1 Porosity	24
4.2.2 Cracking and delamination	24
4.2.3 Poor surface finish	24
4.2.4 Residual stress & Distortion	25

4.2.5 Balling phenomenon	25
4.3 Limitations	25
4.3.1 Material Limitations	25
4.3.2 Strength and compatibility	25
4.3.3 Cost	26
4.3.4 Quality Control	26
4.3.5 Post Processing	26
4.3.6 Build Failure	26
 Chapter 5 – Generative Design	 27-29
5.1 Generative Design	27
5.2 Generative Design and Additive manufacturing corelation	27
5.3 Generative Design examples	28
 Chapter 6 – AM Application in Aftermarket	 30-37
6.1 Background	30
6.2 Potential application areas	30
6.3 Material Selection	32
6.4 Flammability & Certifications Requirements	33
6.5 Design considerations	35
6.6 Cost Analysis	36
6.7 Manufacturing & Supply chain	37
6.8 Prototyping & Testing	37
6.9 Future Scope	37
 Chapter 7 – AM Aerospace Applications	 38-43
7.1 Currant Aerospace market Scenario	38
7.2 AM application Success Stories	38
7.2.1 Safran’s AM Journey	39
7.2.2 Boeing’s AM Journey	39
7.2.3 GE Aviation’s AM Journey	39
7.2.4 Airbus’s AM Journey	40
7.2.5 Stratasys & 3D Systems	41
 Chapter 8 – Supply Chain management	 44-47
8.1 Adoption of AM technology	44
8.2 Impact of AM on supply chain	45
8.3 Impact of AM on Aircraft Industry Spare parts supply chain	47
8.4 Impact of AM on Logistics	47
 Chapter 9 – Impact on Environment	 48-50

9.1 Energy Consumption	48
9.2. Build Failure & Energy consumption	49
9.3 Circular Economy	49
9.4 Further Study	50
Chapter 10 – Conclusion & Recommendations	51-53
10.1 Findings	51
10.2 Conclusion	52
10.3 Role of organisations & education system	53

Abbreviations

AM	Additive Manufacturing
AMT	Additive Manufacturing Technology
.STL	Standard Triangle/Tessellation Language (STereo Lithography interface)
FAA	Federal Aviation Administration
EASA	European Aviation Safety Agency
FAR	Federal Aviation Regulations (FAR & CFR are interchangeable)
CFR	Code of Federal Regulations (FAR & CFR are interchangeable)
CS	Certification Specification
MMC	Metal Matrix Composites
FST	Fire, Smoke & Toxicity
GD	Generative Design
AIG	Application Innovation Group
R & T	Research and Technology
LSAM	Large scale additive manufacturing
FST	Fire Smoke Toxicity
ABS	Acrylonitrile butadiene styrene
SLS	Selective Laser Sintering
ISO	International standardisation organisation
ASTM	American Society for testing and materials
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
CAD	Computer Aided Design
PLA	Polylactic Acid
SLA	Stereolithography
CAA	Civil Aviation Authority of UK
OEM	Original Equipment Manufacturer
TPL	Third party Logistic Provider
PIT	Production Inventory Transportation
ASTM	American Society of Testing and Materials

Chapter 1 – Introduction

1.1 Research Background

Additive manufacturing or 3D printing is the process of producing physical components by printing it layer by layer. In future we will be able to produce complex parts without needing any tools or complex machinery. Many kinds of raw materials will be used in AM printing technology such as polymers, aluminium alloys, steel alloys, composites, ceramic, or some advance alloys. This technology is already being used in different range of applications from making toys to turbines. (Schwab, 2017 p70).

AM technology offers lots of different options to design and manufacture parts. Designers can come up with completely out of the box ideas for any new or existing products. Present manufacturing processes like CNC machining involves metal removal to get final part. Parts are manufactured from large billet or bars to produce final shape. For injection moulding or stamping dies metal tools are required which are again manufactured using machining process of metal removal. So, in many current manufacturing processes lots of raw material is wasted which results in scrap. It's not uncommon for CNC machining to produce a 50% scrap rate. We can imagine high cost involved in raw material, machining time, energy consumption, disposal of waste & resources needed to perform all these tasks. (Freemer, 2023).

GE aviation experimented 3D printing technology to manufacture aerospace parts in last decade. In 2015 FAA approved GE's first 3D printed part "The housing for T25 sensor" in a commercial jet engine. And after that GE introduced 3D printed fuel nozzle injectors for LEAP jet engine. Originally there were total 20 different parts welded & brazed together to produce nozzle injector. And by using additive manufacturing technology this whole assembly is created as a single part. And in this process 25% weight reduction is also achieved. GE had produced 180,000 nozzle injectors by Jul 2023 (GE Website 2015 & 2018)

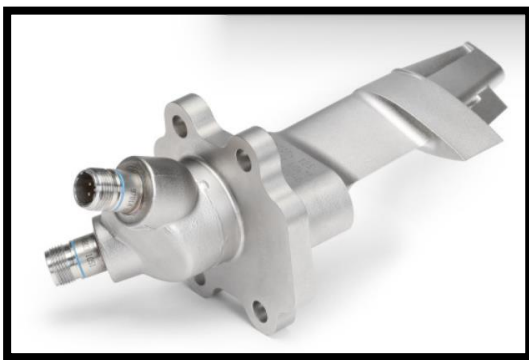


Fig. 01: 3D printed housing for T25 sensor
Image credit: GE Aviation



Fig. 02: 3D printed fuel nozzle for LEAP.
Image credit: GE Aviation

Additive manufacturing technology shows considerable amount of material & weight saving over conventionally machined parts. High value materials such as titanium, cobalt-chrome alloy are successfully used in this new technology. In coming days additive manufacturing will become faster & reliable to suit the application. And more widespread commercial use will result in cheaper price for 3D printing machines & raw material. This shift in the technology will increase demand for engineers from all part of the world without any location restriction & design data can be sent for 3D printing anywhere in the world. Existing workforce will need to learn new skill sets to operate & mange 3D printing machines effectively.

1.2 Research methodology

In the initial stage we are starting with Qualitative research methods. As the research progresses, we will refine methodology.

Case Study Research

Safran Group is operating in multiple domains in the aerospace sector. And group companies are located all over the world. All these group companies are experimenting with industry 4.0 technologies. Apart from Safran other major players in the aerospace industry are also trying to utilise advantages of AM technology. We will study & understand experiments done by other industry leaders.

Focus Group

Safran seats has a research & technology team working constantly on advance technology projects. Design team working on the project can provide valuable inputs about possible technology improvements.

Design Forum (Advance Manufacturing Shows)

All across the UK advance manufacturing events are happening. These events are beneficial for gaining knowledge about new experiments happening in the world of Industry 4.0 technology. Different manufacturers, suppliers demonstrate their capabilities of 3D printing technology, advance materials, latest improved designs.

Reference material:

Research based on latest research papers; journals, reference books published in the area of additive manufacturing will be helpful to complete the Dissertation.

1.3 Aims

The aim of this dissertation is.

- To provide a guide for reference for AM implementation aircraft seating products.
- To use a case study example throughout, analysing the implementation against existing literature.
- Encourage use of AM technology where possible.
- Help manufacturers and airlines to reduce carbon footprint.
- Detail the benefits, challenges, risks, and considerations while utilising AM technology.

1.4 Objectives

The aim of this dissertation is based on a literature review in the specific area of additive manufacturing in Aerospace industry. Successful implementation of this technology in the form of case studies will be used throughout and will be analysed against the literature.

Specific objectives are:

- Analyse the capabilities of AM technology.
- Analyse different materials & manufacturing methods available in AM in aircraft seating
- Analyse areas where supply chain improvements can be achieved by using AM technology.
- Analyse the types of innovations that can be achieved, detailing the risks and benefits for environment.

1.5 Research Ethics

There are ethical considerations those must be addressed. This dissertation is mainly literature review based, and hence multiple sources of information will be discussed throughout the dissertation. When researcher draw upon other people's work in the research, whether as background information, methodology, inspiration, phrasing or for other purposes, researcher will attribute this fully and correctly. This will be addressed throughout the dissertation by citing the source in the text, and then by providing full details of the source in a list of references. (Cottrell, S 2014, p109.

Regarding implementation of additive manufacturing applications in aircraft seating product details of newly implemented projects will be kept confidential. Only publicly available general applications will be referenced.

Chapter 2 – Additive Manufacturing materials

Everyday new technologies are being developed in the field of additive manufacturing. This allows us to explore new materials & alloys suitable for specific application. Engineering materials can be classified into four main groups, determined by their internal structure and mechanical properties viz. Metals, Plastics, Ceramics & Composites. (Bolten W, 2020.)

2.1 Plastics

Plastic materials are created using naturally available resources like cellulose, coal, salt, crude oil. Polymerisation or polycondensation process is used for manufacturing of plastic parts. Plastic materials are chemically stable, water & shock resistant & lightweight. Plastics have comparatively lower thermal conductivity & very good insulation properties at working temperature. (Plastics Europe website, 2023)

Nowadays there are more environment friendly sources are used to produce plastics. This plastic which is known as renewable plastic or bioplastics is manufactured using [recycled food waste, vegetable fat, wood fibre, or bacteria. These plastics are less harmful for humans & environment. It gets dissolved in couple of months' time. (Nikolovska, G 2023.)

There are numerous ways to classify plastic materials. For this dissertation purpose we will investigate below main plastic categories. 1. Thermosets & 2. Thermoplastics (amorphous & semicrystalline)

2.1.1 Thermosets

Thermoset plastics have high melting points. After heating to specified temperature & cured to final solid state their components & physical properties become permanent. Thermosets become very hard & rigid which offers stable performance under varying temperature conditions. These materials can be further reinforced with Carbon or fibreglass to improve strength. This makes thermosets much stronger during operation. additive manufacturing process make use of thermosets materials.

Thermoset plastics are rigid in terms of shape and size. These are hard and highly stable & resistant to high temperature conditions. These can be reinforced by adding carbon, Kevlar, or fibreglass to improve performance. Once produced for any specific application, it can't be reshaped or recycled for another application. But these thermoset materials are long lasting due to structural integrity and better heat resistance. After completion of defined life, it becomes scrap & need to be thrown in the atmosphere which is not ideal situation for circular economy. Thermosets account for 15-20% of global plastic production. Thermosets are important because of their high-performance applications, but it is not possible to recycle them. (Sardon H, Zi-Chen Li 2020)

2.1.2 Thermoplastics

Thermoplastic materials have low melting points. After heating, these materials will soften to malleable state, or it will melt into proper liquid. In injection moulding or extrusion resins it can be shaped as per design requirement. After completion of defined life, it can be heated & converted into liquid to be utilized for another application in different shape or size. Even extreme heat does not affect original material properties. It can be re-used again & again without losing characteristics of the original thermoplastic material. In short thermoplastics behave like water under heat treatment. (API Website, 2023)

Thermoplastics are further subdivided into two categories as Amorphous & semi-crystalline thermoplastic. Amorphous thermoplastics do not have specific molecular structure. These are normally solid, clear, and stiff material with low shrinkage.

Semi-crystalline thermoplastics has crystal-like structure. Those are comparatively stronger & less fragile. Distortion temperature of crystalline thermoplastic is higher. Semi-crystalline thermoplastics can soften with minor temperature & changes its viscosity considerably. As Thermoplastics have low melting point, we are limited with the application of these materials. These materials are suitable for applications at room temperature. But at high temperature working conditions these parts may change shape or soften which will result in poor strength & performance. (Bourell D., 2019)

After years of research & testing Ultem 9085 resin material is developed for high performance & high durability applications. Its strength & toughness makes it preferred 6choice for aerospace industry.

Below are some important characteristics of Ultem 9085 resin

Heat resistance: Ultem resin can withstand high temperatures. (Its heat deflection is tested at 307 ° F.

Aerospace grade certifications: ULTEM™ resin is FST (Fire-Smoke-Toxicity) rated and one of the only 3D printing plastics certified for aircraft components. FAR 25.853 is the key regulation in the aerospace industry. (FAR 25.853 will be discussed in detail in the Chapter 05 AM Application in Aftermarket.)

Strength & Weight: Ultem resin can provide weight reduction benefits as compared to materials used in the aircraft components. (Stratasys 2019)

Thermoset materials (These cant be reused by melting)	Thermoplastic Materials (These can be reused by melting)	
	Semi-Crystalline Thermoplastics (some molecular structure)	Amorphous Thermoplastics (no molecular structure)
1. Phenolics 2. Epoxy 3. Silicon 4. Polyurethane	5. Polypropylene (PE) 6. Polyamide (Nylon) 7. Polypropylene terephthalate (PET) 8. Polytetrafluoroethylene (PTFE) 9. Ultem	10. Acrylonitrile butadiene styrene (ABS) 11. Polycarbonate (PC) 12. Polystyrene (PS) 13. Polyetherimide (PEI)

Table 1: Types of Plastic material
(Based on information referred from A Classification of plastics materials,
Artificial Intelligence in Engineering, Volume 10, Issue 1, 1996,)

For material extrusion amorphous thermoplastics are preferred due to their melting properties. These polymers, which include popular material like ABS and PLA, soften in a wide temperature range up to the glazing temperature. This results in a high-viscosity material suitable for extrusion through nozzle of 0.2-0.5 mm dia. Material extrusion processes need support structures, which need to be removed as a part of post processing. Normally, gaps exist between the deposited layers of extruded material. As a result, mechanical characteristic of the finished part maybe poor & it may show anisotropy effect.

2.2 Metals

There are variety of metals commercially available for additive manufacturing process. But in aerospace sector there is strict requirement of strong, lightweight & aero sector compliant materials. These stringent requirements reduce available material choices. Aluminium, Stainless steel, Titanium alloys, Cobalt chrome alloys & Nickel super alloys are specially used in the aerospace sector.

In the AM process input raw materials in the form of powder, sheet or wire is converted to thick metallic final product. This is achieved by melting or solidification process performed layer by layer using suitable energy source. This energy source can be laser, electric arc, electron beam or using ultrasonic vibration. (Debroy, 2018)

2.2.1 Titanium alloys:

compared to steel & aluminium alloys, titanium alloys are considered new structural material. Due to good strength to weight ratio & corrosion resistance ability titanium alloys became preferred options quickly. It offers combination of lightweight and strong structure, corrosion resistance & stability at high temperature working conditions. Ti-6Al-4V alloy is largely used in the aerospace industry. Titanium density is 4.5g/cm³ whereas steel density is 7.8g/cm³. Titanium alloys are 40% lightweight as compared to steel alloys.

Titanium alloys are used at higher scale in the military fighter plane applications. Large scale application in military fighter planes is driven by design in response to the larger thermal & mechanical loads, which are associated with ultra-high speed & improved maneuverability. Titanium alloys perform exceptionally well as a spring material. As compared to high strength steel, the density corrected modulus of elasticity can achieve even 70% saving in the weight, volume reduction up to 50% & also improved corrosion resistance. (Peters M, AEM 2003)

2.2.2 Special materials:

Additive manufacturing can be used to produce fine design & delicate shapes. Medical & Jewellery industry uses precious metals for this application. Gold, Platinum, Ceramics are used to create dental crowns, Jewellery, and electric connectors are some of the examples.

2.2.3 Metal Matrix composites

Metal Matrix Composites are also preferred over conventional options because of their improved mechanical properties. MMC offer greater hardness, corrosion resistance & high strength to weight ratio. Many research projects are conducted to understand the feasibility of AM techniques to utilise best properties of 3D complex MMCs parts. Aluminium, Steel, Gold, Titanium, Nickel, Iron are used as main matrix materials whereas graphite, Aluminium oxide, Boron carbide, Silicon carbide, Beryllium oxide, Titanium carbide are used as reinforcement materials. (Bhuvanesh Kumar & Sathiya, 2021)

Lots of research is happening for developing complex structures with these alloys suitable for application in extreme conditions in the aerospace and nuclear industries. AM technology has the potential to enhance the use of these materials as it can eliminate the need for conventional processing steps, produce any required geometry by utilising less quantity of expensive materials.

Chapter 3 – Additive Manufacturing Processes

3.1 Introduction

Additive manufacturing or 3D printing is in discussion since 1980s. In 1986 first patent in the field of additive manufacturing technology was granted for an “Apparatus for production of three-dimensional objects by Stereo lithography”, and its inventor was Hull USA Patent No. 4,575,330, 1986. (Arcos-Novillo & Güemes-Castorena, 2017)

Selective laser sintering (SLS), which utilises a laser to melt powdered material to create new part was developed in the early 2000s. (Han, 2022). Metal 3D printing was developed during the mid-2000s using new technology known as direct metal laser sintering (DMLS), This technology utilizes a laser to sinter metal powder to to create new part. (Ishfaq, 2021)

In early days there was little growth in the field of 3D printing or additive manufacturing technology. however, the 3D printing market has increased exponentially since year 2021. This has happened because of the involvement of independent researchers, hobbyists, and early industry adopter. This has created lots of interest and publicity on the subject (2016)

3.2 Classification

For additive manufacturing technologies, the raw material needs to be in the form compatible with the process. (e.g., powder, sheet, wire, liquid). And the material must show required service properties to perform successfully in the operation. For some applications, AM parts need to be post-processed to improve the performance by enhancing microstructure, surface finish & by reducing porosity, roughness so that final part will have provide accurate size, shape. This is needed to ensure that AM parts perform at the highest performance level.

For example, in vat polymerization and photopolymer-based material jetting, the feedstock (raw material) must be a liquid thermoset plastic monomer that will crosslink when exposed to the appropriate electromagnetic radiation. Finally, the material must have appropriate service qualities in order to function successfully in the specified application. Material extrusion, powder bed fusion, and other procedures make use of thermoplastic polymers. Both require thermal layer adhesion but have distinct processes. For material extrusion, amorphous thermoplastics perform most suitably, while semicrystalline polymers are typically used for powder bed fusion. (Bourell, 2017).

Today there are number of different additive manufacturing technologies commercially available in the market. These technologies have similarity and differences based on process, material, machine type, source of energy, surface finish, required post processing. It was difficult to identify and categorize all available

technologies. For educational & commercial purposes it was important to classify all available technologies.

The *International Standardisation Organisation* (ISO) and *American Society for Testing and Materials* (ASTM) in ISO/ASTM 52,900, classified all available technologies in to below 7 categories. This classification helps in understanding and deciding which technology is suitable for specific application. And for academic purpose it gives clear direction to students & researchers. (Damir, Joamin, 2022).

Additive Manufacturing Processes				
Liquid Based		Solid Based	Powder Based	
Molten	Polymerizable	Bonded Object	Melting	Binding
1. Material Extrusion	2. Vat Polymerization 3. Material Jetting	4. Sheet Lamination	5. Powder Bed Fusion 6. Direct Energy Deposition	7. Binder Jetting

Table 02: Classification of additive manufacturing according to ISO/ASTM
(Table referenced from book, A Guide to Additive Manufacturing, 2022)

3.3 Established Technologies

There are lots of different AM technologies available in the market. And everyday innovators are coming up with advancements in these technologies. Below are some of the commercially available and successfully implanted technological examples.

1. Material Extrusion

- a) Fused deposition modelling (FDM) / Fused Filament Fabrication (FFF)
- b) Construction 3D Printing, Micro 3D Printing, Bio 3D Printing

Fused deposition modelling (FDM) / Fused Filament Fabrication (FFF)

FDM AM technology is generally used to produce models, prototypes, and products. This process is simple & fast to produce personalized objects at lower cost. This is one of the popular 3D printing extrusion based technology. CAD data in .stl format is processed by internal software to create mathematical layers. This internal software orients part geometry suitable for the build process. Normally thermoplastic or thermoset solid filament received from a coil, is heated above the melting/transition point of the filament. This heated material is then transferred to an extrusion nozzle, which controls the flow. Then the drive mechanism directs the

melted filament inside the nozzle at a predefined speed. At the tip of the nozzle, the melted material is then deposited on a heated support platform to create physical part in the layer-by-layer format. At the end of first layer, the platforms lower by the defined value & then next layer is printed on top of the first layer. This step is then repeated at predefined speed. (Mohd Puad, 2020)

Materials such as acrylonitrile–butadiene styrene (ABS) and polylactic acid (PLA) have suitable thermal and rheological properties which are important for the easy fabrication process. That is the reason ABS & PLA materials are commonly used as the filament for FDM process. (Mohan, 2017)

2. Vat Polymerization

- a) Stereolithography (SLA)
- b) liquid crystal display (LCD)
- c) digital light processing (DLP)
- d) micro-stereolithography (μ SLA)

Stereolithography (SLA)

Stereolithography (SLA) is one of the earliest forms of additive manufacturing. This process fabricates 3D parts by selectively solidifying the liquid resin through a photopolymerization reaction. (HUANG, 2020). The basic fundament of this process is the curing reaction of resins, which is an exothermic polymerization process characterized by chemical cross-linking reactions. This cross-linking reaction is started by providing the energy of Ultraviolet light. (Olayan, 1996)

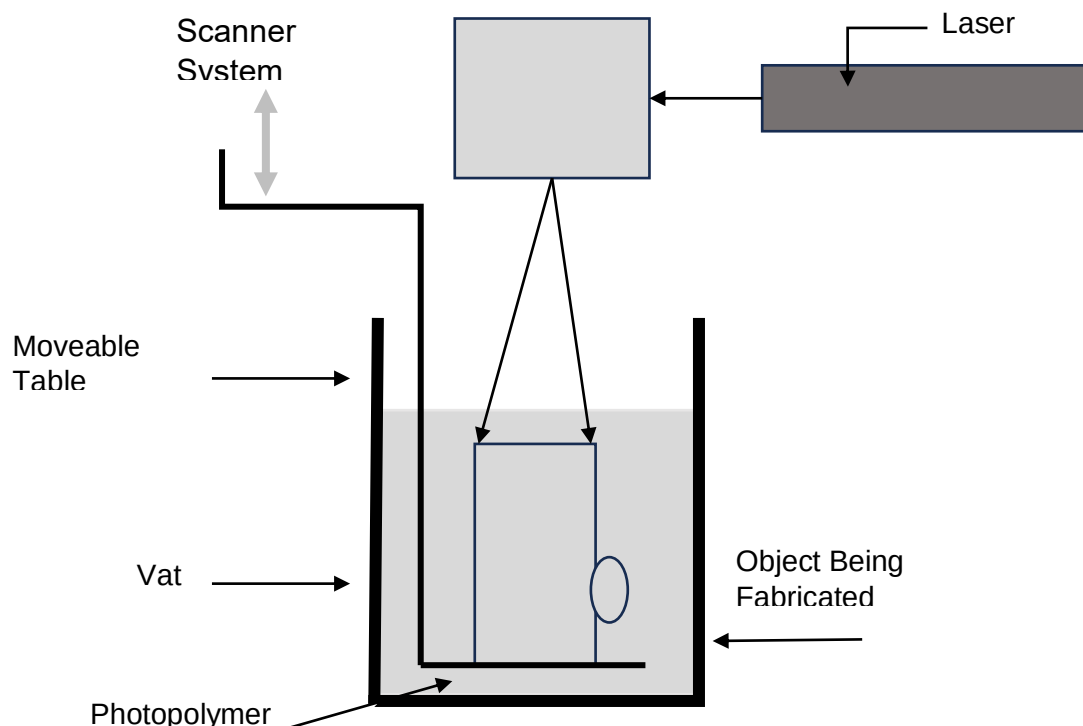


Fig. 03: Stereolithography (SLA) build process.
Image source: [DTS Bromsgrove Ltd. \(n.d.\)](#)

3. Powder Bed Fusion

- a) Selective laser sintering (SLS)
- b) Selective Laser Melting (SLM)
- c) laser powder bed fusion (LPBF)
- d) electron beam melting (EBM)

Selective laser sintering (SLS)

SLS process creates 3D profile by laser energy to selectively heat powder particles which results in fusion. The fused powder particles are solidified to achieve the 3D profile. The SLS system is made of three main parts, i.e. a powder bed, a spreading platform, and a laser system. Laser system is made up of laser and the scanner. This spreading system is made up of a slot feeder and the roller/scrapper blade which is used to even the surface. Spreading platform is used to spread the powder evenly on the building platform. The 3D part of the system is processed as planes. Each plane represents the basic laser scanning element which is known as vectors. The scan pattern of these vectors is determined based on the final product characteristics. The material is heated to a temperature just below the melting point so that it is sufficient to cause fusion by laser sintering/melting between powder particles. The powder bed surface is lowered by a height of one-layer thickness and another layer of powder is deposited and fused by the laser. This process is repeated till the final part is produced. The finished product is still kept inside the printer so that it cools down properly. (Charoo, 2020)

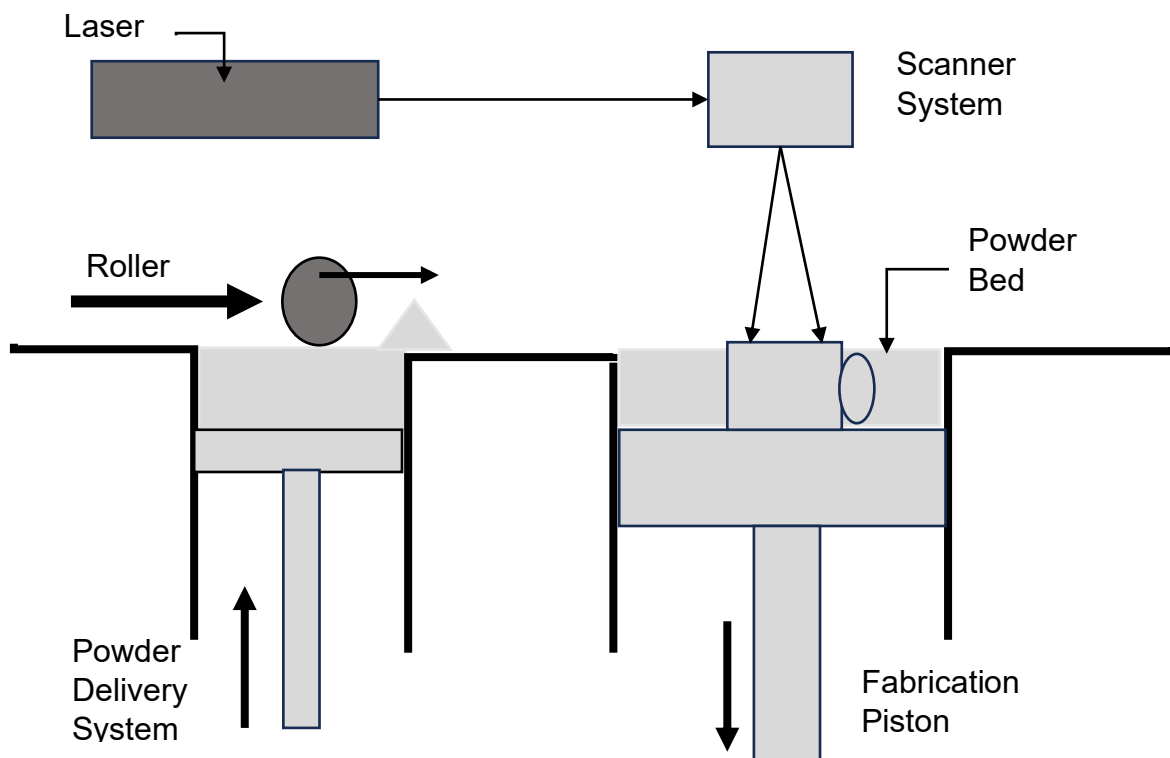


Fig 04: Selective Laser Sintering (SLS) build process.
Image source: [Top Max Technology \(2017\)](#)

Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is an becoming popular form of additive manufacturing. SLM offers customized metal part printing directly from the CAD model. This process uses high energy laser beams for melting and consolidating the powder bed as per predefined scan paths. Consecutive layers of powder are metallurgically bonded together to produce final 3D part. (Qingbo, 2019)

For Metal Manufacturing SLM and Powder Laser Energy Deposition are both widely used. Metal Binder Jetting. (MBJ) method is also used for metal manufacturing. Metal 3D printing and welding are similar manufacturing processes. For both, there is an effect of the localised heat source on the materials. Melting, solidification, solid state phase changes, residual stress, and distortion all occur in AM and welding processes, and the underlying mechanisms for each of these effects are same. AM creates a single component that can later be welded or connected to additional components.

AM offers a significant advantage in manufacturing complicated pieces that are difficult to manufacture using conventional technologies. In powder bed fusion, high scan speeds are essential to achieve the appropriate spatial resolution while minimising keyhole mode interactions, which can result in increased porosity.

4. Material Jetting

- a) Aerosol Jet
- b) Plastic Free forming
- c) Nanoparticle Jetting (NPJ)

5. Binder Jetting

- a) Metal Binder Jetting
- b) Polymer Binder Jetting, Sand Binder Jetting,
- c) Multi Jet Fusion
- d) High Speed Sintering
- e) Selective Absorption Fusion

6. Directed Energy Deposition

- a) Powder Laser Energy Deposition
- b) Wire Arc Additive Manufacturing (WAAM)
- c) Wire Electron Beam Energy Deposition
- d) Cold Spray

7. Sheet Lamination

- a) Laminated Object Manufacturing (LOM)
- b) Ultrasonic Consolidation (UC) (Kumar, 2020)

3.4 Process Selection

It is important to select appropriate AM process which suits the requirements.

Application of AM process depends on below criteria. We need to understand how it affects cost & production time and how it affects supply chain.

Design Vs Manufacturing Vs supply chain
Cost Vs Processing Time Vs Strength & durability

Costly tools are needed to produce high-volume parts. Initial investment in the tooling is high & long lead times are involved in tool manufacturing. But after the tool availability we can produce any required part quantity within short time frame. When required part volume is low, tooling investment is not justifiable. In this situation additive manufacturing can be more economical & faster manufacturing option. AM processing time will vary as per the part size and complexity. AM technology can produce complex part geometry within short time. In an assembly different part can be combined together, which will result in a smaller number of child parts & reduction in assembly time.

AM technology offers use of local supply chain. Parts can be made locally near end user. Part production near end customer means reduced logistics. Part inventory can be kept as minimum as parts can be produced quickly as per the demand. Local supply chain and reduced logistics are helpful for reducing carbon footprint.

Parts produced by AM technology will have different strength & durability as compared to machined or tooled parts. This is important consideration point for strength and durability requirements.

Fig. 03 shows traditional manufacturing graph for output Vs cost & Fig. 04 shows AM graph for output Vs cost. Initial cost is higher in traditional manufacturing because of tooling cost. But as the volume increases, per unit cost reduces considerably. Whereas in AM technology initial machinery costs are very high & with volume cost goes down very marginally. When we plot both graphs together, we can understand breakeven point for selecting correct manufacturing process. (Attaran, 2017)

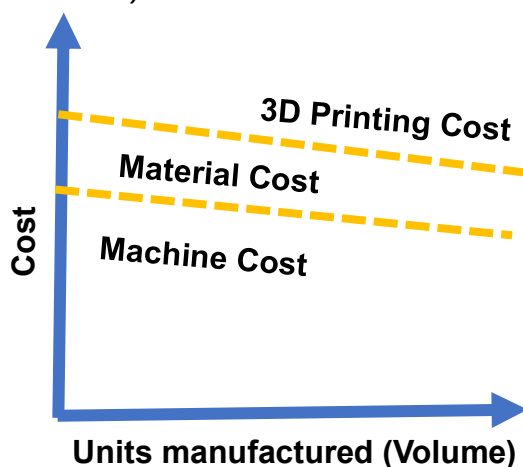


Fig. 05: 3D Printing Output Vs Cost

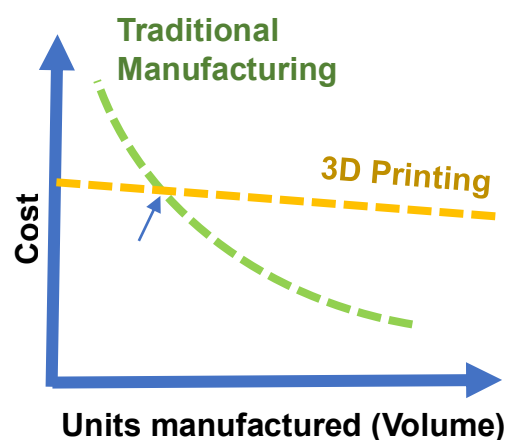


Fig. 06: Traditional Manufacturing Vs 3D Printing

Chapter 4 – AM Advantages, Defects & Limitations

4.1 Advantages

The advantages of additive manufacturing are important drivers in the adoption of this technology in the field of aerospace engineering.

Below chart shows potential benefits of AM in the aerospace industry by year 2025.

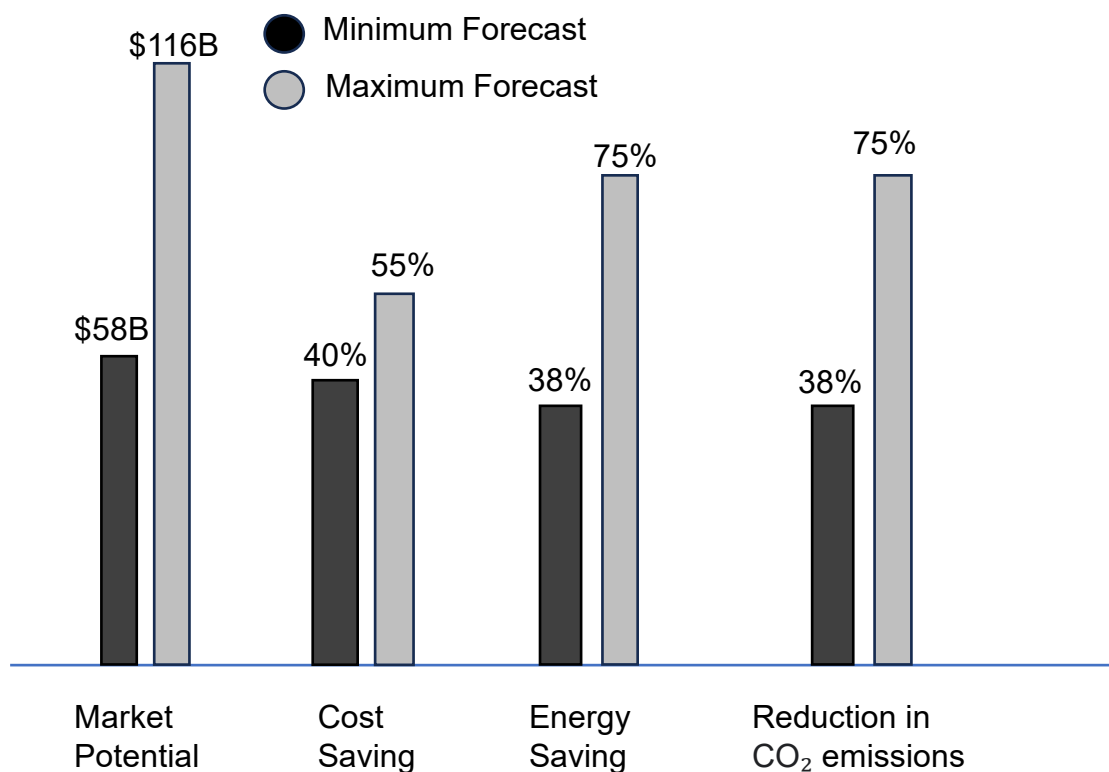


Fig. 07: Expected benefits of AM process in the aerospace industry until 2025
(Image Source: Gebler, 2014)

AM technologies offers great advantages over traditional manufacturing processes. Every AM user is experiencing own advantages of AM technologies.

Complex Geometry manufacturing: AM allows complex geometry manufacturing without requirement of special tools or machines.

Reduction in Assembly parts: Multiple parts under assembly can be combined under one or few parts.

Speed up product development cycle: Once design is completed, prototypes or final parts can be manufactured directly. AM don't need any intermediate tooling to facilitate manufacturing. (Safran website, 2020)

Strength to weight ratio: GE experimented AM technology to produce its fuel nozzle injectors for LEAP jet engine. This nozzle injector is now produced as a individual part in place of existing assembly of around 20 parts which were welded and brazed together. This new 3D printed injector is 25% lighter and almost five times stronger than the existing assembled parts. (GE Website, 2018)

Supply chain improvement:

AM technology is capable of reducing the requirement of both high-volume production infrastructure & low skilled/ semi-skilled workforce. This will considerably reduce supply chain cost. With AM technology production can be done at any location at same manufacturing cost. This means we don't have to transport products across the globe to get to the customer. Local manufacturing with locally sourced raw material & resources. Nyman & Sarlin (2014)

Additionally AM technology builds a close bond within different departments such as engineering design, manufacturing and marketing. As the parts are produced close to end user destination, there is the potential to reduce transportation costs and time. This will result in reduced carbon foot-print and positive impact on the environment.

The use of AM technology holds the potential to utilize local supply chain & reduced transportation which will be closer to the end customers. The technology could transform the global supply chain which will be connected globally but manufactured using local supply chain. (Attaran, 2017)

Cost Saving: From Safran & GE examples we have seen that AM parts are lighter in weight. Parts manufactured using AM technology are proving are more efficient and lighter. A lightweight aircraft provides great cost savings. A 1 kg weight reduction is equivalent to saving of \$1,300 in fuel per year (King, 2012).

Buy to Fly ratio: Aerospace application structural parts are manufactured using stronger & expensive raw materials like Titanium or nickel chromium alloys. Conventional subtractive machining accounts for 80-90% of scrap ratio compared to final part against original raw material size. AM processes can reduce the scrap ration down to 10-20%. (DUP, 2014)

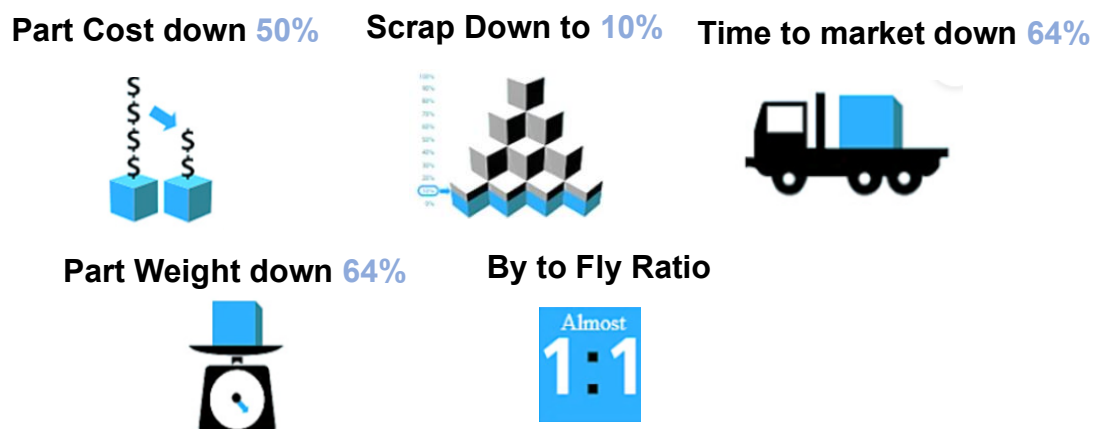


Fig. 08: AM benefits
(Image source: Deloitte University Press | DUPress.com)

4.2 Defects

Additive manufacturing is disruptive technology which is being experimented in many industries. After research and experiments there are some observations about defects in the AM technology. These defects limit the application of this technology in certain application areas. These defects may result in undesirable variations in the mechanical response of AM parts that. It is important to understand defects & find out appropriate measures to reduce the impact of these defects.

4.2.1 Porosity:

Porosity is a discontinuity of the material, and this is one of the main causes of cracks in the 3D printed parts. (Kim & Moylan, 2018)
Porosity is a common defect found out in the 3D printed parts. Main reason for porosity defect is binding mechanisms driven by thermal changes, gravitational force & capillary forces without any external pressure. There are two types of porosity visible in the 3D printed parts, viz keyhole pores or spherical pores. Main causes of these pores are material shrinkage, lack of binding between layers, shortage of feedstock. (Debroy, Wei, Zuback, Mukherjee, Elmer 2018)

4.2.2 Cracking and delamination

Cracking is a serious problem in AM materials forming due to several reasons. solidification cracking can be observed along the grain boundaries of the build. liquation cracking is observed in the partially melted zone of the build. e.g., Laser based AM metal-based processes produces large amounts of thermal stresses, originating from the rapid shrinkage of the melt pool and high temperature gradients in the solid material. This creates cracks in the final part.

Delamination is basically the separation of two consecutive layers. Delamination is caused by the residual stresses at the interface of the adjacent layers exceeding the yield strength of the alloy. Delamination reduces products structural integrity.

4.2.3 Poor surface finish:

Proper surface finish is important for any product. In AM parts poor surface finish is important concern. This can be observed due to several reasons. For poor surface finish main contributing factors can be the 'staircase' effect which is associated with layer thickness and build orientation, coarse deposit beads, incorrect tool precision, surface tension or semi-melted powders.

Poor surface finish can even be caused by aging of the used raw material. Surface roughness can be improved using a smaller powder deposit and smaller layer thickness. But this will result in slow production & higher energy consumption.

To improve surface finish of complex AM parts post processing is required. But again, these post processing operations results in lower production & increased production cost. (Debroy et. al, 2018)

4.2.4 Residual stress and Distortion:

High thermal gradients are observed in AM metal parts as these parts are created at high heat input using laser or UV rays. This heat input causes localised heating and cooling, which results in residual stresses. These residual stresses are responsible for local lower elastic limits which finally results in local failure. High cooling speeds results in increased residual stresses (Kim & Moylan, 2018).

Heat treatment is needed to eliminate these defects. Distortion or deflection defects are the results of internal stress which is caused by changes in material volume in some cases. Distortion or deflection can result in delamination or splitting of the part layers. These defects are driven by processing parameters, material characteristics.

4.2.5 Balling phenomenon:

Balling phenomena happens because of either laser power or scan speed. Low laser power or high scanning speed causes balling phenomena. When the laser is applied over the powder bed, the metal powder locally melts on a flat path, but when the process parameters are inconsistent, the melted powder or in-process part is affected by this balling phenomenon. Part begins to show cracks because of low surface tension. This phenomenon results in physical defects such micro-cracks, porosity, micro-cracks & reduced surface finish. (Bellini et. al, 2021)

4.3 AM Limitations

AM technologies are offering tremendous opportunities in the field of design and manufacturing. As a emerging technology there are certain limitations which we need to understand before selecting appropriate AM technology.

4.3.1 Material Limitations:

Aerospace industry is highly regulated under global authorities of FAA & EASA. Title 14 Aeronautics & Space has Part 25 for Airworthiness Standards for Transport Category Airplanes. FAR 25.853 specifies details for fire protection of aircraft interior compartments. All aerospace materials need to pass the flammability certification criteria specified under FAR 25.853. Currently ULTEM (polyetherimide) is one such certified polymer material for aerospace application. (Code of Federal regulations, 2024). process, compatibility, and performance factors also drive material selection.

4.3.2 Strength and compatibility

In traditional manufacturing parts are manufactured from a billet of raw material. This raw material is homogenous & shows good mechanical properties. In additive manufacturing parts are manufactured using raw material in powder format & parts are manufactured by adding material layer by layer.

This layer-by-layer approach introduces discontinuities and varying layer adhesion. This affects final part strength and its mechanical properties. AM technologies shows inherent inconsistencies in mechanical strength when the build orientation is changed, further affecting product integrity. (Rath et. al, 2023).

4.3.3 Cost:

It is claimed that AM technologies will save money in long run. But initial investment in AM technology is very high. The equipment and materials used in AM are expensive. More time and expertise are necessary to manage the software and technology that runs the AM machines. We have seen for aerospace industry materials need to meet aerospace regulations. Fulfilling these regulations costs time & money. This makes the raw material very expensive. (Nago et. Al, 2018)

4.3.4 Quality control

Using AM technology, we can produce very complex & large geometry, which is great, but at the same time it becomes challenging to achieve & inspect consistent quality. Temperature, humidity, machine accuracy, machine calibration can impact printing process variables. The final output can exhibit variations due to factors such as temperature, humidity, and machine calibration. Printing procedure, source of feedstock (Raw material) and the post-processing stages also affect quality of the finished product. It is challenging task to inspect complex geometries of 3D printed parts using conventional tools & techniques. Design errors or software errors can result in the finished parts with defects, structural weaknesses, defects, or other quality issues. (Lee & Yun, 2022)

4.3.5 Post Processing

3D printed parts require support structures during the printing process to prevent deformation or collapse. This support structure/material needs to be removed. Additionally, many 3D-printed objects need post-processing to achieve the required finish and functionality. Post processing operations can be sanding, painting, or coating. Sometime 3D printed parts are not dimensionally accurate and may need machining to achieve accurate dimensions & to maintain design tolerances. These post processing operations need extra time & expense to the production process. (Nazir, et. Al, 2022)

4.3.6 Build Failure

Research has showed that build failure has a major impact on the costs of AM and that this results from comparatively high level of process instability. The risk of build failure results in increase in energy usage by roughly 30-32% compared to the full capacity utilization. And it results in reprinting of part with additional raw material requirement. Build failure can happen because of different reasons viz. feedstock quality, temperature changes, insufficient heating/cooling between layers, printing speed, varying feed rate. (Wang et al, 2022)

Chapter 5 Generative Design

5.1 Generative Design

Generative Design combines computer-aided design with artificial intelligence. Artificial intelligence is core technology in the GD system. Designers need to provide basic geometry, constraints and variable factors. Artificial intelligence offers multiple outputs structural requirements, weight optimisation, economic efficiency & possible manufacturing methods. This system will bring about great variation in product design & manufacturing process. (Hyunjin, 2020).

From the studies and applications, it is observed that GD can automatically generate different design concepts in short duration. Then designers can choose most appropriate option which suits design specifications. Options provided by this system considers manufacturing processes, weight optimisation, part geometry constraints & structural requirements. (Han et al. 2022).

As an industry 4.0 advance manufacturing student, we studied subject 'Design for industry 4.0'. Under this subject we explored potential of GD. We studied Autodesk Fusion 360 software for Drawing definition, Part Modelling, Simulation for GD. Using this technology, we get the opportunity to analyze multiple options that meet our design specifications which offer light weight design and improved performance. This technology can generate designs based on our design specification, constraints, materials, and manufacturing preferences. It can generate designs which are manufacturable under specified methods. It allows us to evaluate different design solutions based on performance requirements & manufacturing preferences. The current design process involves multiple iterations & design modifications based on feedback loops, whereas generative design provides multiple design options at the same time. CAD data is immediately available to start manufacturing. This design capability helps in amplifying human ability to innovate & reach to market in shorter timeframe. It improves designers' talent by uniting designers with machine learning tools & cloud computing power. (Autodesk website , 2022)

5.2 Generative Design and Additive manufacturing corelation

Generative design is part of the family of Design for Additive manufacturing. GD combined with AM offers several benefits including, Faster product development, Improved design optimization, Improved efficiency, better optimisation and performance. Using GD system, we can generate optimized complex shapes and internal profiles. We can utilize the power of Additive Manufacturing and GD application to reduce part weight & to reduce no of child parts under an assembly. GD offers Increased design freedom. Its algorithms can generate designs those are unique for human designers & those would have been time consuming to explore. AM technologies has potential to manufacture complex shapes and geometries those are difficult or impossible to manufacture by current manufacturing processes. (EPD 2017)

5.3 Generative Design examples

GD offers flexibility to choose manufacturing methods. This allows us to utilize available resources. We can optimize part geometry for existing parts keeping same manufacturing process. But its real advantage is to explore its innovative capabilities to come up with unique solutions. In combination with AM technology, we can achieve better shape, performance, and lightweight design in a cost-efficient manner. Below are some of the case studies of GD combined with AM technology. It can provide geometry meeting structural requirements In these case studies it is observed that part geometry can be optimized with substantial weight reduction.

Junk & Rothe experimented capabilities of addresses the potential of generatively developed part which can be manufactured using AM technology. Wheel carrier with A-arm and control arm for student racer car was optimised using GD and AM technology.

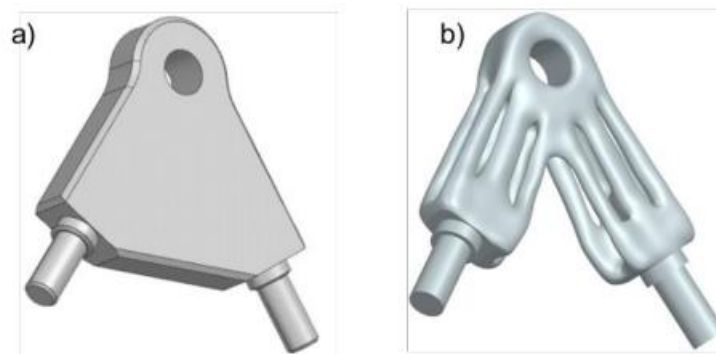


Fig. 09: Variations of the sample part
a) conventionally manufactured part b) generative designed Part
Image source Junk & Rothe 2022.

Production Process	Design method	Materials	Weight (g)	Costs [%]
Milling	Traditional	Aluminium	286	100
Hand-laminating	Traditional	Plastic	192	300
AM Technology	Traditional	Plastic	76	26
AM Technology	Generative Design	Plastic	46	19

Table 2. Comparison of manufacturing processed and design methods
cost and weight analysis
Table data referenced from (Junk & Rothe 2022).

Researchers Junk & Rothe In the above case study using the example of a chassis part concluded that it was possible to show that the combination of GD and

AM offers significant cost & weight reduction, when compared with traditional production processes and with AM.

Generative design is beneficial for multiple applications in all manufacturing industries. It can offer weight reduction benefits & result in cost saving in wide range of applications across all the industries.

Engineering: GD capabilities can be utilized to design cost effective, lightweight, stronger products in aircraft and automotive industry. It can be used to optimize the performance of mechanical systems, such as pumps, engines, turbines, and ducting.

Product Design: GD can be used to design domestic products, such as furniture and household goods. It can optimize design for ergonomics, material & production methods.

Manufacturing: GD can be used to optimize the production process, improve process efficiency, waste reduction, and to improve product quality. (EDP 2017)

Chapter 6 AM Application in aftermarket Engineering

6.1 Background

I am working with Safran seats GB as a Senior In-Service Solution Design Engineer in the Aftermarket engineering department. Safran Seats GB is a main player in First Class & Business class passenger seats for commercial aircrafts. It is one of the few original equipment manufacturers to provide luxury and advance features in the passenger seats for commercial aircraft.

Working as part of the aftermarket engineering team, it is our main job to investigate and create design solutions for customer in-service issues. In this job role, we proactively support the customer (Airlines & their representatives) and ensure that the engineering service levels provided maintains customer satisfaction for the complete portfolio of our company. For In-service issues, we develop design solutions which need to be implemented on the aircraft within a short time scale & with minimal impact on the existing product design.

Aftermarket Engineering Responsibilities

As a department we provide technical support and expert knowledge for all company products. We identify product improvements and service offerings that enhance customer satisfaction. We support the customers in service operation, maintain regular communication and resolve all customer concerns within planned timescales.

We provide 'on-wing' support when it is necessary for the customers. During our on-wing visits we study the seat product on the aircraft. We try to understand customer concerns, conduct trials of impacted seat sub-assemblies or mechanisms. These visits help us to Log, investigate and coordinate root-cause analysis reviews to understand cause of in-service failures. (Safran website, 2023)

6.2 Potential Application area

We have seen that for In-service issues, we need to come up with unique design solution which can be implemented within a short time scale & with minimal impact on the existing product design. We need to ensure that the new design meets structural & mechanical certification requirements. Selected materials meet the flammability certification requirements for aerospace domain. Short time scale for aftermarket design solutions leads to finding out ways to produce required assembly parts quickly. Conventional manufacturing processes have longer lead times. Injection moulded parts, Vacuum formed parts or composite parts need tooling and much bigger manufacturing setup. Tool design and tool making is detailed & long lead time activity. Looking at these constraints, additive manufacturing seems to be a very good alternative to manufacture new parts. On the seat product there are some potential applications of additive manufacturing.

Commercial aircraft first & business class seat products are mainly made up of different materials as specified below.

Sheet metal parts: Normally sheet metal parts with cutting & bending operations are used. Complex sheet metal parts which require tooling are avoided. Al alloy brackets are used for secondary/tertiary load case applications. Steel brackets are used for primary structural load case requirements.

Composite parts: Composite parts are used for structural requirements. Composite parts have long lead times & complex parts need tooling.

Machine parts: Al alloy & Steel machined parts are widely used on the seating application. Machined metal parts are heavy in weight but those are needed for strength of the seating mechanisms & sub-assemblies.

Vacuum formed / Injection moulded parts: Vac formed / injection moulded parts can have smooth profile & complex shapes as per the requirements. These parts are used for lightweight applications. These parts are used along with paint application or leather/fabric trim material wrapped around it.

Foam, leather, fabric, Schneller, paint are also used in the seating system etc.

Selection Criteria:

Based on the research findings in the chapter 4.1 Advantages of AM below are some of the criteria which can help in selection of AM application for manufacturing parts.

1. Parts which are complex to manufacture with conventional manufacturing processes.
2. Parts which need long lead time tooling or existing tooling is not available
3. An assembly where multiple parts can be combined together to reduce total number of parts in the assembly.
4. Complex machined part geometry where buy to fly ratio is very high.
5. Required part quantity is small (Part quantity is important parameter for AM process selection. Any change in the required quantity needs to be evaluated)

R & T, Safran's center of excellence, Additive Manufacturing inputs:

The R & T department and Safran's center of excellence, Additive Manufacturing, are working on implementation of AM technology in the seating product. Design team conduct timely review with them to understand potential AM technology implementation. We discussed one such potential application scenario with the R & T team.

We have had first class & business class aircraft seats in the commercial aircrafts market for a long time. For a product old that 10 years there was a requirement to replace seat cappings due to damage. (part shown in fig.12). These cappings are produced from an injection mould & paint is applied as finish for the final part. Injection moulded tool is not available for operation. The original tooling was planned for 8 years of operation & now the tool is not in usable condition.

So, in the first phase of AM technology application these lightweight & non-structural parts are chosen. Vacuum formed / Injection moulded parts need tooling. So those are chosen for alternative additive manufacturing applications. Metal parts which are used for the structural strength of seating product involves

detailed stress analysis & mechanical certification. So, metal AM application will be considered in next phase.

6.3 Material Selection

In the second chapter Material for AM, we have seen that thermoplastic & thermoset plastic materials are used as feedstock in the AM processes. For the aerospace industry there are very strict regulations for flammability, smoke, density, heat release.

The main challenge for AM production parts is the complicated certification process for airworthiness compliance. Traditionally, AM parts for aerospace application are individually qualified. The qualification process includes testing of raw material, produced part and final post processed part. Regulatory agencies like FAA, EASA or CAA defines necessary specifications, but the decision-making process in design and development stages is very slow and costly, in addition to the testing and validation cost (Yang, 2020).

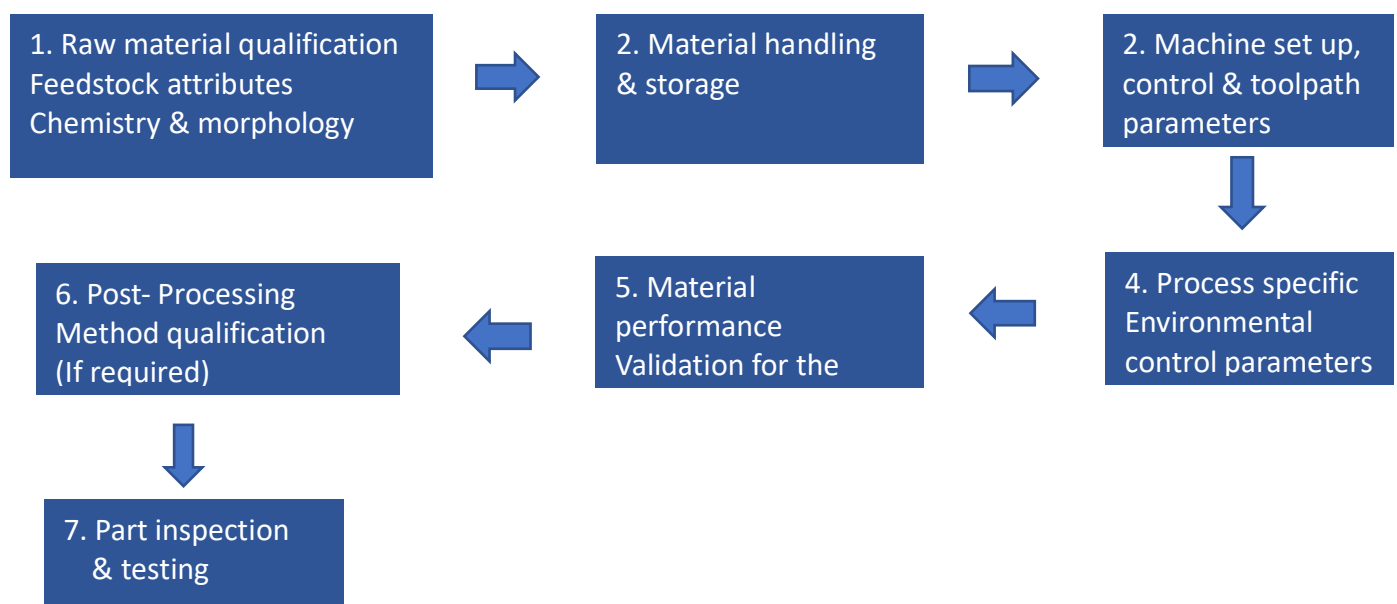


Fig. 10: Sample workflow of airworthiness certification process
(Workflow process source: Yang, 2020)

As per the inputs from R & T, Safran's center of excellence Ultem 9085 CG material is selected for the application. Stratasys certified Ultem material for aerospace applications. The build material is Ultem 9085 CG and support material is Ultem support. This material is available in natural or black colour as per the requirement. This material is available in filament format suitable for Fused Filament Fabrication process.



Fig. 11: Ultem 9085 PEI 3D Printing Filament $\varnothing 1.75$ mm
(Image source: Plastock website 2023)

6.4 Flammability & Certification requirements

The Aerospace industry is governed by stringent industry regulations. The Federal Aviation Authority (USA), European Union Aviation Safety Agency (Europe) Civil Aviation Authority (UK) are the main central agencies who define & control regulations for all the aerospace industry. After Brexit in 2016, UK formally left the EASA system on 31 December 2020. From 01 Jan 2021 CAA is the statutory corporation which manages and regulates all aspects of civil aviation within the United Kingdom. (CAA website, 2023)

All these authorities define certification requirements for all the materials used in the manufacturing of aircraft & all interior inside it. All the materials need to undergo below 03 tests and meet the criteria for successful implementation. These tests are for flammability, heat release & smoke density as per the sections specified in the below table. Min. three samples are tested and average result is considered to define pass or fail criteria.

Test 01: 60 sec Vertical Burn flammability

Test 02: 25.1.2 Heat Release (65/65)

Test 03: 25.1.3 Smoke Density (200)

Code of Federal Regulations (CFR) and Certification specification (CS) are equivalent regulatory requirements for FAA & EASA respectively.

Sr. No.	Test Name	FAA regulation	EASA regulation
1	60 sec Vertical Burn flammability	14CFR 25.853(a) Appendix F, Part I	CS 25.853(a) Appendix F, Part I
2	Heat Release (65/65)	14CFR 25.853(d) Appendix F, Part IV	CS 25.853(d) Appendix F, Part IV
3	Smoke Density (200)	14CFR 25.853(d) Appendix F, Part V	CS 25.853(d) Appendix F, Part V

CS 25.853 Compartment interiors certification criteria (FAA & EASA websites)

(a) Materials must meet the applicable test criteria as per **Part I of Appendix F** or other approved methods. (This includes trim & finish applied to the part)

(d) the following interior parts of aircrafts with 20 or more passenger capacity must also meet the test criteria **part IV and V of appendix F**, or other approved equivalent method, including the the flammability requirements specified in sub-paragraph (a)

Appendix F

Part I –procedure and Test Criteria to show compliance with CS 25.853

This criterion applies to all aircraft interior parts including floor covering, seat cushions, padding, coated fabrics, leather, trays and galley parts, electrical cables & parts, floor panels, covers, moulded and vacuum formed parts, ducting and trims

(iv) below, must be self-extinguishing when tested vertically as per the applicable portions of Part I of this Appendix or other approved equivalent methods. The average burn length will be up to 20 cm (8 inches), and average flame time after withdrawing fire source may not exceed 15 seconds. Drippings from the test sample may not continue to flame for more than 5 seconds after falling on average.

Part IV – Test Method to Determine the Heat Release Rate from Cabin Materials Exposed to Radiant Heat

Summary of Method: The sample for testing is injected into an environmental chamber through which a constant flow of air passes. The sample's exposure is defined by a radiant heat source adjusted to produce the desired total heat flux on the sample of 3.5 Watts/cm², using a calibrated calorimeter. The combustion products leaving the chamber are monitored to measure the release rate of heat.

Criteria: The total positive heat release over the first two minutes after exposure for each three or more samples will be averaged. The total heat release must not exceed 65 kilowatt-minutes per square meter when averaged, and peak heat release rate must not exceed 65 kilowatts per square meter when averaged.

Part V – Test Method to Determine the Smoke Emission Characteristics of Cabin Materials

Summary of Method. The sample must be built conditioned and tested as per (ASTM) Standard Test Method ASTM F814-83.

Acceptance Criteria. The specific optical smoke density (Ds) which is obtained by averaging the reading obtained after 4 minutes with each of the three samples shall not exceed 200

6.5 Design considerations

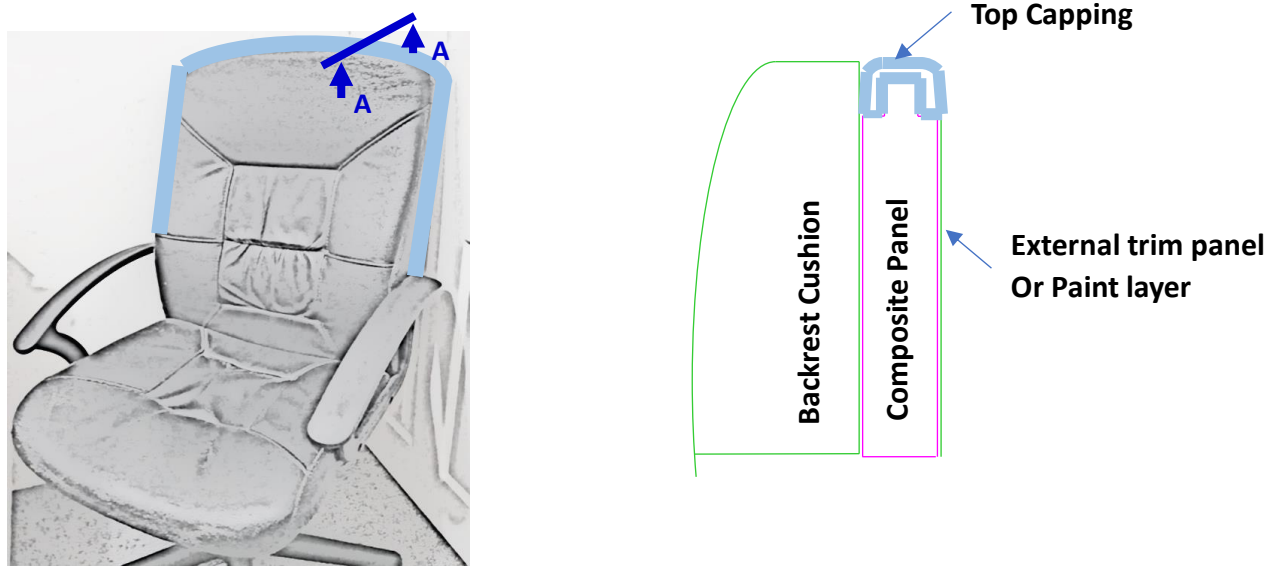


Fig. 12: Seat potential application area

Image source: Home chair used to replicate application scenario.

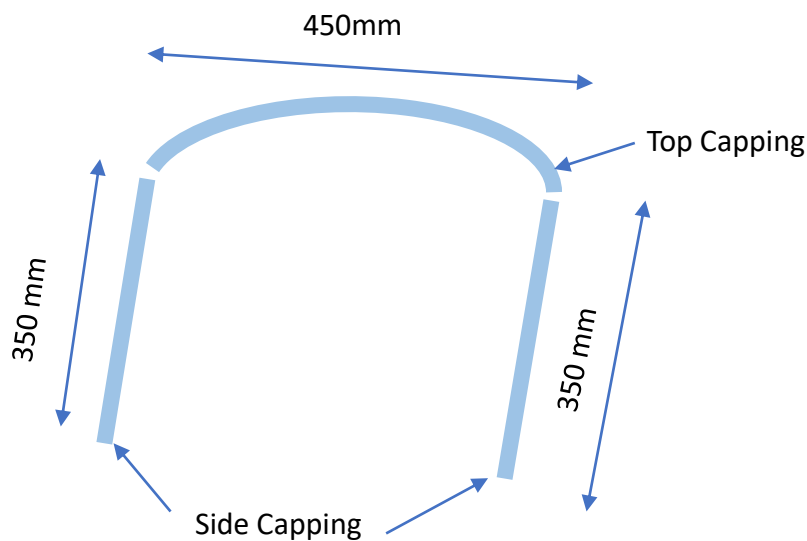


Fig. 13: Top & Side capping reference dimensions

CAD models for existing cappings are available in the system. But CAD models need to be modified to suit AM process design requirements. Overall dimensions and part profile are maintained as per existing geometry. There are minor modifications like adding extra material for inserts installation or changing female radius value to suit AM process. One additional requirement is to create test coupons models. These test coupons are small cross sections of part in XY, YZ & XZ direction. These test coupons need to be produced for each batch to ensure that each manufactured part is with consistent quality & strength. And there are no defects or build quality issues.

6.6 Cost Analysis

Part Description: Top Capping & Side Capping (As shown in the Fig. 12)

Existing material	Ultem 9085 – BAC70107
Existing Manufacturing method	Injection Moulding
Existing Tooling	This was used on old project 10 years ago. Tooling not available for use now.
Total tools needed.	Top Capping -01 LH Side capping -01 RH Side Capping -01
New Tooling cost	£XX000 (For 03 tools)
Lead Time	04 months (Depending on project planning)
Minimum part quantity to justify tooling requirement	20
Total Cost for 3 capping (20 qty each)	£XX000

Details of AM process

Proposed AM material	Ultem 9085
Proposed AM process	FDM (Stratasys)
Tooling & Lead time	No Tooling required. As per design part can be directly manufactured
Raw material cost	£XX0 (Estimated cost for each part)
Minimum part quantity	01 (For each capping)
Total Cost for 3 capping (20 qty each)	£XX000

From the above comparison we can see that AM cappings are **40%** cheaper than injection moulding process & can be manufactured immediately without waiting for any tooling. **(Actual prices hidden to avoid any confidentiality issues.)**

We need to understand that this assumption is based on the required quantity of 20 for each capping. We need to refer to fig. 5 & 6 for Cost Vs Volume graph discussed in chapter 03. If the required quantity is more than 50, we need to reconsider our manufacturing process selection approach.

In the example table existing material was Ultem 9085 – BAC70107. And in some other potential application cases existing material is Polyurethane. After prototyping and testing AM material Ultem 9085 CG will be finalised.

6.7 Manufacturing & Supply chain

Safran's center of excellence, Additive Manufacturing Campus offers all required facilities for AM. This center of excellence provides Materials testing plans, topology optimization, product development support & part manufacturing facility. Ultem 9085 is already chosen & approved material. The cost of Ultem 9085 is very high due to the fact that it has gone through the complete airworthiness cycle. But thanks to Safran's center of excellence where all Safran groups are consolidated under one roof. Safran gets the advantage of central supply chain to meet requirements of complete group for AM. This advantage allows us to get raw material at comparatively cheaper price & can be made available when needed.

6.8 Prototyping & Testing

We have seen that all 3D printed parts need to be quality tested.

Injection moulded cappings are produced with good surface finish & it does not need any post processing operation. Injection moulded cappings have paint finish as per the specified colour. AM cappings need post processing operation of fill and fair to achieve good quality surface finish. After that cappings need to be painted as per existing colour. Post processing & painting operation involves additional testing for flammability, heat release & smoke density. These additional post processing operations & testing add cost & risk to the application.

6.9 Future Scope

Use of Ultem 9085 for non-structural capping parts will be the first step toward AM application. In the next phase we will consider metal AM for non-structural parts & at a later stage even structural parts can be experimented with AM technology.

Design Forum

Safran seats GB have a Research and technology department working on latest innovation projects. The R & T team work closely with sales, marketing & design engineering departments. New ideas are conceptualized in the R & T department. To promote innovative ideas, R & T arranges innovation day when all the ideas & concepts are shared with different departments. Even Safran Seats France & USA participates in this event. The latest material, process improvements, and new technology implementation stories are shared with all the participants. Such events promote innovation culture & enhance existing workforce's knowledge about latest industry 4.0 technologies.

Design & Manufacturing engineers are encouraged to participate in the latest technology exhibitions. The Advance engineering exhibition show organized annually at Birmingham NEC is a good forum for all design and manufacturing engineers. Manufacturers, design engineers, regulatory bodies, and international speakers collaborate with each other. These forums are the right platforms for sharing technological advancements in design and development. Such forums are playing a really important role in the successful implementation of industry 4.0 technologies.

Chapter 7 – AM Aerospace Applications

7.1 Currant Aerospace market Scenario

Additive manufacturing is a disruptive industry 4.0 technology which enables the production of complex products without complex equipment or expensive tooling. AM has potential to significantly reduce raw material consumption & amount of waste generated. Due to these benefits AM has attracted attention of high demanding sectors, including automotive and aerospace. Improving Buy-to-Fly ratio of final product, which is the mass of raw material required per mass of final part, is highly desirable in these sectors. This promotes reduction in raw material costs, energy efficiency & reduction in operation fuel consumption. Key aviation players such as Boeing, Safran & GE are investing in AM technology & already producing number of AM aeroplane parts. (Gisario et al. 2019)

Metal mining & manufacturing industries accounts for 12% global carbon dioxide (CO₂) emissions. And aerospace industry accounts for 9% of CO₂ emissions of all transport modes available today. Till Covid-19 number of commercial flights increased steadily since year 2009, which resulted in 918 million tons of CO₂ emissions in the year of 2019. And from 2022 again commercial flights are increasing steadily. (Monteiro et al. 2022)

It is necessary to study material and energy efficiency of AM processes and products to promote sustainable manufacturing & to achieve carbon neutral targets. This will help in reducing environmental impact of AM processes and products. (Ford & Despeisse, 2016)

In year 2023, the EU adopted a set of Commission proposals to ensure that EU policies for climate, energy, transport and taxation policies are suitable for reducing net greenhouse gas emissions by at least 55% by year 2030 as compared to year 1990 emission levels. This will be one important step to make EU first climate-neutral continent by year 2050. This aims at an economy with net-zero greenhouse gas emissions. Power sector, all industries, transportation, infrastructure will play an important role. The EU will support by investing in technological solutions, educating citizens.

7.2 AM application success stories

Aerospace industry has most stringent regulations in terms of materials & product definition. Under these regulations AM technology is being tested for high performance applications. The commercial and military aerospace products demand for durable high-performance materials. All major aerospace industry players are utilising & experimenting AM technology to excel performance in terms of weight reduction, cost reduction, performance enhancement. Below are some of the success stories of AM application.

7.2.1 Safran's AM Journey

In Oct-2022, Safran opened Additive Manufacturing Campus for utilising benefits of latest industry 4.0 technologies in France. This new facility provides all the processes required to produce parts using AM, from R & D to engineering & large-scale manufacturing. Safran's CEO Oliver Andries said, "It is our strategic decision to develop this new centre of excellence to consolidate Safran's expertise in AM and accelerate the application of this industry 4.0 technology, We will utilise the benefits of this technology to produce lighter products, while improving its performance, which is the key to achieve aerospace industry's objective of reducing its environmental impact."

Safran helicopter engines are using 3D printed parts produced in this facility. Total 4000 3D printed parts were delivered in year 2022. And plan was to double the production in year 2023. (Safran Website, 2022)

7.2.2 Boeing's AM Journey

Boeing is working on innovation of AM technology since last 30 years. Boeing opened centre of additive manufacturing excellence in Auburn, USA. Boeing uses this AM facility for manufacturing parts, prototypes, or tools. There are over 70,000 parts manufactured in this facility. Boeing has AM capability to produce parts using polymer, metal & LSAM (Large scale additive manufacturing). (Boeing Website, 2023)

Example of Boeing's AM journey is the winglet component. Traditional manufacturing of this part at supplier had six-week lead time. AM process is producing this part in 41 hours & additional post processing of 85 hours. Traditional machining cost was \$60,000 & with AM this part is produced at \$40,000. This example shows time reduction by 50% & cost reduction of 25%.

7.2.3 GE Aviation's AM Journey

In the introduction chapter we saw that GE aviation experimented 3D printing technology to manufacture aerospace parts in last decade. GE aviation started additive manufacturing facility in its manufacturing plant in Auburn, Alabama in the year 2015. This was first site for mass production using the AM process in the aerospace industry. T25 sensor & fuel nozzle for the LEAP are examples of initial trials of AM technology for Aviation production parts. AM technology offered great advantages of 25% weight reduction & even stronger product than the previous conventionally manufactured version. Single 3D printed part against assembly of 20 parts resulted in reduction in total manufacturing & assembly time, simpler and quicker supply chain. With this early success of AM technology GE invested about £1.2 billion into additive manufacturing research. GE aviation's research and development work is resulted in more than 300 patents in the field of AM technology. (GE additive 2018)

7.2.4 Airbus's AM Journey

Airbus Helicopters has opened a new AM technology centre at its Donauwörth, Germany facility. Purpose of this innovation centre is to expand its capacity in the field of AM. Stefan Thomé, MD of Airbus Helicopters said "Our extensive capabilities in this process along the manufacturing chain are a real competitive advantage," AM technology is offering us several advantages of weight reduction of aircraft parts which leads to less fuel consumption. This will result in financial benefits and contribute to reducing CO2 emissions during operations. (Airbus Newsroom, 2023)

Airbus Helicopters used powder bed fusion (selective laser sintering) for cabin ventilation distributor. Its main function is to pressurize cabin air and ventilate it. Originally this was mechanical assembly function including flanges at top and bottom sides. Design requirement is to perform ventilation function and to provide structural carrying.



Fig 14: Cabin ventilation distributor
Image source: (Poyraz & Kushan 2019).

Using AM technology this part is now produced by keeping all the geometrical features with better strength. New additively manufactured part is made from polyamide powder PA12. This resulted in the simplification of design, reduction in the assembly child parts, faster production time. This resulted in simpler supply chain offering financial benefits. Company plans to apply AM technology for other cabin interior parts. (Poyraz & Kushan 2019).

Airbus developed first metal 3D printer for space. This metal 3D printer is developed for the European Space Agency (ESA) program. It will be soon tested aboard the Columbus module of the International Space Station.

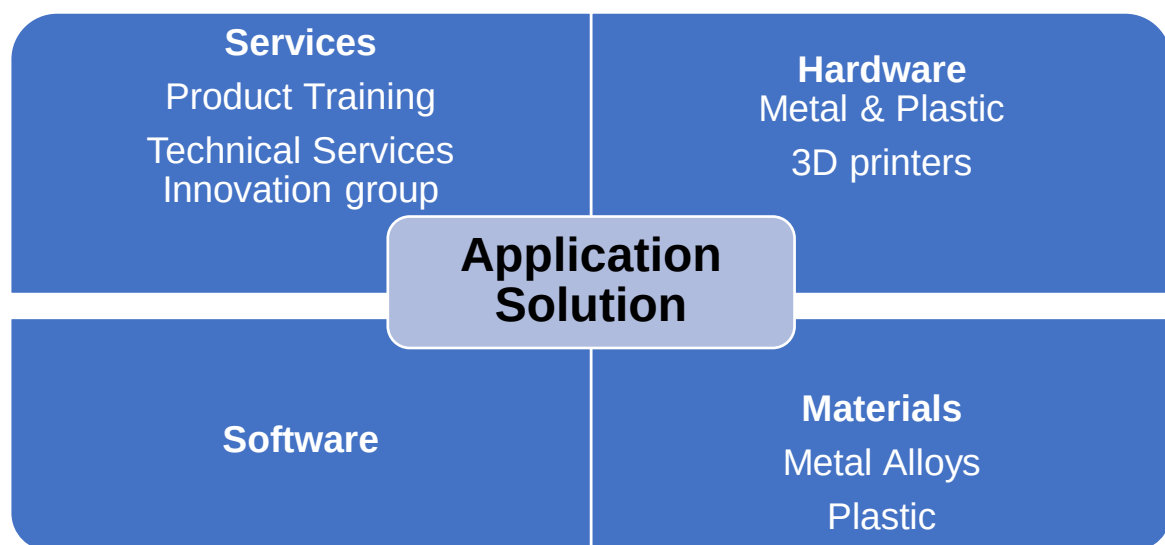
Plastic 3D printers are already in use at the International Space Station (ISS) since year 2014. And Astronauts are already using it to repair & replace plastic parts. With metal 3D printer astronauts will be able repair and replace structural and stronger metal parts. In space programs the major problems is the availability of replacement parts and equipment, which may take long time to arrive. It might take several months to arrive.

Gwenaëlle Aridon, who is Airbus Space Assembly lead engineer says that, "The metal 3D printer will offer lots of new on-orbit production possibilities, including potential production of load-bearing structural parts which are more resilient than its plastic alternative. Astronauts will be able to directly produce required tools and handy equipment such as wrenches or mounting interfaces that will connect multiple

parts together. This flexibility and rapid availability of 3D printing will greatly improve astronauts' autonomy.”
(Airbus Newsroom, 2023)

7.2.5 3D Systems & Stratasys

Stratasys and 3D systems are one of the major players in the field of additive manufacturing. These companies are offering additive manufacturing solutions to different industries from last 35-40 years. These companies offer metal & plastic 3D printing machines, related software, metal & plastic input raw material, training & technical support as shown in the below figure.



Typical Direct Manufacturing Applications
(Image Source: 3dsystems.com)

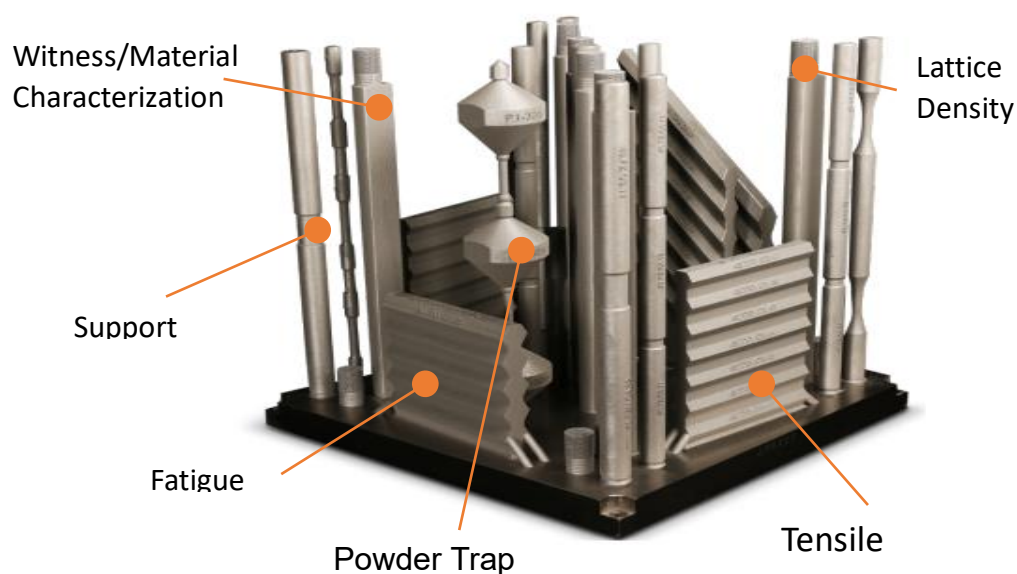
3D Systems: 3D Systems Inc. introduced first 3D printing technology in the commercial market in 1987. (Hull, 2015).



FIGURE 1 . The first 3D-printed part
(Image source: Hull, 2015)

3D system has Application Innovation Group (AIG) with aerospace industry engineering experts. In aerospace domain need to meet stringent requirements of

the industry. 3D system's AIG takes a consultative, requirement-based approach to provide most effective solution using AM technologies to customers difficult design and production challenges & ensures that all industry standards are followed & final output meets all regulatory requirements. Its global AIG anticipates potential risks, offers faster ROI for end customers by developing certified, transferrable, and scalable AM production processes. 3D system offers 3D printing hardware, software support, input raw materials, and service solutions. AIG, innovative solutions helps end customers to maximize the value of AM by eliminating conventional manufacturing limitations and heavy costs associated with it. Function led design, quicker approach to market, optimisation of supply chain, repeatable as well as reliable production & Scalability with reduced risk are the key offerings by 3D system's AM technology.



Build plate for mechanical property testing
(Image Source: 3dsystem.com)

Stratasys

Stratasys Inc offers 3D printing solutions for customised production parts on-demand. Customer don't have to invest in high cost and long lead times of traditional manufacturing. Stratasys offers wide range of material selection and simple post-processing. Print on-demand, cost saving on inventory, storage, simpler supply supplier chain and reduction in costly lead times. This makes low to high-volume production economically feasible. 3D printing solutions are optimised for customization which results in reduced cost of design changes for complex parts. Stratasys offers AM solutions which can meet varying and highly customised demands quickly without the tool-up costs and long lead times. It offers Streamline supply chains, reduce costs and boosts competitive advantage. Lead times can be reduced by up to 83%. Stratasys offers manufacturing of production-grade parts within very short duration. This benefit can result in increased revenue by improving

lead time to market. associated with products at the end of their life cycle. 3D printing provides cost-effective on-demand production that eliminates physical inventory & reduce supply chain costs (Stratasys website, 2023)

These are some of the prominent examples of AM technology applications in the aerospace industry. There are many small-scale companies and enthusiastic individuals who are actively working on AM applications experiments. Scientists & Students are constantly working on the development of new materials, enhancement in the AM processes & reducing defects of existing AM processes. In coming years this disruptive technology will reshape the whole aerospace industry and other industries also.

Chapter 8 – Supply Chain management

8.1. Adoption of AM Technology

The benefits of AM technology are one of the important aspects in the adoption of this technology, which will result in the growth in the aerospace AM market. We have seen benefits of AM technology providing in the aerospace market in terms of cost reduction, weight reduction, improvement in buy to fly ratio, improvement in time to market, reduction in scrap & wastage. Some major players like Airbus, GE, Safran have adopted AM technology, and many other companies are also showing interest in the AM technologies. (Altıparmak & Xiao, 2021)

According to Deloitte University press release, 2014, the four tactical ways in the adoption of Additive manufacturing technology are as follows:

- (i) exploring AM process to enhance the value delivery of existing products in supply chains
- (ii) utilising benefits of scale economics offered by use of AM process facilitating supply chain improvements
- (iii) achieving an improved level of innovation & performance of the products that companies offer.
- (iv) Altering existing products and supply chains. (Deloitte University Press, 2014)

Supply Chain actors & their relationship.

The manufacturing process begins with raw materials and completes with finished product in the hands of the end user. We can simplify supply chain in below workflow process:

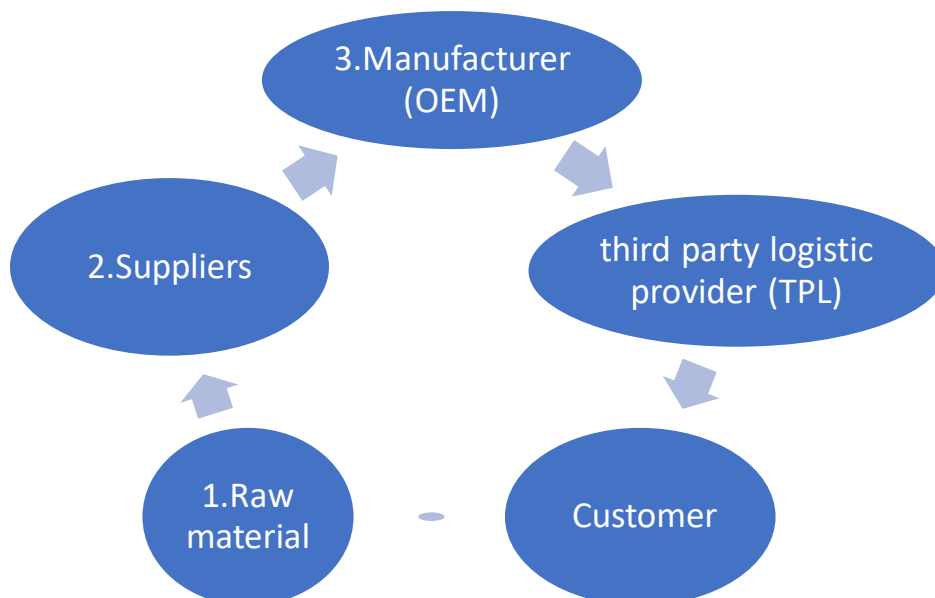


Fig. 15 Supply Chain Flowchart
(Image source: Attaran, 2007)

Raw Material → Supplier → Manufacturer (OEM) → Third party logistic provider (TPL) → Customer

The first and important actor within a production process are the suppliers. Suppliers provide required resources, raw material, hardware, parts, sub-assemblies to manufacture final products or services.

Logistics is managed by separate entity called as third-party logistics providers. These TPL providers deliver, manage & independently control all the logistics activities within in complete supply chain. TPL providers role is not limited to pure transportation of goods. Its role may involve warehousing, assembly or customs clearance. Complete supply chain must be fully integrated to get competitive advantage in the global market.

Supply chain contribute to major expenses for a company. The supply chain expense is more than 5% of the total value of goods. Improvement in the overall supply chain management will be substantial. To stay competitive in the global market, it's important to reduce expenses on supply chain. AM technologies have potential to offer cost saving benefits in the overall supply chain including raw material, transportation, inventory control, warehouse requirements. (Attaran, 2007)

UPS (United Parcel Service Inc.) is one of the biggest package delivery companies which offers supply chain management solutions. As per company report 2015, UPS is looking for its positions in coming years discussing supply chain challenges & additive manufacturing. AM has the potential to positively impact supply chain in terms of parts manufacturing, inventory control & reducing lead time. (Johnson, 2015).

8.2 Impact of AM on supply chain

AM technologies will have positive impact on chains in many ways. This will include faster product development, smaller & economical lot size, improved production flexibility, and reduction in material wastage. Early adopters of AM technology will gain the benefits from sourcing of materials to logistics and product distribution. The study done by Attaran (2017) used research material & and concluded that companies are using AM to modify their supply chains to enhance the performance in the main areas of raw material cost, faster production, improved quality, and positive environmental impact.

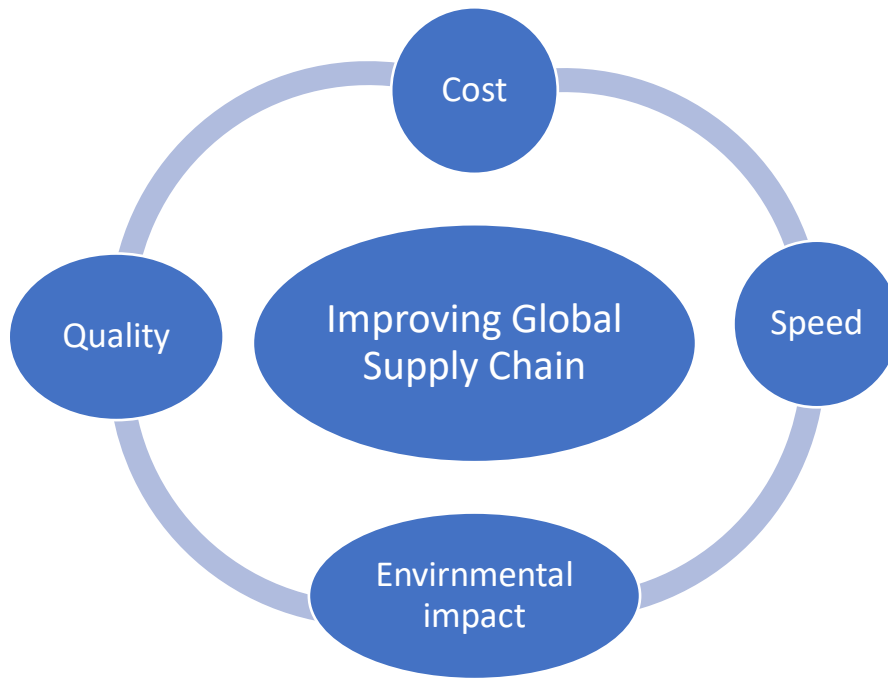


Fig. 16: Improving Global Supply Chain
(Image source: Attaran, 2017)

An important market trend which is leading to increased demand for AM technology is mass –customization of low volume product. AM technologies offer enhancement in the customization and improves company profits by reducing tooling cost to zero. It can offer significantly reduced production time for single part or low volume products. These benefits ultimately impact on existing supply chain positively.

AM technology offers mainly two opportunities as below.
To redesign final product with a smaller number of parts & to produce products near the end customer. This will result in less inventory & less requirement of warehousing, packaging & transportation. (Huang, et. al, 2013)

It has been pointed out that AM has the potential to reduce the number of stages in the traditional supply chain. (Reeves, 2008)

Di and Yang (2022) studied the environmental benefits of the integrated Production-Inventory-Transportation (PIT) supply chain structure. Their study showed that this supply chain structure enabled by AM technology will allow for more than 25% reduction in greenhouse gas emissions.

8.3 Impact of AM on Aircraft Industry Spare parts supply chain

Fast repair and maintenance services at minimal cost is the significant challenge in the aircraft industry spare part supply chain. Any large commercial airplane needs number of parts, sub-assemblies, hardware items. And these parts have to specific grade and finish. All these parts need to be kept in the stock to ensure quicker maintenance and servicing operations. But in reality, many parts are not needed frequently.

As per current supply chain for aircraft spare parts, Standard replacement parts are kept in stock at airline's warehouse. And airlines have to plan regular purchasing of these parts as per maintenance plan. Remaining less frequently required parts are purchased directly from suppliers. Suppliers need to maintain stock of these parts to ensure in-time delivery to ensure quick response. To keep the stock of these parts as small as possible these parts are stored at central warehouse. But this option results in higher delivery cost and additional logistics. Second issue with these parts is production batch size of these parts. Due to small batch size, it is difficult to take advantage of mass production or else total inventory cost will be higher if large quantity of these parts are produced.

AM technology provides potential solution to this problem. Suppliers can produce parts in small quantity or as and when required. As AM technology is at development stage only a limited range of parts can be produced economically. AM technology is constantly evolving, so it is important to revisit the decisions periodically to select appropriate applications. (Walter, Holmstrom & Yrjola, 2004)

8.4 Impact of AM on Logistics

AM technology offers decentralised manufacturing which will result in reduced logistics of parts, sub-assemblies & finished goods. Most of the logistics movements shift upstream in the supply chain & are handled in the form of raw materials.

Rationalization of stock and logistics: Print on-demand or just in time production using AM technology will help in reduction of inventory. This will result in low volume inventory, less logistics & lesser warehouse requirement. (Kocovic, 2017).

When parts are produced closer to their end user destination, we can potentially reduce the logistics costs and its environmental impacts. This will result in potentially moving some production away from low-wage countries and closer to the end customers. This technology has potential to transform the global supply chain into a universally connected, but completely local supply chain. (Nyman & Sarlin, 2014)

But we need to remember that, AM service providing companies will have to face additional complexity for raw material purchase. For example, AM raw materials can be purchased from AM machinery provider, independent raw material suppliers, or directly from powder producers. Each supply chain will have its own benefits and challenges. (Kunovjanek et. al, 2022)

Chapter 9 – Impact on the environment

9.1 Energy Consumption

The World Resources Institute has estimated that 73% of Global Greenhouse Gas emissions are because of energy generation and consumption to in 2017. Manufacturing companies are major energy consumers & It is estimated that manufacturing energy consumption will continue to grow until 2050. (Friedrich et al., 2020).

AM technologies use only the amount of material needed for final part. AM technologies have the potential to reduce raw material requirement and energy consumed during manufacturing as compared to conventional subtractive manufacturing techniques by reducing in-process scrap. Water pollution & waste disposal is much less in AM technologies than in conventional manufacturing processes. AM processes does not require any cutting fluids. These cutting fluids are major hazard in the manufacturing waste streams (Luo et al, 1999)

Manufacturing is about converting input raw material input into finished products and services. The efficiency of this conversion process is main parameter for analysing environmental impact associated with the manufacturing process. (Gutowski et al., 2009).

There are economic benefits as a result of efficiency and process improvements in design, quality testing and production. Additionally, no requirement of tooling offers additional time and cost saving benefits. Immediately after part design is completed production can be started. Immediate production as soon as design is completed results in cost savings. Using additively manufactured components can also lead to cost savings in the use phase. Lighter parts will result in less energy consumption and can deliver savings up to \$56– \$219 billion by 2025 (Gebler et al., 2014).

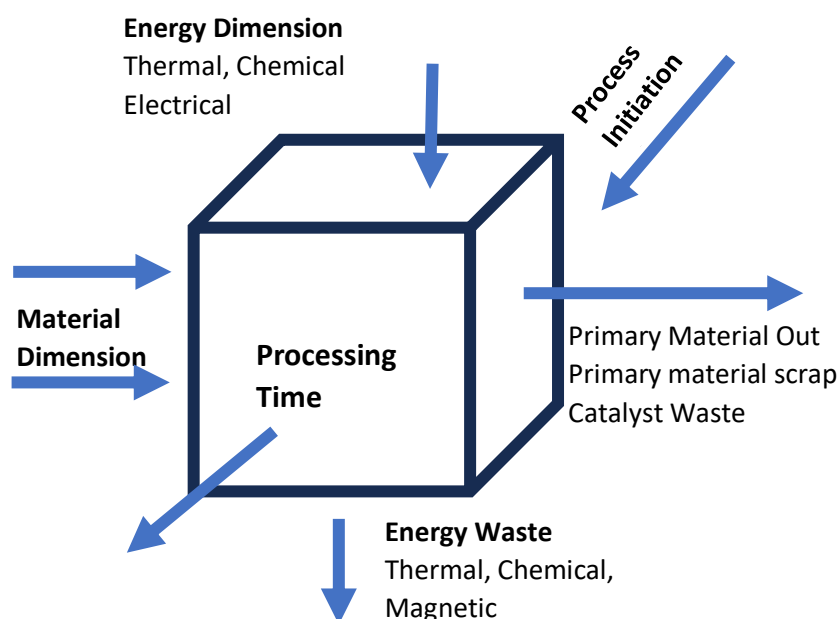


Fig. 17: Environmental analysis for manufacturing processes
(Image source: Baumann et al., 2013)

We know that energy consumption accounts for only a small portion of total production costs. But from environmental impact point of view, energy efficient operation of AM is important step for the future. (Baumers et al., 2013)

9.2 Build Failure & Energy consumption

In Chapter 04 we have seen that build failure possess the risk to quality of the final part and ultimately affects the energy and material flows in AM. And finally, it will result in the reprinting of the part. This failure will result in increased energy demand, material supply and the nature of production planning & it will affect delivery schedule also. (Holmstrom et al., 2016).

In AM processes there is high risk of build failure due to several reasons. It is possible that the available methodologies for energy consumption measurement of AM processes understate the actual levels of energy consumption. (Baumers & Holweg 2019). It has been observed that the risk of build failure has major impact on the costs of AM, and it results because of relatively higher process instability. For this disruptive technology, the impact of build failure risk on energy consumption have not yet been studied. This creates a significant gap in the understanding of the real environmental performance of AM. (Wang et al, 2023) Wang et al (2023) suggested that processes and part designs need to be leveraged to minimize the Z-height of builds. Smaller z-height reduces the chances of build failure.

9.3. Circular Economy

At present, commercial applications of AM technology are already enabling more circular production systems. This is achieved by using recycled and reclaimed materials as a feedstock for AM processes. For example, in metal AM, more than 95% of the unused feedstock can be filtered locally and then reused for next lot of manufacturing. Remaining 5% can be sent to established recycling facility to prepare new powder. AM technology itself utilises only required material and additionally the system around the process is designed to offer recycling of raw material. (Vayre et al., 2012, Faludi et al., 2015),

Plastic raw material used in the AM processes are mainly recycled plastics. Plastics are still recycled at reduced rate in the centralised recycling facilities. Distributed plastics recycling to produce filament for AM processes can promote recycling rate at a lower economic and environmental cost (Baechler, Devuono & Pearce 2013).

European Union's Circular Plastics Alliance

AM processes use plastics & metals as an input material. Due to defects and limitations in the AM processes some amount of scrap is generated. If the finished products do not meet quality requirements due to any of the defects, part need to be scrapped. This scrap leads us to important aspect of recycling of AM processes waste. This need results in the improvement of the circular economy for plastics. The Circular Plastics Alliance is an important initiative which was launched in year 2018 by European union. This initiative will help plastics value chains boost the EU market for recycled plastics to 10 million tonnes by 2025.

9.4 Further Study

AM processes has the potential of energy saving & generate reduced amount of waste than the current manufacturing processes. (Ahmed, 2023)

At the same time, it needs to be noted that the production and disposal of 3D printed products may have negative impact on the environment. Manufacturing companies need to develop ways to reduce energy consumption required for AM processes. AM processes need intense heat to melt or fuse input material which results in high energy consumption. Many materials used in the AM processes cannot be recycled. Many 3D printed parts are difficult to recycle or dispose of in a sustainable manner because their end-of-life design is overlooked. The software data & electronics utilized in the AM processes will create electronic waste. This electronic waste can be a potential problem if not addressed correctly. Future challenge is to figure out more sustainable AM processes. (Kanishka & Acherjee, 2023)

AM processes are digital in nature. Once CAD model is completed parts can be manufactured using AM technology without needing to wait for tooling. And design can be modified at any stage. As AM technologies are improving on technical side the potential to use AM as a direct manufacturing process is gradually accepted in all the sectors e.g. aerospace, automotive, healthcare & pharmaceuticals. In these sectors customization & personal requirements are key parameters. All these sectors are at different stage of maturity & adoption of AM. (Despeisse et al. 2017)

The study, conducted by Gutowski et al. showed that new manufacturing technologies are capable of achieving more tight tolerances & small batch size but at lower rates, which results in extra electrical energy requirements. It has also been observed that these new processes make more use of high-energy value materials in very inefficient ways. The authors acknowledged that new advance processes are capable of manufacturing finished products with better performance at lower energy consumption. Although AM is considered to be more energy efficient & positive impact on the environment, it is important to conduct detailed analysis of AM technologies.

Chapter 10 – Findings & Conclusion

10.1 Findings

In Chapter 2,3 & 4 we studied about the available materials available for AM technology. Which different AM processes we can apply in the manufacturing companies based on their requirements. And, what are the advantages, limitations & defect in the different AM technologies. And there is furthermore research is happening in the field of AM. This research will bring more knowledge in this field.

In Chapter 08 we have seen how AM technologies will impact supply chain management. One common finding is that AM will positively influence supply chain management and it will promote local business & local supply chain resulting in less logistics. This will be important step towards reducing carbon footprint.

In Chapter 09 we have seen how AM technologies will impact environment. Current studies show that AM technologies will positively affect the environment by reducing energy consumption. But further research is recommended by several researchers. Huang et al. (2013) study shows that, when we consider complete operating procedure, AM might not be energy efficient, as the literature on this topic is limited, It is difficult to draw firm conclusion.

Additionally build failure & other AM limitations increase energy consumption which will adversely affect the environment. Detail study of each process & material will provide required knowledge.

10.2 Current market situation

In chapter 07 we have seen case studies of aerospace applications. Companies like Boeing, Airbus, Safran, GE, Stratsys & 3D system are successfully implementing AM technology in aerospace applications. AM technology is dominated by aerospace industry leaders.

It is difficult for aerospace industry suppliers to produce parts with AM technology because of airworthiness requirements for the final part. As per the industry norms aerospace grade AM parts are certified individually. This certification includes right from the raw material sourcing to post processing and all intermediate stages. This exhausting & costly certification process is the main barrier in front of many small-scale aerospace suppliers. Industry leaders in the aerospace domain have developed their own proprietary design parameters and process specifications which are too costly to develop for small scale suppliers. This is one of the biggest obstacles for aerospace industry for going ahead with AM technology at larger scale. (Yang, 2020)

10.2 Conclusions

One of the problems with AM technologies w.r.t latest innovations, new material development, process improvements is that most of the knowledge is patented & it is available to proprietary firms those are developing them.

At present easily available neutral knowledge about these technologies is rarely available. only small amount of data on AM technologies is openly accessible. On other hand we may have detailed information of manufacturing processes like CNC machining, casting, injection moulding, forming. This issue shows importance of improving understanding of the real capabilities and limitations of AM and making this knowledge accessible to everyone. (Dickens and Minshall, 2015).

Role of Education system

In this situation Higher Education Institutions have important roles to play in developing new generation of designers & professional. It will be important to develop designers with capabilities to design for a Circular economy utilising advanced manufacturing tools and techniques in the field of AM.

New designers & developers need to learn to design for longevity of product through product repair, upgrades and remanufacturing. Also new designs need to be with reduced environmental impact and increased efficiency. Design for disassembly, efficient material utilisation, energy efficient products & processes and circular economy considerations will be important factors to consider. (Baumers et al., 2015, Holweg, 2015).

Role of Government & Private companies

Industry 4.0 impact on manufacturing industry will be different for each individual company depending on their journey towards industry 4.0. It is important to understand that Industry 3.0 is still present, most of the factories being at this level of evolution. (Dima, 2023).

This means that existing manual jobs will be replaced by lots of digital & high-tech jobs. Manufacturing companies need to ensure that existing workforce and young generation are getting required training to cope up with the requirements of industry 4.0. And existing employees need to ensure to keep themselves up to date with the latest technologies & learn new skills. Schwab (2017, p.45). Manufacturing companies need to need to invest in the Continuous Professional Development of existing workforce. Implementation of any new technology depends on the adoption by employees who are responsible for using these technologies. Short training programs, seminars & visits to advance technology exhibition will generate interest and required knowledge in the technologies.

MADE Cymru is a University of Wales Trinity Saint David's innovative program which aims to offer necessary support and enhance capabilities of the manufacturing sector in Wales through R&D projects and accredited courses. This initiative has successfully generated a collaborative support network all over the Wales. Its Industry 4.0 Level 5 & Level 7 courses provide a platform to study latest

technologies. These courses have equipped individuals with the necessary skills and knowledge to drive change in their respective organisations. The R&D initiatives have had a transformative effect on Welsh businesses' products, processes, and productivity. (MADE Cymru, 2023)

MADE Cymru is helping Welsh manufacturing sector to gain advantage of Industry 4.0 technologies and Innovation Management which will result in positive economic impact. Workforce involved in industry 4.0 courses are guided by the experienced staff through the entire R&D process.

Regulators like FAA, EASA & leading aerospace companies need to develop AM standards. Based on these standards design culture will be developed to reflect AM process capabilities. More consistent materials and processes in the field of AM will be helpful for future expansion of this disruptive industry 4.0 technology. (Leeham news, 2018)

10.3 Future Scope

Aerospace industry is driven by strict industry regulations & it demands very high standards in terms of performance. Aerospace industry is one of the early adopters of additive manufacturing. As of today, there are few plastic material options for aerospace application. In future more materials will be available & AM technology will be available at cheaper prices. This will help small scale companies to adapt these technologies. Large scale implementation of AM technology will help in reducing environmental damage happening because of existing conventional manufacturing processes & machinery.

AM technology is helping to produce difficult parts in short time with improved strength which is main requirement of aerospace industry. In old days it was used to produce prototype parts at faster & economical way during development process of the product. And now, it is impacting final product design, production part, assembling and fixing up in the aerospace applications. AM technology offers improved designs with weight reduction & less material requirement, which is key factor for the aerospace industry. Lightweight designs reduce fuel consumption & results in reduced carbon footprint.

In terms of Metal additive manufacturing, there are still developments happening. There are some successful implantation stories of metal AM as explained in chapter 07 aerospace application case studies. There is scope to improve quality of metal 3D printed parts in terms of mechanical properties like surface finish, balling phenomena & distortion. (Vhanmane, 2022)

References: Chapter 1 – Introduction

Cottrell, Stella. *Dissertations and Project Reports : A Step by Step Guide*, Bloomsbury Publishing Plc, 2014. *ProQuest Ebook Central*, <http://ebookcentral.proquest.com/lib/trinity/detail.action?docID=4763634>. (Accessed on 15-Nov-23)

Schwab, K. (2017) *The Forth Industrial Revolution*. Great Britain: Portfolio Penguin. (Accessed on 25-Nov-23)

Freemar T, 2023. Additive Manufacturing vs. CNC Machining – Which is Best? <https://www.alphaprecisionpm.com/blog/pros-cons-of-additive-manufacturing-vs.-cnc-machining>

(accessed on 30-Nov-23)

GE Website, 2015. The FAA Cleared the First 3D Printed Part to Fly in a Commercial Jet Engine from GE <https://www.ge.com/news/reports/the-faa-cleared-the-first-3d-printed-part-to-fly-2> (Accessed on 02-Dec-23)

YouTube Video The CFM LEAP Fuel Nozzle <https://www.youtube.com/watch?app=desktop&v=rMzVSbNebCg> (Accessed on 02-Dec-23)

New manufacturing milestone: 30,000 additive fuel nozzles: <https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles>

(Accessed on 05-Dec-23)

References Chapter 2 – Additive Manufacturing materials

Godec, Damir., Gonzalez-Gutierrez, Joamin., Nordin, Axel., Pei, Eujin., & Ureña Alcázar, Julia. (2022). *A Guide to Additive Manufacturing* (1st ed. 2022.). Springer International Publishing. <https://doi.org/10.1007/978-3-031-05863-9>

Bolton, William., R.A. Higgins (2020). *Materials for Engineers and Technicians*. (7th ed. 2020.). Routledge. <https://r2.vlreader.com/EpubReader?ean=1781000209303#> (Accessed on 15Dec23)

API Website, 2023 Thermoplastics Vs. Thermoset Materials | Plastics Manufacturing <https://advancedplastiform.com/thermoplastics-vs-thermoset-materials/> (Accessed on 15Nov23)

Demaid A, Spedding V, Zucker J, Classification of plastics materials, Artificial Intelligence in Engineering, Volume 10, Issue 1, 1996, (<https://www.sciencedirect.com/science/article/pii/0954181095000127>) (Accessed on 12Dec23)

Plastics Europe, 2023 [How plastics are made](https://plasticseurope.org/plastics-explained/how-plastics-are-made/) <https://plasticseurope.org/plastics-explained/how-plastics-are-made/> (Accessed on 10Dec23)

Nikolovska, G 2023 How is Plastic Made? A Step-by-Step Explanation <https://www.thomasnet.com/articles/plastics-rubber/how-is-plastic-made/> (Accessed on 28Dec23)

Haritz Sardon, Zi-Chen Li Introduction to plastics in a circular economy [Introduction to plastics in a circular economy - Polymer Chemistry \(RSC Publishing\)](https://doi.org/10.1039/D0PY90117B) DOI:10.1039/D0PY90117B (Accessed on 05Dec23)

Dynisco. 2019. *Understanding Plastics and Polymers - The Different Types of Plastic*. AZoM, <https://www.azom.com/article.aspx?ArticleID=17477> (Accessed on 28Oct23)

Stratasys 2019, [ULTEM Resin Takes 3D Part Strength to Another Level](https://www.stratasys.com/uk/stratasysdirect/resources/articles/3d-printing-ultem/) <https://www.stratasys.com/uk/stratasysdirect/resources/articles/3d-printing-ultem/> (Accessed on 09Dec23)

Real engineering, 2019 [The Material Science of Metal 3D Printing](https://www.youtube.com/watch?v=fzBRYsiyxjI&t=4s) <https://www.youtube.com/watch?v=fzBRYsiyxjI&t=4s> (Accessed on 15Dec23)

David Bourell, Jean Pierre Kruth, Ming Leu, Gideon Levy, David Rosen, Allison M. Beese, Adam Clare, Materials for additive manufacturing, CIRP Annals, 2017, <https://www.sciencedirect.com/science/article/abs/pii/S0007850617301488?via%3Diuhub> (Accessed on 12th Sep 2023)

NETZSCH Analyzing & Testing, 2021 Overview of Materials Used in Additive Manufacturing <https://www.youtube.com/watch?v=BpMu3ymrwpU> (Accessed on 19th Sep 2023)

T. DebRoy, H.L. Wei, J.S. Zuback, T. Mukherjee, J.W. Elmer, J.O. Milewski, A.M. Beese, A. Wilson-Heid, A. De, W. Zhang, Additive manufacturing of metallic components – Process, structure and properties, Progress in Materials Science, Volume 92, 2018, <https://doi.org/10.1016/j.pmatsci.2017.10.001>. (<https://www.sciencedirect.com/science/article/pii/S0079642517301172>)

Peters, M., Kumpfert, J., Ward, C. H., & Leyens, C. (2003). Titanium Alloys for Aerospace Applications. *Advanced Engineering Materials*, 5(6), 419–427. <https://doi.org/10.1002/adem.200310095> (Accessed on 12Jan24)

References: Chapter 3 – Additive Manufacturing Processes

David A. Arcos-Novillo, David Güemes-Castorena, Development of an additive manufacturing technology scenario for opportunity identification—The case of Mexico, *Futures*, Volume 90, 2017, Pages 1-15, <https://doi.org/10.1016/j.futures.2017.05.001>. (<https://www.sciencedirect.com/science/article/pii/S0016328716301744>) (accessed on 06Dec23)

Basiliere, P. (2016, 10 24). Market guide for 3D printer manufacturers, 2016. Gartner. 2017: <https://www.gartner.com/document/3489417/market-guide-d-printer-manufacturers> (accessed on 06Dec23)

Wei Han, Lingbao Kong, Min Xu (2022) Advances in selective laser sintering of polymers *Int J Extrem Manuf*, 4 (4) (2022), 10.1088/2631-7990/ac9096

K. Ishfaq, M. Abdullah, M.A. Mahmood (2021), A state-of-the-art direct metal laser sintering of Ti6Al4V and AlSi10Mg alloys: Surface roughness, tensile strength, fatigue strength and microstructure *Opt Laser Technol*, 143 (June) (2021), Article 107366, 10.1016/j.optlastec.2021.107366

David Bourell, Jean Pierre Kruth, Ming Leu, Gideon Levy, David Rosen, Allison M. Beese, Adam Clare, *Materials for additive manufacturing*, CIRP Annals, Volume 66, Issue 2, 2017, <https://doi.org/10.1016/j.cirp.2017.05.009>. (<https://www.sciencedirect.com/science/article/pii/S0007850617301488>) (Accessed on 06Jan24)

Godec Damir., Gonzalez-Gutierrez Joamin., Nordin Axel., Pei Eujin., & Ureña Alcázar Julia. (2022). *A Guide to Additive Manufacturing* (1st ed. 2022.). Springer International Publishing. <https://doi.org/10.1007/978-3-031-05863-9> (Accessed on 01Jan24)

N.A.S. Mohd Puad, R.H. Abdul Haq, H. Mohd Noh, H.Z. Abdullah, M.I. Idris, T.C. Lee, Review on the fabrication of fused deposition modelling (FDM) composite filament for biomedical applications, *Materials Today: Proceedings*, Volume 29, Part 1, 2020, <https://doi.org/10.1016/j.matpr.2020.05.535>. (<https://www.sciencedirect.com/science/article/pii/S2214785320341377>)

HUANG, J., QIN, Q. and WANG, J., 2020. A Review of Stereolithography: Processes and Systems. *Processes*, **8**(9), pp. 1138. (Accessed on 12Jan24)

Olayan, H.B.; Hami, H.S.; Owen, E.D. Photochemical and Thermal Crosslinking of Polymers. *J. Macromol. Sci. Part C Polym. Rev.* 1996, **36**, 671-719 (Accessed on 12Jan24)

Charoo, N. A., Barakh Ali, S. F., Mohamed, E. M., Kuttolamadom, M. A., Ozkan, T., Khan, M. A., & Rahman, Z. (2020). Selective laser sintering 3D printing - an overview of the technology and pharmaceutical applications. *Drug Development and Industrial Pharmacy*, **46**(6), 869–877. <https://doi.org/10.1080/03639045.2020.1764027> (Accessed on 06Feb24)

Matthias Schneck, Matthias Gollnau, Max Lutter-Günther, Benjamin Haller, Georg Schlick, Marius Lakomiec, Gunther Reinhart,
Evaluating the Use of Additive Manufacturing in Industry Applications,
Procedia CIRP, Volume 81, 2019, <https://doi.org/10.1016/j.procir.2019.03.004>.

Qingbo Jia, Paul Rometsch, Philipp Kürnsteiner, Qi Chao, Aijun Huang, Matthew Weyland, Laure Bourgeois, Xinhua Wu,
Selective laser melting of a high strength AlMnSc alloy: Alloy design and strengthening mechanisms, *Acta Materialia*, Volume 171, 2019,
<https://doi.org/10.1016/j.actamat.2019.04.014>.
(<https://www.sciencedirect.com/science/article/pii/S1359645419302149>) (Accessed on 05Feb24)

(<https://www.sciencedirect.com/science/article/pii/S2212827119303087>) (Accessed on 16Jan24)

Kumar, S. (2020). Classification. In: *Additive Manufacturing Processes*. Springer, Cham. https://doi.org/10.1007/978-3-030-45089-2_2

Mohsen Attaran, The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing, *Business Horizons*, Volume 60, Issue 5, 2017,
<https://doi.org/10.1016/j.bushor.2017.05.011>.
(<https://www.sciencedirect.com/science/article/pii/S0007681317300897>)

Malte Gebler, Anton J.M. Schoot Uiterkamp, Cindy Visser,
A global sustainability perspective on 3D printing technologies,
Energy Policy, Volume 74, 2014, Pages 158-167, ISSN 0301-4215,
<https://doi.org/10.1016/j.enpol.2014.08.033>.
(<https://www.sciencedirect.com/science/article/pii/S0301421514004868>)

Mohsen Attaran, 2017. Journal of Service Science and Management 10(03)

Additive Manufacturing: The Most Promising Technology to Alter the Supply Chain and Logistics DOI:10.4236/jssm.2017.103017 (Accessed on 26Jan24)

Nyman, H.J. and Sarlin, P. (2014) From Bits to Atoms: 3D Printing in the Context of Supply Chain Strategies. 47th Hawaii International Conference on System Science, Waikoloa, 6-9 January 2014, 4190-4199. (Accessed: 10th Feb 2024)

R. King (2012) 3-D printing coming to the manufacturing space — and outer space, <https://www.bloomberg.com/news/articles/2012-01-09/3-D-printing-coming-to-the-manufacturing-space-and-outer-space>

T. DebRoy, H.L. Wei, J.S. Zuback, T. Mukherjee, J.W. Elmer, J.O. Milewski, A.M. Beese, A. Wilson-Heid, A. De, W. Zhang,
Additive manufacturing of metallic components – Process, structure and properties, Progress in Materials Science, Volume 92, 2018,
<https://doi.org/10.1016/j.pmatsci.2017.10.001>.
(<https://www.sciencedirect.com/science/article/pii/S0079642517301172>)

Costanzo Bellini, Filippo Berto, Vittorio Di Cocco, Francesco Iacoviello, Larisa Patricia Mocanu, Nima Razavi,
Additive manufacturing processes for metals and effects of defects on mechanical strength: a review, Procedia Structural Integrity, Volume 33, 2021,
<https://doi.org/10.1016/j.prostr.2021.10.057>.
(<https://www.sciencedirect.com/science/article/pii/S2452321621001529>)

Safran website, 2020 Metal and polymer 3D additive manufacturing

<https://www.safran-group.com/products-services/additive-manufacturing>
(Accessed on 22Jan2024)

GE Website (2018) New manufacturing milestone: 30,000 additive fuel nozzles
<https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles> (Accessed: 10th Jan 2024)

Code of Federal regulations, 2024
<https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/subpart-D/subject-group-ECFR1e1f52030ba4797/section-25.853> (Accessed on 15Jan24)

L. Rath, Z. Kallien, A. Roos, J.F. do Santos, B. Klusemann (2023)
Anisotropy and mechanical properties of dissimilar Al additive manufactured structures generated by multi-layer friction surfacing
Int J Adv Manuf Technol, 125 (5–6) (2023), pp. 2091-2102, [10.1007/s00170-022-10685-3](https://doi.org/10.1007/s00170-022-10685-3)

Kumar Kanishka, Bappa Acherjee,
Revolutionizing manufacturing: A comprehensive overview of additive manufacturing processes, materials, developments, and challenges,
Journal of Manufacturing Processes, Volume 107, 2023, Pages 574-619,
ISSN 1526-6125, <https://doi.org/10.1016/j.jmapro.2023.10.024>.
(<https://www.sciencedirect.com/science/article/pii/S1526612523009726>) (Accessed on 11-Feb-24)

T.D. Ngo, A. Kashani, G. Imbalzano, K.T.Q. Nguyen, D. Hui
Additive manufacturing (3D printing): A review of materials, methods, applications and challenges
Compos Part B Eng, 143 (February) (2018), pp. 172-196, [10.1016/j.compositesb.2018.02.012](https://doi.org/10.1016/j.compositesb.2018.02.012) (Accessed on 11-Feb-24)

K.H. Lee, G.J. Yun
Design optimization of thermally conductive support structure for laser powder-bed fusion process with part-scale thermal history
Addit Manuf, 51 (2022), p. 102627, [10.1016/j.addma.2022.102627](https://doi.org/10.1016/j.addma.2022.102627)
(Accessed on 6-Feb-24)

Aamer Nazir, Ozkan Gokcekaya, Kazi Md Masum Billah, Onur Ertugrul, Jingchao Jiang, Jiayu Sun, Sajjad Hussain,
Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials, Materials & Design, Volume 226, 2023,
<https://doi.org/10.1016/j.matdes.2023.111661>.
(<https://www.sciencedirect.com/science/article/pii/S026412752300076X>)

Kim, F. H., & Moylan, S. P. (2018). Literature Review of Metal Additive Manufacturing Defects, US Department of Commerce, National Institute of Standards and Technology. 1–17. (Accessed on 12-Feb24)

Costanzo Bellini, Filippo Berto, Vittorio Di Cocco, Francesco Iacoviello, Larisa Patricia Mocanu, Nima Razavi, Additive manufacturing processes for metals and effects of defects on mechanical strength: a review, *Procedia Structural Integrity*, Volume 33, 2021, Pages 498-508, <https://doi.org/10.1016/j.prostr.2021.10.057>. (<https://www.sciencedirect.com/science/article/pii/S2452321621001529>) (Accessed on 10-Feb-24)

Holmström, J., Holweg, M., Khajavi, S.H., & Partanen, J. (2016). The direct digital manufacturing (r)evolution: definition of a research agenda. *Operations Management Research*, 9(1-2), 1-10. <https://doi.org/10.1007/s12063-016-0106-z>

Wang, H., Baumers, M., Basak, S., He, Y., & Ashcroft, I. (2022). The impact of the risk of build failure on energy consumption in additive manufacturing. *Journal of Industrial Ecology*, 26(5), 1771–1783. <https://doi.org/10.1111/jiec.13318>

Deloitte University Press, Additive manufacturing takes flight, 3D opportunity in aerospace and defense, USA, 2014
https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-3d-opportunity-in-aerospace/DUP_706-3D-Opportunity-Aerospace-Defense_MASTER2.pdf

References: Chapter 5 Generative Design

Hyunjin, C. (2020). A Study on Application of Generative Design System in Manufacturing Process. *IOP Conference Series. Materials Science and Engineering*, 727(1), 12011-. <https://doi.org/10.1088/1757-899X/727/1/012011>

EPD, (2017) Generative Design
<https://engineeringproductdesign.com/knowledge-base/generative-design/>
(Accessed on 30th Nov 2023)

Autodesk (2022) Generative Design

<https://www.autodesk.com/solutions/generative-design> (Accessed on 5-Jul23)

HAN, L., DU, W., XIA, Z., GAO, B. and YANG, M., 2022. Generative Design and Integrated 3D Printing Manufacture of Cross Joints. *Materials*, **15**(14), pp. 4753.

Junk, S., & Rothe, N. (2022). Lightweight design of automotive components using generative design with fiber-reinforced additive manufacturing. *Procedia CIRP*, 109, 119–124.
<https://doi.org/10.1016/j.procir.2022.05.224>

References: Chapter 6 AM Application in aftermarket Engineering

Plastock website 2023 Ultem 9085 PEI 3D Printing Filament

<https://www.plastock.co.uk/products/ultem-9085-pei-3d-printing-filament?variant=44282940752096> (Accessed on 30-Nov-23)

Yang, J. 2020. Pat to Aircraft certification for additive manufacturing with Stratasys F900.

<https://www.javelin-tech.com/blog/2020/10/path-to-aircraft-certification-for-additive-manufacturing-with-stratasys-f900/> (Accessed on 30-Nov-23)

CAA Website, 2023. The UK aviation system <https://www.caa.co.uk/safety-initiatives-and-resources/how-we-regulate/state-safety-programme/safety-policy-objectives-and-resources/the-uk-aviation-system> (Accessed on 15-Dec-23)

Job description, 2024. In-Service Solution Design Engineer
<https://www.safran-group.com/jobs/united-kingdom/cwmbran/service-solution-design-engineer-128581> (Accessed on 15-Feb-24)

References: Chapter 7 – AM Application Aerospace Case Studies

Gisario A., Kazarian M., Martina F., Mehrpouya M, (2019)

Metal additive manufacturing in the commercial aviation industry: A review, *Journal of Manufacturing Systems*, Volume 53, 2019, Pages 124-149,
<https://doi.org/10.1016/j.jmsy.2019.08.005>.

(<https://www.sciencedirect.com/science/article/pii/S0278612519300731>)

Monteiro H., Carmona-Aparicio G., Lei I., Despeisse M.,

Energy and material efficiency strategies enabled by metal additive manufacturing – A review for the aeronautic and aerospace sectors,

Energy Reports, Volume 8, Supplement 3, 2022, Pages 298-305,

<https://doi.org/10.1016/j.egyr.2022.01.035>.

(<https://www.sciencedirect.com/science/article/pii/S235248472200035X>)

Ford S., Despeisse M., (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, *Journal of Cleaner Production*, Volume 137, 2016, Pages 1573-1587, <https://doi.org/10.1016/j.jclepro.2016.04.150>.

(<https://www.sciencedirect.com/science/article/pii/S0959652616304395>)

European Commission, 2023. Climate Action

https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-targets_en (Accessed on 22-Feb-24)

Safran website, 2022. Safran inaugurates the Safran Additive Manufacturing Campus, a new center of excellence

<https://www.safran-group.com/pressroom/safran-inaugurates-safran-additive-manufacturing-campus-new-center-excellence-2022-10-07> (Accessed on 10-Oct-23)

Boeing website, 2023. Boeing Additive Manufacturing Center: Auburn, WA

<https://www.boeingfutureu.com/virtual-site-tours/boeing-additive-manufacturing-center-auburn-wa> (Accessed on 14-Dec-23)

GE Additive, 2018. New manufacturing milestone: 30,000 additive fuel nozzles

<https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles> (Accessed on 10-Jan-23)

Airbus newsroom, 2023 Airbus Helicopters boosts competitiveness with 3D printing

<https://www.airbus.com/en/newsroom/press-releases/2023-10-airbus-helicopters-boosts-competitiveness-with-3d-printing> (Accessed on 10-Dec-23)

Poyraz, Ö. and Kuşhan, M.C., 2019. Design for additive manufacturing with case studies on aircrafts and propulsion systems. *Sci. Res. Educ. Air Force-AFASES*, 2019, pp.1046-1054. (Accessed on 10-Dec-23)

Airbus newsroom, 2024 The world's first metal 3D printer for space is on its way to the ISS <https://www.airbus.com/en/newsroom/stories/2024-01-the-worlds-first-metal-3d-printer-for-space-is-on-its-way-to-the-iss> (Accessed on 10-Dec-23)

Hull, C.W., 2015. The birth of 3D printing. *Research-Technology Management*, 58(6), pp.25-30.

<https://www.tandfonline.com/doi/pdf/10.5437/08956308X5806067> (Accessed on 15-Nov-23)

3D System, 2023. Additive Manufacturing for Aerospace & Defense.
<https://www.3dsystems.com/sites/default/files/2023-07/3d-systems-aerospace-brochure-usen-2023-07-11.pdf?ind=aerospace> (Accessed on 16-Nov-23)

Stratsays, (2023) Production parts. Big business impact

<https://www.stratasys.com/uk/industries-and-applications/3d-printing-applications/production-parts/> (Accessed on 15-Dec-23)

References: Chapter 8 – Supply Chain management

Deloitte University Press, Additive manufacturing takes flight, 3D opportunity in aerospace and defense, USA, 2014.
https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-3d-opportunity-in-aerospace/DUP_706-3D-Opportunity-Aerospace-Defense_MASTER2.pdf on 05Feb24)

Sadettin Cem Altıparmak, Bowen Xiao, 2021. A market assessment of additive manufacturing potential for the aerospace industry, Journal of Manufacturing Processes, Volume 68, Part A, 2021, <https://doi.org/10.1016/j.jmapro.2021.05.072>.
(<https://www.sciencedirect.com/science/article/pii/S1526612521004102>) (Accessed on 05Feb24)

P. Kocovic (2017). 3D Printing and Supply Chain Management. IGI Global.
<https://doi-org.ezproxy.uwtsd.ac.uk/10.4018/978-1-5225-2289-8.ch004>

Johnson, D. (2015). 3D Printing: The Next Revolution in Industrial Manufacturing. UPS.

Attaran, M. (2007) RFID: An Enabler of Supply Chain Management. Supply Chain Management: An International Journal, 12, 249-257.
<https://doi.org/10.1108/13598540710759763>

Reeves P (2008) How the socioeconomic benefits of rapid manufacturing can offset technological limitations. RAPID 2008 Conference and Exposition. Lake Buena Vista, FL, pp 1-12

Huang, S.H., Liu, P., Mokasdar, A. et al. Additive manufacturing and its societal impact: a literature review. *Int J Adv Manuf Technol* 67, 1191–1203 (2013).
<https://doi.org/10.1007/s00170-012-4558-5>

Nyman, H.J. and Sarlin, P. (2014) From Bits to Atoms: 3D Printing in the Context of Supply Chain Strategies. 47th Hawaii International Conference on System Science, Waikoloa, 6-9 January 2014, 4190-4199.

Tuck C, Hague R, Burns N (2007) Rapid manufacturing: impact on supply chain methodologies and practice. *IJSOM* 3:1–22

Maximilian Kunovjanek, Nils Knofius & Gerald Reiner (2022) Additive manufacturing and supply chains – a systematic review, *Production Planning & Control*, 33:13, 1231-1251, DOI: [10.1080/09537287.2020.1857874](https://doi.org/10.1080/09537287.2020.1857874)

Walter M, Holmstrom J, Yrjola H (2004) Rapid manufacturing and its impact on supply chain management. *LRN Annu Conf*, September 9–10, Dublin, Ireland

[Mohsen Attaran](#) (2017) Additive Manufacturing: The Most Promising Technology to Alter the Supply Chain and Logistics June 2017 Journal of Service Science and Management 10(03) DOI:[10.4236/jssm.2017.103017](https://doi.org/10.4236/jssm.2017.103017)

Di, L., & Yang, Y. (2022). Greenhouse Gas Emission Analysis of Integrated ProductionInventory-Transportation Supply Chain Enabled by Additive Manufacturing. *ASME. J. Manuf. Sci. Eng*, 144(3), 031006.
<https://doi.org/10.1115/1.4051887>

References: (Chapter 9 – Impact on the environment)

Luo YC, Ji ZM, Leu, et al. (1999) Environmental performance analysis of solid freeform fabrication processes. The 1999 IEEE Int Symp on Electron and the Environ. IEEE, NY, pp 1–6

Huang, S.H., Liu, P., Mokasdar, A. et al. Additive manufacturing and its societal impact: a literature review. *Int J Adv Manuf Technol* 67, 1191–1203 (2013).
<https://doi.org/10.1007/s00170-012-4558-5>

Sheng P, Munoz AA (1993) Environmental issues in product design-for-manufacture. The 7th Int Conf on Design for Manuf, Orlando, Oct 1993

T.G. Gutowski, M.S. Branham, J.B. Dahmus, A.J. Jones, A. Thiriez
Thermodynamic analysis of resources used in manufacturing processes
Environ. Sci. Technol., 43 (5) (2009), pp. 1584-1590

Malte Gebler, Anton J.M. Schoot Uiterkamp, Cindy Visser, 2014.

A global sustainability perspective on 3D printing technologies,
Energy Policy, Volume 74,
<https://doi.org/10.1016/j.enpol.2014.08.033>.
(<https://www.sciencedirect.com/science/article/pii/S0301421514004868>)

Simon Ford, Mélanie Despeisse, 2016
Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, Journal of Cleaner Production,
Volume 137, 2016,
<https://doi.org/10.1016/j.jclepro.2016.04.150>.
(<https://www.sciencedirect.com/science/article/pii/S0959652616304395>)

Friedrich, J., Ge, M.P., & Pickens., A. (2020). This Interactive Chart Shows Changes in the World's Top 10 Emitters. <https://www.wri.org/insights/interactive-chart-showschanges-worlds-top-10-emitters/> [Accessed on 10-Feb-2024]

B. Vayre, F. Vignat, F. Villeneuve 2012. Metallic additive manufacturing: state-of-the-art review and prospects. Mechanics & Industry, Volume 13, 2012.
<https://doi.org/10.1051/meca/2012003>
Accessed on 12-Jan24)

[Faludi, J.](#), [Bayley, C.](#), [Bhogal, S.](#) and [Iribarne, M.](#) (2015), "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment", *Rapid Prototyping Journal*, Vol. 21 No. 1, pp. 14-33. <https://doi.org/10.1108/RPJ-07-2013-0067>

Kumar Kanishka, Bappa Acherjee, 2023.
Revolutionizing manufacturing: A comprehensive overview of additive manufacturing processes, materials, developments, and challenges,
Journal of Manufacturing Processes, Volume 107, 2023,
<https://doi.org/10.1016/j.jmapro.2023.10.024>.
(<https://www.sciencedirect.com/science/article/pii/S1526612523009726>)

Ahmed G.H., 2023. A review of '3D concrete printing': materials and process characterization, economic considerations and environmental sustainability J Build Eng, (2023), p. 105863, [10.1016/j.jobee.2023.105863](https://doi.org/10.1016/j.jobee.2023.105863)

C. Baechler, M. Devuono, J.M. Pearce, 2013. Distributed recycling of waste polymer into RepRap feedstock Rapid Prototyping Journal 19 (2) (2013)
<https://www.emerald.com/insight/content/doi/10.1108/13552541311302978/full/html>
accessed on 12Feb24)

M. Despeisse, M. Baumer, P. Brown, F. Charnley, S.J. Ford, A. Garmulewicz, S. Knowles, T.H.W. Minshall, L. Mortara, F.P. Reed-Tsochas, J. Rowley, 2017.
Unlocking value for a circular economy through 3D printing: A research agenda, Technological Forecasting and Social Change,
Volume 115, 2017, <https://doi.org/10.1016/j.techfore.2016.09.021>.
(<https://www.sciencedirect.com/science/article/pii/S0040162516303341>)

(Accessed on 26Jan24)

Han Wang, Martin Baumer, Shreeja Basak, Yinfeng He, Ian Ashcroft, 2023. The impact of the risk of build failure on energy consumption in additive manufacturing https://nottingham-repository.worktribe.com/preview/8848143/HW_Paper1_17%20June%202022_pre-publication.pdf (Accessed on 12-Feb-24)

Baumers, M., & Holweg, M. (2019). On the economics of additive manufacturing: Experimental findings. *J. Oper. Manag.*, 65, 794–809. <https://doi.org/10.1002/joom.1053> (Accessed on 12-Feb-24)

Holmström, J., Holweg, M., Khajavi, S.H., & Partanen, J. (2016). The direct digital manufacturing (r)evolution: definition of a research agenda. *Operations Management Research*, 9(1-2), 1-10. <https://doi.org/10.1007/s12063-016-0106-z> (Accessed on 16-Feb-24)

European commission 2023. Circular Plastics Alliance

https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/circular-plastics-alliance_en (Accessed on 16-Jan-24)

References: Chapter 10 Findings & conclusion

Huang, S.H., Liu, P., Mokasdar, A. *et al.* Additive manufacturing and its societal impact: a literature review. *Int J Adv Manuf Technol* **67**, 1191–1203 (2013). <https://doi.org/10.1007/s00170-012-4558-5>

Dickens, P. and Minshall, T., 2015. UK National Strategy for additive manufacturing, update report 2: what did the initial evidence reveal. <http://www.amnationalstrategy.uk>

Martin Baumer, Phill Dickens, Chris Tuck, Richard Hague, 2016. The cost of additive manufacturing: machine productivity, economies of scale and technology-push, *Technological Forecasting and Social Change*, Volume 102, 2016, <https://doi.org/10.1016/j.techfore.2015.02.015> <https://www.sciencedirect.com/science/article/pii/S0040162515000530>

MADE Cymru, 2023. <https://www.madecymru.co.uk/> accessed on 15-Nov-23

Adrian dima, 2023. Short history of manufacturing: from Industry 1.0 to Industry 4.0
<https://kfactory.eu/short-history-of-manufacturing-from-industry-1-0-to-industry-4-0-2/>
(Accessed on 05-Nov-24)

Leeham news and analysis, 2018. Additive manufacturing: Huge potential, big barriers
[Additive manufacturing: Huge potential, big barriers - Leeham News and Analysis](#)
(Accessed on 28-Feb-24)

Vikram Vhanmane, 2022. Research methods & professional development
assignment. (Accessed on 28-jan-24)