3D Printing and the Aviation Industry: the Likely Impacts of a Disruptive Technology in the Manufacturing & Designing Processes.

DAVID BAUSSART

KTH VETENSKAP OCH KONST

KTH Industrial Engineering and Management

Master of Science Thesis
Stockholm, Sweden 2014

3D Printing and the Aviation Industry:
the Likely Impacts of a Disruptive Technology in the Manufacturing & Designing Processes.

David Baussart

Master of Science Thesis INDEK 2014:10
KTH Industrial Engineering and Management
Industrial Management
SE-100 44 STOCKHOLM

KTH Industrial Engineering and Management	**Master of Science Thesis INDEK ME2004x** **3D Printing and the Aviation Industry: the Likely Impacts of a Disruptive Technology in the Manufacturing & Designing Processes.** David Baussart	
Approved 2014-05-21	Examiner Terrence Brown	Supervisor Gregg Vanourek
	Commissioner	Contact person

Abstract

The need for lighter and more sustainable aircraft has led manufacturers to consider additive manufacturing, also called "3D printing". This technology is currently used in some aerospace companies, and could constitute a game changer in the way we design and manufacture products. Indeed, additive manufacturing gives us the possibility to build what we could not build with traditional processes.

This research is making an assessment of how additive manufacturing is currently used in these companies. It analyses additive manufacturing as a disruptive technology for the European and Northern American aviation industry using Clayton Christensen's theories, and strives to forecast the likely impacts of the technology on the manufacturing and designing processes within the aviation industry.

This study was built on 6 semi-structured phone interviews of managers and engineers working with additive manufacturing within the Northern American and European aviation industry. Two other interviews were conducted (a written interview and a phone interview) with expert working with traditional manufacturing tools to understand more deeply the topic.

Keywords: additive manufacturing; aviation industry; manufacturing; designing; innovation; exploration.

Acknowledgments

I would like to express my gratitude to my advisor Gregg Vanourek for his help, support, enthusiasm, and extensive knowledge. His guidance and great feedback helped me in each steps of this thesis, and I am thankful for that.
I would like to thank again the 8 people who kindly accepted to have a discussion with me and contributed in increasing the quality of this research.
A special thank to my friends Guillaume and Arthur, who shared with me their opinions on my research, to my parents who supported me in everything I undertook until now, and to Gizem who comforted and encouraged me.

Contents

1 Introduction

1.1 Problem

Increases in air passenger traffic and in jet fuel prices, as well as the demand for more sustainable aircrafts, lead aircraft manufacturers to build lighter products. This industry is subject to technological limitations due to the need to manufacture complex, cost effective, reliable and light products at high rates. Indeed, aircrafts are made of products designed by taking into account firstly feasibility then functionality. (Carpel & Julian, 2013) Designs that can be conceptualized on a computer are sometimes not feasible or financially viable with the traditional manufacturing processes.

In response to these technological challenges and limitations, companies have developed Design For "X" rules (DFX) (Herrmann et al., 2004).
Those rules are made to help designers in their choices, considering product life cycle. The "X" in DFX stands for any design considerations, such as Manufacturing (DFM) or Assembly (DFA). By respecting those rules, designers will be assured that the design produced will be suitable for manufacture (DFM rules) or for assembly (DFA rules).

To address these and related challenges, aviation companies are now considering additive manufacturing, also called "3D printing," as an alternative to existing manufacturing processes. General Electric is about printing 85000 fuel-nozzles for its new Leap jet engines. (Catts, 2013)
Additive Manufacturing (AM) is a manufacturing process, which was invented in 1984 by Chuck Hull. The official definition for additive manufacturing by the ASTM International Committee F42 on additive manufacturing is the "Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"(ASTM, n.d.).
This new way of building products could offer those companies new solutions and could result in faster production of better and cheaper aircraft, while decreasing risk.

By answering these two questions, we would like to help businesses within the aviation industry to understand what is additive manufacturing, what is a disruptive technology, and how this technology could likely impact the aviation industry.

Is additive manufacturing (also known as 3D printing) a disruptive technology for the aviation industry in Europe and Northern America?

How could additive manufacturing likely impact the aviation industry processes, in term of designing and manufacturing?

1.2 Research gap and purpose of the research

In the literature, several researchers agree on qualifying additive manufacturing as a disruptive technology (Campbell & Ivanova, 2013; Hopkinson, Hague, & Dickens, 2006; Jarboe, 2014; Sealy, 2012), but they do not extensively use the disruptive innovation theories to do so.
After explaining first what is a disruptive technology to the reader, our aim is to analyse if AM is truly disruptive as suggested in the literature, and to give an overview of likely impacts of the technology on the aviation industry, using the data collected during our research.

To give the reader a better understanding of the technology, a short description of the aviation industry will be included, we will also explain what is AM, what are the gains and the challenges of using AM in the aviation industry, and we will illustrate the paper with current applications.

This research has been realized within the Industrial Management department of KTH. It places itself in the subject of Industrial Management, by analysing how a technology would likely impact an industry.
After choosing the relevant research methods, this study gave us the opportunity to understand what is AM, how it is used currently within the aviation industry, why it is a disruptive technology for this industry, and how it would likely impact the industry.

2 Methods

2.1 Interpretivism

The research paradigm is interpretivism, in a context of high uncertainty, since the additive manufacturing technology is just starting to be used to produce non structural aircraft parts, in other words, parts that are not submitted to structural efforts, such as fuel-nozzles, seat buckles, air-conditioning parts etc.
Interpretivism is a paradigm developed as a critique of Positivism. For interpretivists, reality is subjective and socially constructed, and they inductively develop a theory while studying a phenomenon, as opposed as positivists who strive to test a theory (Mackenzie & Knipe, 2006). Interpretivists are more likely collecting qualitative data.
This paradigm fits this research work since the interviewer is implied in every step of the research.

2.2 Semi structured interviews

An interview can be defined as an "interpersonal situation, a conversation between two partners about a them of mutual interest" (Kvale, 1996) in which knowledge evolves through a dialogue. The quality of the interview led in the first place is decisive for the quality of the outcome data, it is therefore important to take time in preparing it.

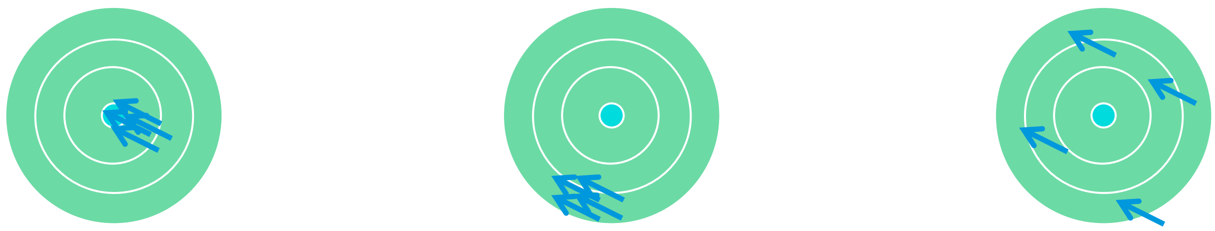
The research was built on 6 semi-structured interviews of managers and engineers working with additive manufacturing in the aviation industry in Europe and Northern America.
Another two interviews were held to collect data on traditional CNC machining (a phone interview and two written interviews).

Title	Type of contact
Dr. in the manufacturing and materials department at Cranfield University — working with Arc+Wire technology.	Phone interview: 28 minutes
Research Engineer on Additive Layer Manufacturing at Airbus Group Innovation France	Phone interview: 39 minutes
Research Engineer on Additive Layer Manufacturing at Airbus Group Innovation England	Phone interview: 37 minutes
Cabin Innovation Manager at Airbus	Phone interviews: 36 minutes + 20 minutes
Managing Director at Crucible Industrial Design	Phone interview: 36 minutes
Founder at PAR Manufacturing Technologies (CNC machining)	Mail interview
Director of Operations at Ardel Engineering (CNC machining)	Phone interview: 35 minutes
Centre of Additive Layer Manufacturing of Exeter University Co-ordinator	Phone interview: 38 minutes

This approach has been chosen to give rich and qualitative data, with high validity but low reliability. The advantage of using semi-structured interviews was to learn a lot on the technology, while collecting information
Semi-structured interview offers the interviewer the freedom to ask additional questions on a particular topic to get more detailed information about a particular topic or to explore new issues that are relevant to the study and arise during the conversation.

2.3 Reliability and Validity

Validity refers to “the degree to which a study accurately reflects or assesses the specific concept that the researcher is attempting to measure” (Colorado State University, 2010). This study has been built on interviews of experts working with additive manufacturing and traditional manufacturing. The validity of the study can be considered as high regarding the questions about the current additive manufacturing technology, but it will be considered as low when it comes to questions about the potential impacts of the technology on the aviation industry.



Valid & reliable — Reliable but not valid — Neither valid nor reliable

Reliability refers to “the extent to which an experiment, test, or any measuring procedure yields the same result on repeated trials” (Colorado State University, 2010). Therefore the reliability can be considered as low because the findings of this qualitative research are based on a few semi-structured interviews. The implication of the researcher in the study makes the reliability low as well, because of his background, knowledge and its interpretation of data he gathered.

2.4 Scope

2.4.1 Limitations

The main constraints of this study were the limited time frame to realize it, and the high uncertainty induced by the fact that this study will give a forecast of likely impacts of additive manufacturing on designing and manufacturing processes of Northern American and European aviation companies.

2.4.2 Delimitation

Because of the limitations and the complexity of the research, we decided to impose some delimitation to improve the quality of the thesis.

This study will focus only on Northern American and European aviation companies. In the same time, the forecast will only talk about potential impacts in manufacturing and designing processes in those companies.
This study analyse if additive manufacturing technology is a disruptive technology, and will analyse how it could likely impact the aviation industry, by using theories of Clayton Christensen from *The Innovator's Dilemma*.

3 Literature review

3.1 What is a disruptive technology?

In his book *The Innovator's Dilemma* (1997), Clayton Christensen distinguishes between sustaining and disruptive innovations. He highlights that a successful firm with the best practices in term of management could fail in introducing a new and disruptive technology in its business. Indeed, he noted that conventional managing approaches, which are really good to handle sustaining innovations, are not efficient when it comes to handle disruptive innovations.

Sustaining innovations are incremental improvements: they help companies to improve their products to stay in the run. These innovations do not create any new market but evolves in established markets, within the existing value networks, offering better value to the customer.
Christensen defines the concept of value network by "the context within which a firm identifies and responds to customers' needs, solves problems, procures input, reacts to competitors, and strives for profit" (Christensen, 1997).

Disruptive innovation is "a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors" (claytonchristensen.com, n.d.).
This term disruptive innovation came with the follow-up book *The Innovator's Solution* arguing that the previous term "disruptive technology" was not clear enough: it was not only the technology but also the business model around it.

As said in the methodology part, this paper will not address the business model and therefore will analyse additive manufacturing as a *disruptive technology* and not as a disruptive innovation.

For instance, the changes in disk drives can be considered as disruptive innovations, according to Christensen. Every new disk drive was cheaper, simpler and had lower performance level than its predecessor, and could be considered as a disruptive technology. Each new disk drive was offering lower profits than the previous one, was not satisfying mainstream market performance requirements and was rolled out in emerging markets before reaching the mainstream one.

These are the main components of Christensen's theory of disruption:

First, the pace of progress that markets demand or can absorb may differ from the progress offered by the technology currently sold to customers in these markets. Even if disruptive technologies are used initially in small markets, they eventually move up market and enter the mainstream market. This is explained by the fact that the pace of technological improvement in product performance is higher than the rate of improvement that mainstream customers want or can absorb. Products that overshoot the level of performance demanded create opportunities in the bottom of the market for simpler and cheaper products. When two products offer the performance demanded, the customer will find another criterion for choosing. These criteria are usually moving to reliability, convenience and price. These criteria often benefit firms offering disruptive technologies because their products are usually smaller, simpler, and cheaper.

At the same time, he points out that a product that does not address a need of a customer today may be able to do it tomorrow. He argues that listening to customers can be relevant and useful when it comes to sustaining innovation, but can mislead companies when it comes to disruptive innovation. Indeed, investing early in disruptive technologies can give companies a real advantage. If a company does not invest in a disruptive technology today because its current customers do not see the need for it, it may already be too late for the company when the market sees the need tomorrow.

Matching the disruptive technology with the right market is a challenge that companies should address. Contrary to disruptive innovations, sustaining innovations do not involve looking for any new market or customers: companies introduce their new and better products to their mainstream customers.
Most companies think facing a technological challenge when introducing a disruptive technology, because of its attributes (smaller, simpler, cheaper and lower level of performance). That is because they try to introduce the disruptive technology in their existing value network. As said earlier, Christensen defines the concept of value network by “the context within which a firm identifies and responds to customers' needs, solves problems, procures input, reacts to competitors, and strives for profit” (Christensen, 1997).

Here, Christensen notes a marketing challenge. He suggests that these companies should focus on finding new markets and customers with needs that match the performance levels of the new disruptive technology.

It is not possible to know well in advance how the disruptive innovation will evolve. Disruptive innovations are more likely to evolve in new markets, and it is impossible to collect data on a market that does not exist yet. For this reason, Christensen advises companies to set in place fast, flexible and inexpensive trials to learn quickly about the technology being introduced and the markets that could be targeted. Managers should be able to try, fail and learn quickly about the market in an iterative process. The product or service being introduced should therefore be flexible and cheap to redesign to be able to adapt it to the market being explored.

Resource allocation also has an impact on the introduction of disruptive innovation. Since these disruptive technologies are usually simpler, and cheaper, and compete in smaller markets, incumbent companies do not find these innovations profitable enough. This problem lies in the allocation of resources system of incumbent companies: companies’ executives make allocation decisions within the mainstream value network of the company to improve the growth and profitability of the company. When operating in smaller markets, the expected profits are not large enough to meet their criteria, and executives prefer to allocate resources on more profitable projects that generate money from current customers. For these reasons, it is hard for a manager to allocate resources in pursuit of a disruptive innovation, representing the dilemma of *The Innovator's Dilemma*.

Another component concerns the capabilities of companies created within their value networks. A company's capabilities reside in its resources, processes and values. Resources include people, equipment, technology, cash, information, brands, etc. Processes and values are less visible factors. Processes include not only include manufacturing processes, but also planning, budgeting, market research, or resource allocation. These processes are created to address a specific task and are not flexible. Values guide the company's thinking and actions. They are standards by which employees make prioritization decisions, in other words, the criteria upon which they decide whether an action is attractive or unattractive for the company.

Incumbent companies are dealing with different technologies in different markets. They have their own ways of doing business, gross margin requirements with particular sales volume etc. Because these capabilities created through time, companies can have problems when launching a disruptive innovation in another market because it does not meet the company's gross margin requirements. Launching this kind of innovation requires the company to be able to use different capabilities that they do not have, when it comes to processes and values to accompany disruptive innovation.

To summarize, Christensen writes that incumbent companies are excellent at introducing sustaining innovations that improve the performance of products used by their mainstream customers. This is because management practices are based on listening to customers and investing in technologies that customers say they want, seeking higher margins and targeting larger markets rather than small ones. When it comes to disruptive innovations, these management practices are not relevant.

Christensen offers a framework of four principles of disruptive technology to help in understanding why these management practices are not efficient at handling disruptive innovation:

1. Companies depend on customers for resources.

Companies should provide customers and investors with the products, services and profits that they require in order to survive. Successful companies are good at providing these things to their customers, but consequently it is really hard for them to invest in lower margin disruptive technologies, because their customers simply do not want these technologies yet.

2. Small markets don't solve the growth needs of large companies.

To maintain their target share price and create internal opportunities for their employees, incumbent companies need to grow. They should at least maintain their growth rates. But as they get bigger, the amount of new revenue needed to maintain this growth rate gets bigger as well, making small markets with lower revenues not as interesting for them. The problem is that those small markets will often become larger with time.

3. Markets that do not exist cannot be analysed.

Market research and good planning followed by executing according to the plan are pillars of good management. Dealing with disruptive innovations that may evolve in new markets, companies relying on these practices will be stuck: they need data on markets that do not exist yet.

4. Technology supply may not equal market demand.

Because the pace of technological performance improvement is higher that the rate of progress in performance demanded by the mainstream market, disruptive technologies will move from small markets to the mainstream market, according to the theory. The high pace of technological improvement is also responsible for overshooting the performance demanded by the mainstream market. Once a technology has overshot the performance demand of the mainstream market, it creates an opportunity for lower performing technology to be introduced: because the new technology gets better and better, it will finally reach the level of performance demanded by the market.

When two or more products are offering same performance, customers will use other criteria for choosing, such as convenience, reliability and price.

Because disruptive technology is usually simpler, smaller, and cheaper with a lower level of performance, these new criteria favour the disruptive technology (the level of performance is still lower than established products, but it includes "extra" performance that customers do not really need).

To conclude, Christensen describes disruptive technologies as:

- Simpler, cheaper and lower performing.
- Generally offering lower profit margins.
- Leading firms' most profitable customers generally cannot use and do not want them.
- First commercialized in emerging or insignificant markets.

3.2 History of additive manufacturing

1980's

1983

Birth of 3D Printing
Hull invents stereolithography process (Ponsford & Glass, 2014).

1986

Foundation of 3D Systems (3D Systems, 2013).
The company started to work on its first additive manufacturing tool, the SLA-1. The company had also to develop the .stl format to create compatible numerical data.

1989

Foundation of Stratatys by S. Scott Crump and Lisa H. Crump (Fundinguniverse, n.d.). Crump invented and patented Fused Deposition Modelling (FDM) and created the company.

1990's

1991

Introduction of non-stereolythographic systems (Wohlers & Gornet, 2011).
Stratatys introduced its new technology: fused deposit modelling (FDM).

The same year, Cubital developed its technology called solid ground curing (SGC).

Finally Helisys also developed laminated object manufacturing (LOM) in 1991.

1992

Selective laser sintering (SLS) was developed by DTM, a company which is now part of 3D Systems (Wohlers & Gornet, 2011).

1993

The Massachusetts Institute of Technology patented "Thee Dimensional Printing Techniques" (Cima, Haggerty, Sachs, & Williams, 1993)

1996

The Actua 2100 was developed by 3D Systems.

Z Corporation released it Z402 machine, based on the MIT patented technology (Wohlers & Gornet, 2011).

Stratatys released its Genisys. This machine, priced around $50,000 dollars was the first rapid prototyping machine costing less than $100,000 dollars and was developed with IBM (Fundinguniverse, n.d.)

1997

AeroMet was founded.
The company developed a process called laser additive manufacturing (LAM). This technology was using titanium powder and a high power laser. The company produced parts for the aviation industry as a service provider (Wohlers & Gornet, 2011).

3D Systems acquires EOS' rapid prototyping product line and business for $3.25 million dollars.

1999

Engineered organs bring new advances to medicine (T.Rowe Price, 2012).
The first lab-grown organ is implanted in humans when young patients undergo urinary bladder augmentation using a 3-D synthetic scaffold coated with their own cells.

2000's

2000

The world's first commercially available multicolours 3D printer was released. This machine called Z402C was developed by Z Corporation (Wohlers & Gornet, 2011).

2001

Optoform was acquired by 3D Systems. This company was using stereolithography method with other materials such as ceramics and metals (Wohlers & Gornet, 2011).

2002

A working 3D Printed kidney (T.Rowe Price, 2012).
Scientists engineer a miniature functional kidney that is able to filter blood and produce diluted urine in an animal. The development led to research at the Wake Forest Institute for Regenerative Medicine that aims to "print" organs and tissues using 3D printing technology.

2005

AeroMet ceased activity. Making titanium parts for the aviation industry was found not profitable (Wohlers & Gornet, 2011).
The open-source RepRap project was launched (T.Rowe Price, 2012).

2006

Objet, a 3D printing systems and materials provider, creates a machine capable of printing in multiple materials, including elastomers and polymers. The machine permits a single part to be made with a variety of densities and material properties. (T.Rowe Price, 2012)

2008

The first selft-replicating printer (T.Rowe Price, 2012).
The Darwin developed by the RepRap community was the first low cost and self-replicating 3D printer, allowing users who already have one to make more printers for their friends.
Shapeways launches a private beta for a new co-creation service and community allowing artists, architects and designers to make their 3D designs as physical objects inexpensively.

2009

MakerBot Industries, an open-source hardware company for 3D printers, starts selling kits that allow buyers to make their own 3D printers and products. (T.Rowe Price, 2012)

2010's

2011

First 3D Printed Unmanned Aircraft (Marks, 2011)

i.materialise becomes the first 3D printing service worldwide to offer 14K gold and sterling silver as materials. (T.Rowe Price, 2012)

2012

3D Systems acquires Z Corporation & Vidar Systems for $135,5 million dollars (3D Systems, 2012).

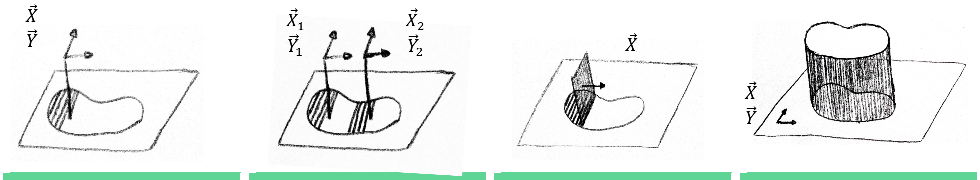
Objet Geometries merges with its rival Stratatys (Reich & Orpaz, 2012).

2013

Stratatys acquires MakerBot for $403 million (Yahoo, 2013).

3.3 The different processes of additive manufacturing

There are different ways to classify the different processes of Additive Manufacturing (AM), taking in consideration technological criteria (the machine can use different kind of technology, like a laser, or an inkjet head, etc.), or the type of raw material.
While these approaches can help to classify the AM processes, we decided to use the classification described by Pham & Gault (1998) to give a more comprehensive and clearer explanation of the different types of processes.



	1D Channel	2 x 1D Channels	Array of 1D Channels	2D Channel
Liquid Polymer	SLA (3D Systems)	Dual Beam SLA (3D Systems)	Objet	EnvisionTech MicroTEC
Discrete Particles	SLS (3D Systems) LST (EOS), LENS, Phenix, SDM	LST (EOS)	3D Printing	DPS
Molten Material	FDM, SolidScape		Thermojet	
Solid Sheets	Solido PLT (KIRA) LOM (Helisys)			

Figure 1: Classification by Pham (Gibson, Rosen, & Stucker, 2009)

The first dimension relates to the method used to construct the layers. The earlier technology used a single point source to create the object by "drawing" its successive layers. Then manufacturers introduced machines with several sources to increase the speed of the process. Finally, they introduced the 2D array technology using Digital Micro-mirrors Devices (DMD) and high resolution display technology, capable to expose a whole surface in a single time (Gibson et al., 2009).

Just using this criterion for the classification would result in an amalgam between the different technologies. Indeed, by introducing the raw material criterion, we are able to identify clearly all processes. In this classification, four raw materials are considered: liquid polymer, discrete particles, molten material and solid sheets.

3.3.1 Liquid polymer

Several manufacturers are using these materials to produce 3D printed objects. The first additive manufacturing system was Stereolithography, a process using liquid photopolymers. Most of the systems using liquid polymers are using liquid photopolymers, even though some machines are using different kind of liquid polymers.
In the case of 1D channel or 2 x 1D channels methods, manufacturers are using a laser to make the liquid polymer solidify.
Objet is using an array of 1D channel deposing droplets of liquid polymer, simplifying the process of curing the polymer with a floodlight (for liquid photopolymer).
By using Digital Micro-mirror Devices (DMD) or other high resolution display technology, some machines are able to expose an entire surface of liquid polymer is interesting because it reduces the number of moving parts in the machine, and increase the speed of the manufacturing process.
Photopolymer systems are interesting because their accuracy is generally very good, but photopolymer have currently poor material properties compare to other materials.

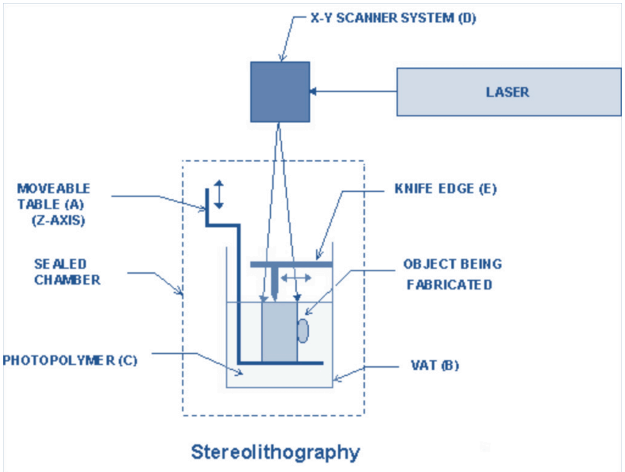


Figure 2: Stereolithography method – Courtesy of www.additive3d.com

3.3.2 Discrete particles

Discrete particles are usually powders made of uniform shape and size particles. The finer particles the better, but it should not be too small to avoid dispersion problems.
Using this type of material with a 1D channel or a 2 x 1D channels consist in a laser which brings thermal energy to melt the powder. The powder can be heat in the process chamber and the laser will only bring the small amount of energy to melt it (McWilliams, Hysinger, & Beaman, 1992). This has the advantage to avoid some "curling" effect on the layers formed, and also to reduce the power of the laser.
The "3D Printing" process developed at MIT use a powder bed and an array of nozzles deposing a binder or glue.
The advantage of using powders is that there is less need for supports to build objects, since objects are built layers by layers (the powder deposited can support the next layer of powder).

If the unused powder is recycled to build other parts, operators should be careful because its property can be modified with the number of time the material has been recycle.

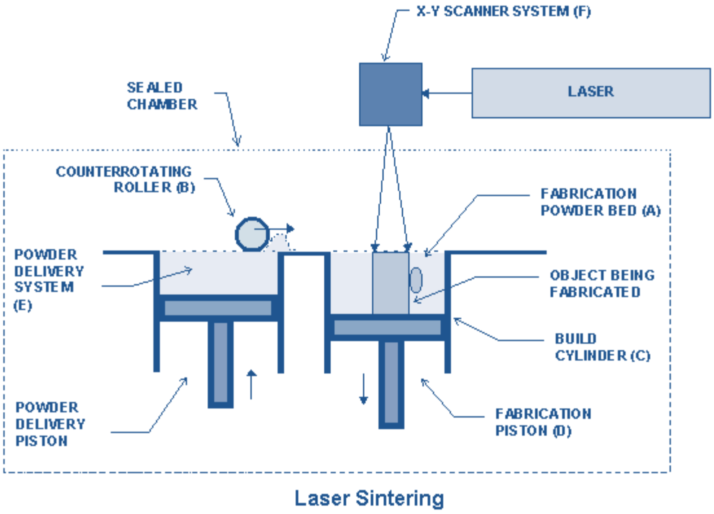


Figure 3: Selective Laser Sintering method
Courtesy of www.additive3d.com

3.3.3 Molten material

Fused Deposition Modeling (FDM) is a well-known method using molten material and deposes it layer by layer to create the object. Most of the desktop 3D printers (MakerBot, RepRap, Bucaneer) are using this principle. By bringing the material temperature to its melting point, the molten material flow through the delivery system. Two channels are usually used to build the object and the support to build it. Indeed, a drawback with this method is that the machine cannot build "in the air" and therefore need to build support to build on. Using two materials makes easier the part clean up and removal.
For instance, Solidscape uses for building support parts a material that has a lower melting point than the material used to build the final object. When the part is done, it will be heated at the melting point of the first material, which will melt and let the other printed part intact.

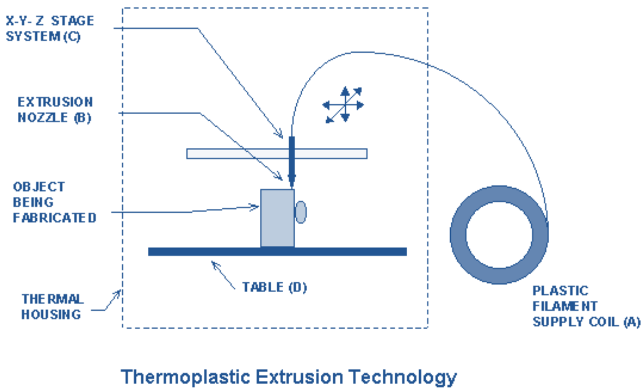


Figure 4: Fused Deposition Modelling method
Courtesy of www.additive3d.com

3.3.4 Solid Sheets

A good example of this method is the Laminated Object Manufacturing (LOM). Invented by the American Helisys, the machine uses a continuous roll of thin sheet, which is cut by a laser. Layers of the cut sheet are bonded together by using a heat-activated resin.
There is no need to build any support while building the part, but removing the waste material might be problematic. Therefore, the operator should know how the final part looks like, not to damage it.

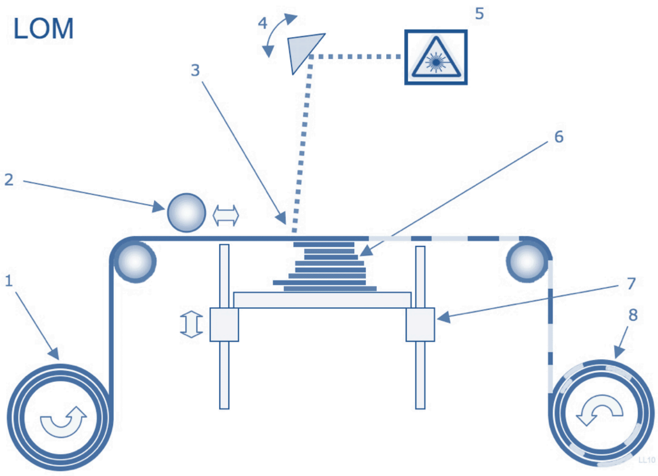


Figure 5: Laminated Object Manufacturing

3.4 The aviation industry

The aviation industry is characterized by a high level of technology. A little wrong variation in the chosen technology, can result in large financial losses for a company (ECORYS, 2009).

In the same time, “the high technological level of current aircraft configurations and its underlying technology imply that a slight improvement in the technology is obtained through great efforts” (ECORYS, 2009). Therefore, optimization is a major concern for aviation companies, since big efforts results in small innovations.

In this industry, it is common to look for the possibility in saving grams, resulting in lower direct operating costs.

It is also characterized by high up-front investments and long break-even times, increasing the risk (ECORYS, 2009). For example, the Airbus A380 program, which development costs are estimated at $15 billion (U.S.), was officially launched in 1994 and is striving to break-even in 2015 (Flottau, 2013).

The aircraft need from the airline companies is tightly linked to different drivers such as passenger demands. Therefore, aircraft manufacturers have to respond quickly to the market. “By the time the planes are ready, the airline companies are facing a low market and therefore withdraw their offers” (Tracy, 2004).

For airline companies, commercial attractiveness is driven by the performance of the aircraft, its life cycle cost and the time needed to manufacture and deliver it (Murman, Walton, & Rebentisch, 2000).

Nowadays, “The commercial aircraft segment is experiencing a virtually unprecedented and prolonged up-cycle” (Deloitte, 2013), resulting in an increased production pace within aircraft manufacturers such as Airbus and Boeing. This need for new aircrafts is induced by the growth of passenger demand from emerging countries, specifically in Asia and the Middle East. It can also be explained by the demand for new and more fuel-efficient aircrafts (Deloitte, 2013).

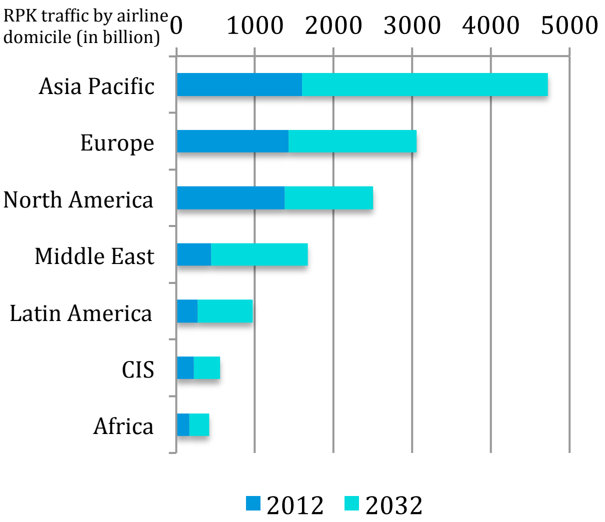
3.4.1 A growing industry

The aviation industry is a growth industry: “demand for air traffic, airline tickets, is doubling every 15 years” says John Leahy, COO Customers at Airbus.
In their forecasts, Airbus and Boeing agree to say that the number of passengers will more than double in twenty-year time (Airbus, 2013; Boeing, 2013).

The Revenue Passenger Kilometres (RPK) is a measure of the volume of passenger carried by an airline company. For example, an airplane that will carry a hundred passengers on a 300 kilometres will generate 300,000 RPMs.

If we take a look at this metric, the two manufacturers are planning a growth of RPM between 4.7% (Airbus, 2013) and 5.0% (Boeing, 2013) every year. In other words, the volume of passengers carried by airline companies is expected to be at least 2.5 times bigger.

This can be explained by the increase of market size in emerging countries. For examples, Asia-Pacific, which was the third biggest market after USA and Europe few years ago, is now the biggest market with 29% of the world total RPK, and is expected to grow even more.



	% of 2012 world RPK	20 year growth	% of 2032 world RPK
Asia Pacific	29%	5,50%	34%
Europe	26%	3,80%	22%
North America	25%	3,00%	18%
Middle East	8%	7,10%	12%
Latin America	5%	6,00%	7%
CIS	4%	5,80%	4%
Africa	3%	5,10%	3%

Figure 6: Evolution of the Revenue Passenger Kilometre between 2012 and 2032.
Source: Airbus Forecast

This increase in the RPK is one of the reasons why airlines will have to purchase more aircrafts.

3.4.2 An industry of high load factor

The load factor represents the percentage of occupied seats relatively to the number of seats available. For instance, an airplane with 100 seats will have a lot factor of 75% if 75 seats are occupied.

As the CEO of the International Air Transport Association (IATA) Tony Tyler says in their Annual Report (IATA, 2013) “profitability is being delivered as a result of efficiency gains and improvements to the industry’s structure. One illustration of this is that the average passenger load factor has increased by some eight-percentage points over the last decade.” An approximation of the evolution of the load factor between 2002 and 2012 can be found bellow.

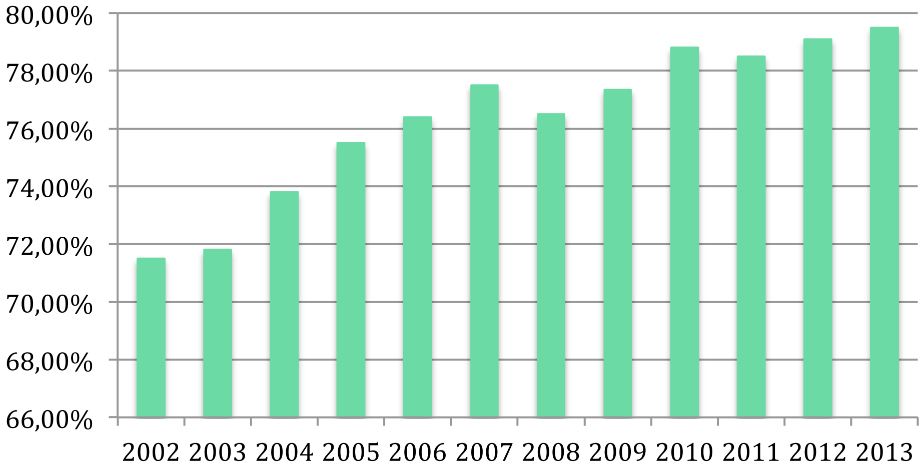


Figure 7: Approximation of the load factor between 2002 and 2013.
Source: Boeing / IATA Air passenger analysis

With the growth in the passenger demand, the problem of congestion in airport will have to be addressed. Airlines have already high load factors; they will therefore not be able to solve the problem by carrying more people in their aircrafts, almost full.
A solution to this problem would be to carry more people in one aircraft, leading manufacturers to build larger and lighter aircrafts that could carry more passengers.

This is another reason why airline companies will need to purchase more aircrafts that could carry more passengers.

3.4.3 The need for more fuel-efficient aircraft

Jet Fuel price is one of the largest components in an airline's cost structure: "fuel costs have surpassed labour as the largest segment of airline operating cost" (Boeing, 2013). Indeed, the price of a barrel of jet fuel has increased a lot the last decade: "fuel costs, approximately 13 percent of total costs in 2002, are closer to 34 percent today" (Boeing, 2013). This trend is illustrated on the figure 1 bellow.

Figure 8: Evolution of the price of a barrel of jet fuel between April 1990 and April 2014.
Source: EIA – data available at www.eia.gov

As we can see on the figure, even though the price is now relatively stable, it is around 6 times higher than 15 years ago, and it is estimated that fuel has doubled as a percentage of airline operating costs (Boeing, 2013).
Because this increase of jet fuel price results in lower profitability of their companies, airlines companies are trying to minimize these operating costs. "Airlines in both developed and developing regions continue to react to high fuel prices by cutting back usage of older, less fuel-efficient aircraft and buying newer, more efficient ones" (Hugel, 2013). Therefore, aircraft manufacturers are expected to build more fuel-efficient aircrafts to respond to their clients' demand. This is one of the reasons why Airbus launched its A320 Neo and Boeing launched its B737 MAX (those planes are "updated" with new and more fuel-efficient motorisation).

Environmental issues drive also aircraft manufacturers to work on more fuel-efficient solutions, to reduce carbon emissions. A working paper of the 38th ICAO assembly (International Civil Aviation Organisation) mentioned that in 2012, "aviation produced 689 million tonnes of CO2, or around 2% of the global total" (2013).
Players in the aviation industry decided to reduce their emissions by 50% by 2050. Following a structured plan of action will reduce theses emissions: fleet fuel-efficiency will have to be improved by 1.5% every year from now until 2020, and after a stabilisation to a neutral growth of carbon emissions, these emissions will be reduced to half of what they were in 2005.

For economical reasons, airlines are therefore willing to purchase more fuel-efficient aircrafts.

All of these reasons can explain the growth of the industry and the demand for new aircrafts. Indeed, in their report both Boeing and Airbus (2013) agree to say that the world aircraft fleet will be twice bigger in 2032 than it was in 2012.

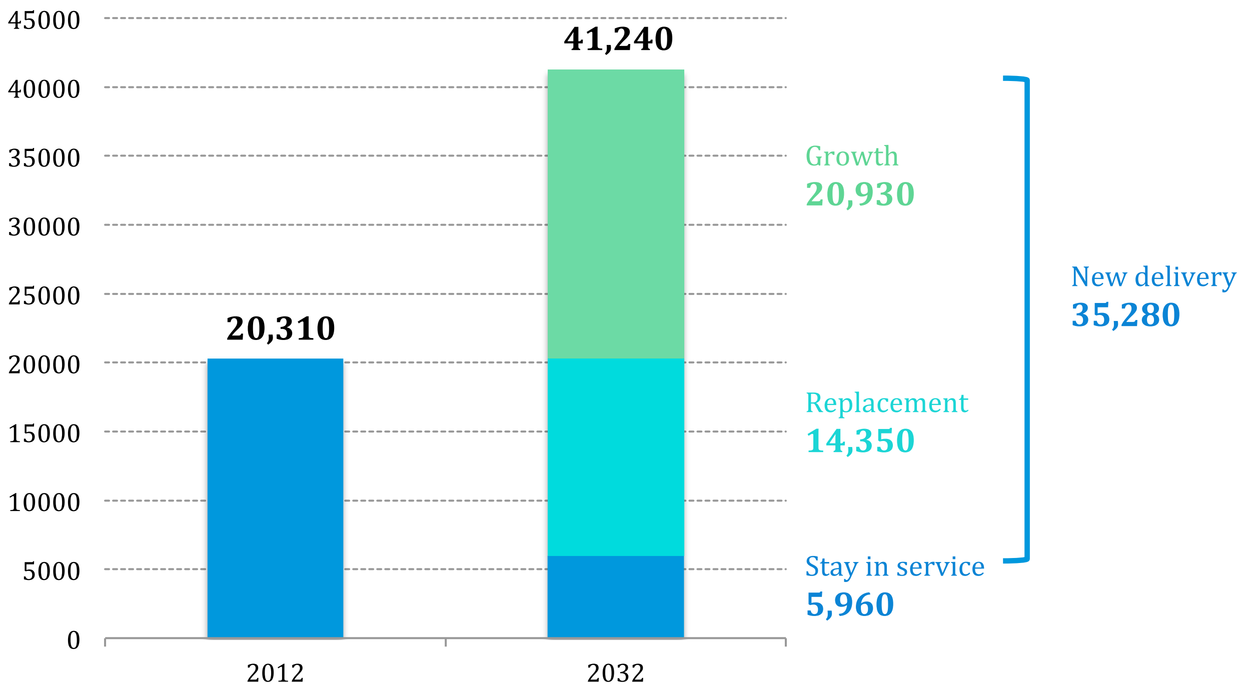


Figure 9: fleet development between 2012 and 2032.
Source: Boeing Forecast

The increase of revenue passenger kilometres driven by the growth of emerging countries, the optimization of airlines' operating costs resulting in high load factors and the rise of the price of oil can explain the demand of airline companies for new aircrafts.

We just took a look at some of the reasons why aircraft manufacturers received and will receive more orders from airline companies. For these reasons aircraft manufacturers have produce lighter, larger, and more fuel-efficient aircrafts, which make additive manufacturing interesting for the industry (c.f. advantages and challenges of using additive manufacturing in the aviation industry). Yet, the question of requirements and regulations proper to the aviation industry has to be addressed.

3.4.4 Aviation requirements & jurisdiction

The aviation industry is subject to significant regulation for safety concerns. The American Federal Aviation Administration (FAA), the ICAO and the European Aviation Safety Agency (EASA), as well as each national organisations, are working on specifying this regulation to make flight operations as safe as possible. Therefore, any new process, material or parts being introduced in the market should be certified by these different organisations.
These certifications cost for aircraft manufacturers time and money, but are necessary to be able to operate safely. Certifications can take several years and aircraft manufacturers have to show regulation organisations that what is being introduced meets regulation requirements.

3.4.5 The growing use of composites

In 1970, after a 15-year assessment, the MacDonnell's DC10 was introduced with a composite rudder that was 33% lighter. In 1984, the Boeing 737 was introduced as the first commercial airplane with a horizontal stabiliser made of composites. A year after, Airbus introduced its A310 with a fin box made of composite. By then, aircraft manufacturers took a step-by-step approach in the adoption of composites on their different aircrafts, as show on the figure below.

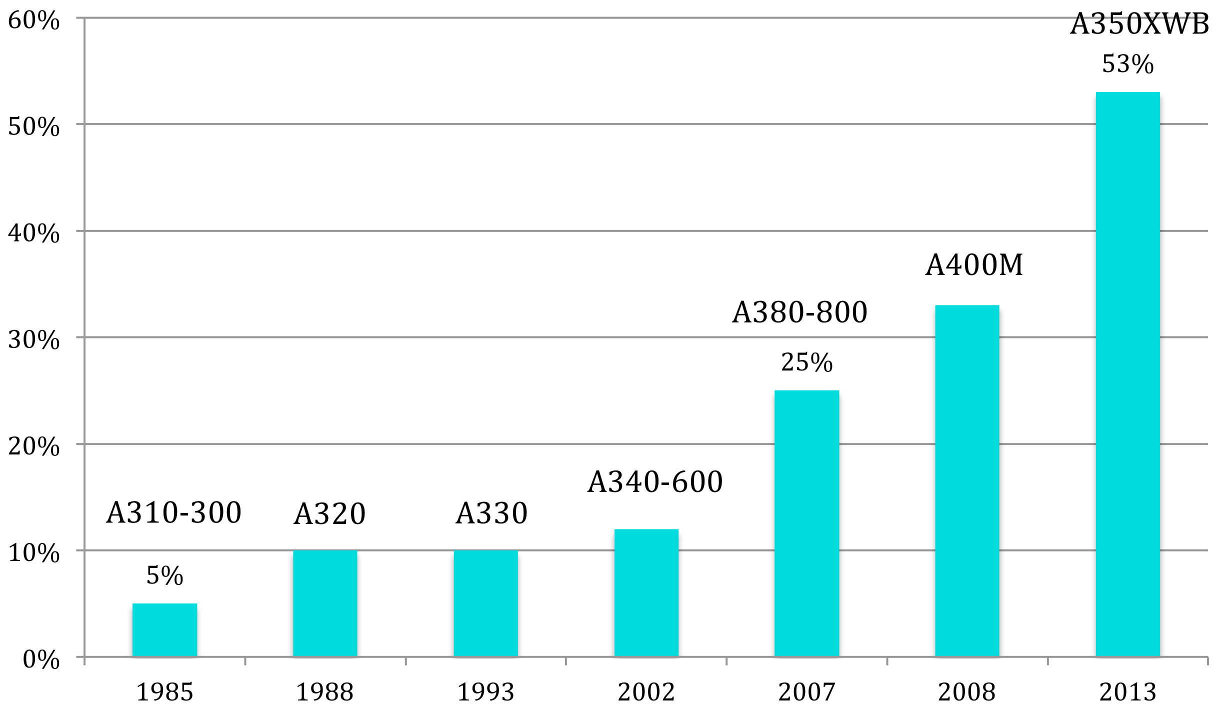


Figure 10: Composites weight compared to overall weight
Source: airbus (Hellard, 2008)

Composites have the advantage to reduce the production lead-time; they reduce the production cost, they are lighter and they offer better mechanical performances. The maintenance costs are also reduced when using composites (Hellard, 2008).
Nevertheless, they also have drawbacks. A post treatment is needed to avoid problems if the aircraft was strike by lightning, since composites do not conduce electricity. These material do not conduce heat neither, which can be problematic for defrosting concerns. Finally, titanium is also needed when composites are used on an aircraft. One of the reasons is because aluminium is exposed to corrosion in contact with composites.

For these reasons, aircraft manufacturers adopted composites progressively, and are now making aircraft such as the A350XWB, made of 53% of composites.

3.5 Gains and challenges of using AM in the aviation industry

Traditional manufacturing is subtractive: starting with a block of raw material, we remove material to shape the part we want to get. With additive manufacturing, the process is reversed, we add raw material where it is needed. This has several advantages, yet the technology has still some challenges to address.

3.5.1 Gains of using additive manufacturing in the aviation industry

The first reason why the technology is very interesting for the aviation industry lies in the "additive" nature of the manufacturing process. The "buy-to-fly" ratio is the ratio between the amount of raw material needed to produce a part and the amount of material of the part itself. For example, if a manufacturer buys 100 kilograms of Titanium, to produce a part of 5 kilograms, the buy-to-fly ratio will be of 20.

The buy-to-fly ratio is high in the aviation industry: a lot of raw material is machined away resulting in a waste of valuable material. "In many cases, 80% or more of the material is machined away to provide a stiff, lightweight frame for aerospace structures" (Gibson et al., 2009). During our meeting, the expert with additive manufacturing at Cranfield University compared buy-to-fly ratios

Reducing the buy-to-fly ratio results in lowering the cost of raw material needed to produce a part. It can represent a tremendous amount of money, when we consider the precious materials used in to build aircraft parts, such as titanium.
However, the question of scale has to be considered: additive manufacturing is a slow process when it comes to the production of the part itself, it is therefore more financially interesting on small volume production.

Case of Rolls Royce

Rolls Royce is considering additive manufacturing to produce some parts of its aircraft engines (Trotman, 2013). Indeed, additive manufacturing offers a faster and cheaper production. For Neil Mantle, working at the Additive Layer Manufacturing Centre of Competence, "AM gives a great opportunity here because conventional methods of manufacture can take 40, 50 or even 60 weeks, while a component using AM will take one month" (Royal Academy of Engineering, 2013). When considering the buy-to-fly ratio, he says that sometimes, "we machine away 90% of the materials to create the final component, but with AM that figure is much reduced".

Method	Lead-time
Traditional	40 weeks
AM	4 weeks
Savings	36 weeks (90%)

A second reason would be the versatility of the machine. Since it offers a direct production of the part needed, additive manufacturing reduces the need for tooling thus the tooling costs and the lead-time to produce a part. However, this advantage remains true only in the production of parts that have high tooling costs and long production lead-time.

This versatility is offering the opportunity to produce different parts without having to produce any tools (e.g. moulds) and therefore the possibility to update the design of a part with no additional production time and costs.

As a third reason, additive manufacturing gives the chance to produce more complex geometries: “AM has the potential to enable novel product designs that could not be fabricated using conventional subtractive processes” (Harris, 2011).

This advantage results in designs that are usually lighter, more functional, and in one block, such as General Electric’s fuel nozzle presented in the next chapter. Nevertheless, we should keep in mind that this technology is not offering limitless freedom of design, new rules has to be followed (Ayre & Sarah Fielding, 2012).

Comparison between brackets made with conventional manufacturing methods (in the back) and with additive manufacturing (in the front).
Courtesy of the MIT Technology Review

In the same time, the cost of additive manufacturing is not linked to the complexity of the part to manufacture, but to the time and the volume of raw material needed to produce it. In other words, a part with fewer raw materials and a design optimised for the manufacturing process will be cheaper to produce.

While the complexity of the part will increase, its cost will not dramatically increase such as other conventional manufacturing processes. This will give the opportunity to offer extra complexity at no additional cost illustrated on figure bellow (RolandBerger, 2013).

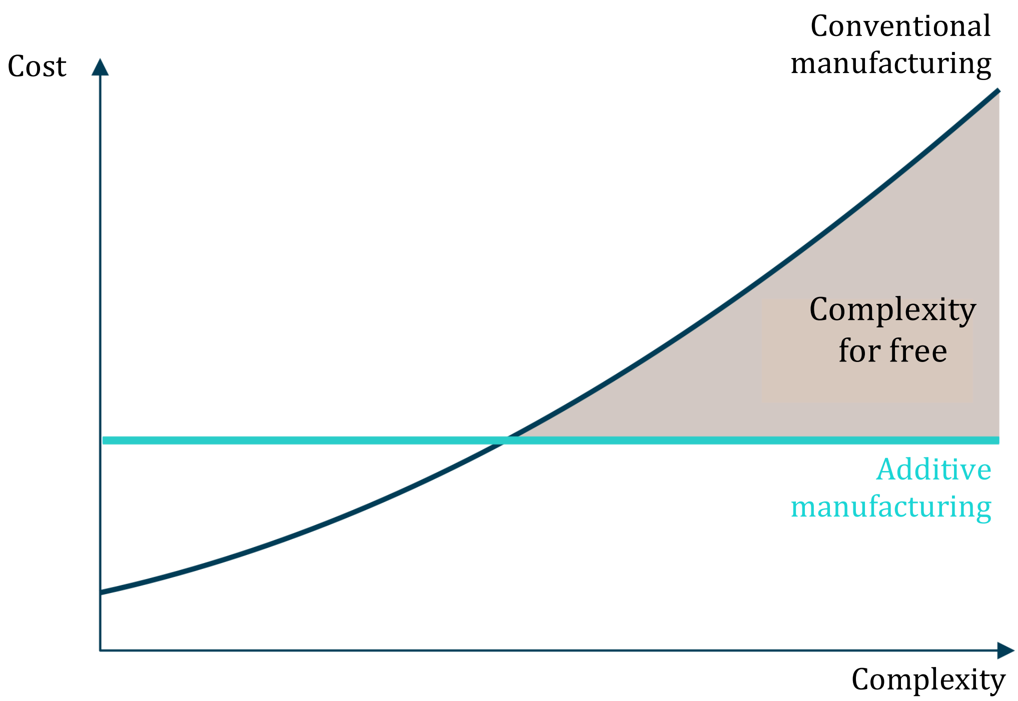


Figure 11: cost of conventional manufacturing vs. additive manufacturing
Courtesy of rolandberger.com

The cost driver of additive manufacturing is quite interesting as well. It is linked to the amount of time and of raw material needed to produce it. Reducing the amount of raw material to depose would reduce the time needed to produce the part, if the design is optimised for additive manufacturing (c.f. new design rules paragraph in the challenges part). It would therefore reduce the mass of the part and the energy needed to produce it. In other words, a part would be cheaper to produce if it is lighter and faster to produce, which is very interesting for the aviation industry.

Another advantage that offers additive manufacturing is the possibility to use material such as titanium. Titanium has really good properties for aviation applications, and its corrosion resistance makes it very interesting with the use of carbon fibres (Henriques, 2009). Indeed, aeronautical aluminium would corrode with the contact of composite parts, degrading mechanical properties of the material.
Titanium has a high-embedded energy, there is a lot of energy required to produce a part in titanium and it is a material hard to machine. During our conversation, the expert working with additive manufacturing at Cranfield University highlighted that using AM, we could reduce "the amount of titanium that is required resulting in significant energy reductions as well".

Finally, additive manufacturing could be considered as a more sustainable manufacturing process for aviation applications.
A study made by EOS and Airbus has highlighted the potential sustainability benefits of using Direct Laser Metal Sintering technology in the redesign of Airbus A320 nacelle hinge brackets: "CO2 emissions of the door hinges were reduced by almost 40 % over the whole lifecycle by optimising the design" (EOS, 2013). The Managing Director of Crucible Industrial Design highlighted during our interview that "you could reduce energy consumption through the use of the part, not through its manufacture". Indeed, he added: "any additively manufactured part at the moment is always going to be very expensive to make in terms of energy".

3.5.2 Challenges AM has to address when used in the aviation industry

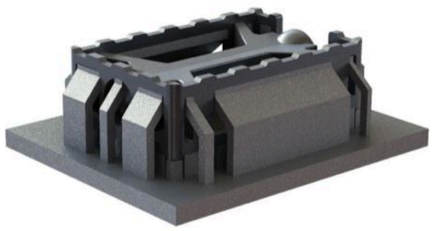
Even if this technology offers great opportunities for the aviation industry, it still has some challenges to address. The recent enthusiasm for this technology should not lead to think that designers will now be free of producing any shape with a limitless freedom in their designs. This technology is certainly promising, it is true to a certain point that this technology enables the user the produce any shape, but every production process has its own limits, and designers should know it before starting to design a part.

As explained earlier in the introduction, companies have developed Design For "X" rules (DFX) (Herrmann et al., 2004) to face technological challenges and limitations of traditional manufacturing processes.
Those rules are made to help designers in their choices, considering product life cycle. The "X" in DFX stands for any design considerations, such as Manufacturing (DFM) or Assembly (DFA).

A first challenge that additive manufacturing technology would have to face lies in the new designing rules of the part being additively manufactured. These rules are of a different kind than the traditional DFX rules, since the limitations of the AM process are different from traditional manufacturing.

These rules exists to minimize costs, waste and the building time, as well as to ensure that the part will be possible to additively manufacture.
When working with Direct Metal Laser Sintering, the first and most important rule is to reduce the number of downward facing surfaces (Crucibleid, 2012a). Indeed, these surfaces will require a support to be built on: the weight of the molten metal being deposited cannot support itself.
These supports will have to be removed after the process, which leads to additional costs and lead-time.
To minimize the number of supports, designers can reduce the number of downward surfaces by adapting their design and replacing these one by curved and angled surfaces. The orientation of the part to be manufactured in the machine has also to be considered.
A good illustration of this rule can be found on a paper made by Crucible Industrial Design, a product design company based in England.

By taking the example of a bicycle pedal, it is explained how we can manage to minimize the amount of supports and therefore take full advantage of the process.



In the first place, the pedal is set on the building support horizontally.

The team decided then to orient the part in a more optimized direction to be manufactured.

But to take full advantage of the additive manufacturing process, they re-designed the pedal to eliminate the need of support.

Courtesy of www.crucibleid.com

A study conduct at Loughborough University by Baumers et Al. (2011) illustrates how the capacity utilisation of an additive manufacturing machine can affect the energy consumption per kg deposited. Capacity utilisation can be defined by the ratio between the actual size of the building platform in the machine, and the space that will be utilized during the manufacturing process.

Since machines have warm-up and cool-down cycles, it is shown that the capacity utilisation of the machine has an impact on the energy consumption of the machine, and therefore on the costs. It has also an impact on production lead-time, because it is faster to produce parts in "parallel", due again to the different cycles that the machine has to go through.

The first challenge that this technology lies in these different rules: before starting to design, designers should understand how the process works, to take full advantage of it, by adapting their designs and building configurations.

From a technical point of view, additive manufacturing should address different challenges. The building chamber volume will limit the size of the part being produced. According to the Research Engineer working on AM at Airbus Group Innovation UK, "with the powder bed processes, it is difficult to scale this processes up". Some technology such as the Wire+Arc developed by Cranfield University (Park, 2014) propose solution to this challenge, by using a robotic arm that deposit a titanium wire being fused by an electric arc (a process similar to arc welding).

Arc+Wire technology
Courtesy of Cranfield University

We should also remind that this process is not "faster" than conventional processes when it comes to the production of the part it self. If it is said that additive manufacturing is quicker to produce a part, we take into account the entire production lead-time of the part, a part that could be complex to produce. Nevertheless, the strength of traditional manufacturing tools lies in its capacity to build high volume at a high production pace, which makes traditional manufacturing more interesting for mass production.

Ensuring quality of the part being additively manufactured is one of the main challenges the technology has to face. If the part present some defects, it can have an impact on its fatigue performance (its tolerance to endure a high amount of repeated cycles) and therefore its lifespan. One cause of those defects can be porosity, usually caused by contamination. A way to avoid this contamination is to use inert gas, such as Argon, to prevent the powder deposited from oxidation.
The different processes have different ways to create a "protection atmosphere" around the part being manufactured. A first way to do so is to work in a close atmosphere full of argon (building in a chamber, or under a tent). Some other processes use argon gas jets around the material being deposited to protect it. Residual stress inside the part due to a melt phase can also be a problem.

One of the great challenges lies also in the powder used to produce additively manufactured parts. The quality of the powder will directly impact the part being printed; therefore this powder should meet some specifications explained the Research Engineer at Airbus Group Innovation France, specifications such as chemical composition, size of the grains and sphericity (is the grain spherical or not?). She also mentioned that powder suppliers were not all ready yet to meet these specifications.

It is also said that each process will not be optimized if it is not working with the powder it should work with. The limited amount of certified powders to be used to additively manufacture aircraft parts can be considered as a challenge for the technology.

The technology should have high deposition rate, while keeping the buy-to-fly ratio low. The deposition rate can be defined as the amount of metal being deposited per hour. “In short, the clear buy to fly ratio advantages of metals AM, reducing from 20:1 or 12:1 to even 2:1 can still be insufficient, if the deposition rate of the manufacturing technology is not high enough, and cost components of finishing technologies is high, affecting the overall cost” (Harris, 2011). According to the expert working with additive manufacturing at Cranfield University, it has been found that higher deposition rates resulted in lower accuracy and therefore higher buy-to-fly ratio.

Finally, for the Centre of Additive Layer Manufacturing Co-ordinator, “in the aviation industry, one of the big challenge is actually a psychological challenge. Trying to get people —that perhaps have been trained to think very safe — to think differently and to accept something new and quite radical is difficult".

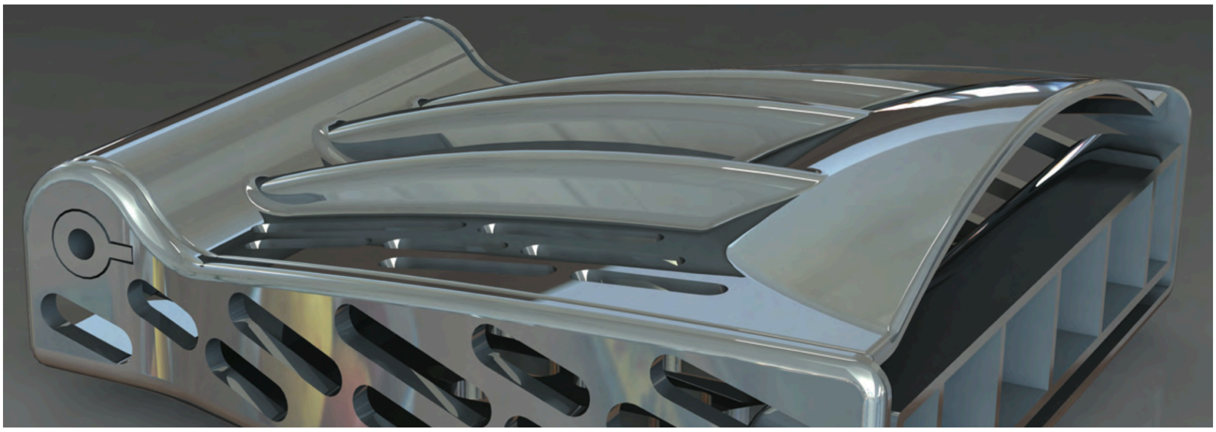
3.6 How the technology is currently being used in the aviation industry?

We just explained why aircrafts manufacturers were considering additive manufacturing as a tool to produce parts in their aircrafts. To illustrate theses reasons, we decided to give some examples of current applications of additive manufacturing in the aviation industry.

These examples are cases from diverse businesses working with additive manufacturing in the aviation industry.

3.6.1 Building lighter parts: the example of an Airline Buckle redesigned by Crucible Industrial Design

This project was part of the SAVING project (Sustainable product development via design optimization and AdditiVe manufacturING). SAVING has for objective to “look at ways to reduce energy consumptions through the use of additive manufacturing” said the Managing Director of Crucible Industrial Design. “We looked at something that would be inside the cabin of the aircraft, so that people could relate to it, as a product, and understand what we were talking about, maybe slightly better. We just came across this idea of looking at the seat buckle, because obviously you’ve got hundreds on the plane, and so if by using AM we could reduce the weight of that product by even a small amount, then over the life of the aircraft, the potential energy saving would be considerable”.

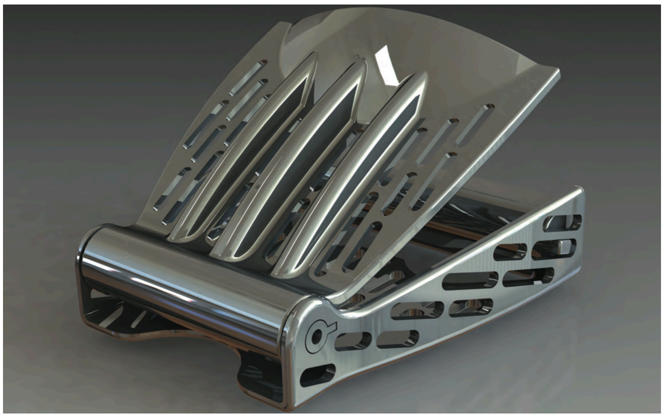


Courtesy of crucibleid.com

The airline buckle project started with a goal of designing an airline buckle that was at least as functional as a conventional one, considering an optimal design for its production using Selective Laser Melting and ensuring that the produced part weighted considerably less than a conventional one.

After passing the Finite Element Analysis, which is an analysis to ensure that the part will be resilient to the efforts it will have to face, the team worked on optimizing the design to suit to the SLM process.
Indeed, with the Selective Laser Melting process, there is a need to build additional supports, because the weight of the metal being deposited cannot support itself. These supports take more energy and time to build; they should be therefore as few as possible.
As we have explained in the chapter on new design rules, the goal is to reduce the number of downward horizontal surfaces.

The final part was weighting 70 grams, when a conventional buckle is weighting around 155 grams. The new buckle was 45% lighter, and an "Airbus A380 configured for all economy seating has 853 seat buckles, which would result in a possible weight saving of 72.5 kg" (Crucibleid, 2012b).
According to a study from Helms & Lambrecht (2006), a reduction of 100kg on an aircraft would save 20,000GJ of energy on its lifecycle.



Courtesy of crucibleid.com

In other words by saving 72.5kg on an airplane, we would save 45,000 litres of jet fuel over its life. This represent \$3.36 million, when the implementation of the buckle would be only \$277,000 (\$1=£0.6) (Crucibleid, 2012b).

3.6.2 A composite part manufacturer reduces its tooling cost and lead-time with Fused Deposition Modeling

Advanced Composite Structures (ACS) repairs composite structures for the aviation industry. To repair composite parts, the company used a mould, tailored for the part to be repaired, to be able to apply the composite material where it is needed.

This mould was previously made using traditional technics, its production lasted usually between 8 and 10 weeks, and the mould total cost was around $2,000.

Courtesy of Stratasys.com

With the use of Fused Deposition Modeling, ACS was able to reduce the mould production cost by 79% while reducing the production lead-time by 96%.

Bruce Anning, owner of Advanced Composite Structures said "FDM tooling can be produced in a single day compared to several weeks for CNC tooling. For the repairs and short-volume production work that we specialize in, tooling often constitutes a major portion of the overall cost. Moving from traditional methods to producing composite tooling with FDM has helped us substantially improve our competitive position" (Stratatys, 2013a).

Method	Cost	Lead-time
Computer Numerical Control (CNC) Machining	$2,000	45 days
Fused Deposition Modeling	$412	2 days
Savings	$1,588 (79%)	43 days (96%)

3.6.3 Fused Deposition Modeling reduces tooling cost and lead-time to produce an Unmanned Aerial Vehicle

Leptron is a company producing remotely controlled helicopters for different markets such as law enforcement, military and civilian uses. The company has developed a quadrotor helicopter called RDASS4 equipped with camera and sensors for low and high altitude surveillance.

Courtesy of leptron.com

The quadcopter's body is made by layer assembled to fit together as Russian dolls. It gives to the quadcopter the ability to change the composition of the layers to adapt to different missions. The challenge for Leptron was to produce 8 different complex layers in a short period of time that would fit to the application.

The traditional approach to realize such parts would have been to use injection moulding (injecting material in a mould to build a the part), which would have cost approximately $250,000. A problem with this approach is the irreversibility of the geometry of the part produced: if the geometry needs to be changed, the company would have to produce another mould, which leads to more expenses and time delays.

The team chose to use Fused Deposition Modeling for its flexibility and its affordability. By using this technology, the company reduced cost by 59% while reducing lead-time by 43%, and they could have a more flexible approach in the way they designed the UAV: "Every single part has changed a minimum of four times. FDM gave us the flexibility to make these changes without incurring a significant time or cost penalty" said John Oakley, CEO at Leptron (Stratatys, 2013b).

Method	Cost	Lead-time
Computer Numerical Control (CNC) Machining	$250,000	14 months
Fused Deposition Modeling	$103,000	8 months
Savings	$147,000 (59%)	6 months (43%)

3.6.4 Direct Metal Laser Sintering, a sustainable technology for the aviation industry

As we said earlier, aircraft manufacturers are expected to reduce the carbon emissions of the airplanes they produce. Airbus Group Innovation (previously called EADS Innovation Works) worked with EOS, an AM machine manufacturer, to gain a better understanding of the aviation requirements, and to assess EOS technology's performance in terms of quality and sustainability.

For this study, the two companies considered energy and raw material efficiency, as well as recycling and CO_2 emissions. When considering the energy consumption, the companies considered not only the production phase, but also the sourcing and transportation of raw material.

Courtesy of eos.com

We have to keep in mind that Direct Metal Laser Sintering is an expensive manufacturing process in term of energy consumption, but "the technology turned out to be a good fit for the design optimization of the nacelle hinge brackets as for this application the operational phase is typically 100 times more important than the static phases (e.g. manufacturing of the part)" (EOS, 2013). Indeed, the additive manufactured part cost more energy to produce, but is less energy consuming over the life of the airplane.

The study consisted also in comparing two optimized brackets, produced by DMLS and by rapid investment casting (another type of manufacturing process, requiring the production of a mould in which we pour fused metal). The joint study conclusion was that EOS' technology was slightly less energy consuming, but the main advantage of the technology was the reduction in raw material consumption. In fact, the technology can save up to 75% of raw material compared to other traditional processes (EOS, 2013).

Courtesy of airbus.com

This study was realized on the comparison of only two parts, while considering its findings we should therefore keep in mind that the question of scalability is yet to be addressed. Nevertheless, the use of this optimized design allowed Airbus to manufacture a part weight, to save around 10 kg per aircraft. As a result, emission of CO_2 were reduced by 40% over the lifecycle of the part, despite the fact the DMLS uses significantly more energy.

3.6.5 General Electric Aviation produces more fuel-efficient engines using additive manufacturing

General Electric claims on its website that additive manufacturing could save up to 450 kilograms per engine (General Electrics, n.d.-b). This is a tremendous saving when we consider that the current CFM56 has a mass of almost 2000 kilograms.

General Electric is clearly interested in the additive manufacturing technology: the group, through the CFM joint venture (GE-Snecma) has already planned to print 85,000 fuel nozzles for the CFM LEAP engines.
Fuel nozzles have complex geometries, and used to be an assembly of 18 different parts, but with the use of additive manufacturing, General Electric and Snecma (Safran Group) manage to produce it in one lighter and more durable part.

Courtesy of www.gereports.com

This process has also offer the chance to include a new internal cooling system, reducing degradation of the nozzle due to the exposure of the fuel to high temperatures. These new design features will result in durability five times higher, it will be made of one solid block (instead of an assembly of 18 different parts) and will be 25% lighter (General Electrics, n.d.-a). GE planned to print 19 nozzles for each of the CFM LEAP engines, starting around 2016 to print around 35,000 nozzles annually (Wohler & Caffrey, 2014).

According to Wohlers Associates, an independent firm providing technical and strategic consulting on additive manufacturing, this fuel nozzle is one of the top 3D printing developments of 2013 (Wohler & Caffrey, 2014).

4 Additive manufacturing, a disruptive technology?

We explained earlier what was a disruptive technology. We will now analyse whether additive manufacturing can be considered as a disruptive technology.

In this chapter, we will identify characteristics of additive manufacturing that fulfil characteristics of disruptive technologies explained in the part on disruptive technology.

According to Christensen, as stated earlier, disruptive innovation describes "a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors".

To clearly analyse whether this technology could constitute a disruptive technology, we should identify the competing processes to additive manufacturing. Nowadays, most of aircraft parts are being manufactured with traditional Computer Numerical Control (CNC) machines (machines that are being controlled by a computer, such as automated mills, drills, and also additive manufacturing processes).

Here we analyse whether AM meets Christensen's criteria of being simpler, cheaper and lower performing. We look at each in turn below:

4.1 Simpler, Cheaper and Lower Performing

4.1.1 Simpler

Do additive manufacturing tools have a simpler architecture than traditional manufacturing tools? We can certainly observe that additive manufacturing can simplify the production chain of aircraft part manufacturers. We define "production chain" by the steps conducted on raw material to produce a final product sold to a customer.

This technology is offering the opportunity for manufacturers to simplify their production chain. The flexibility and reconfigurability of these machines offer the chance to use the same machine to manufacture different components simultaneously and sequentially. To get the right mechanical properties, parts being traditionally manufactured usually need heat treatment. With some additive manufacturing technique such as the Electron Beam Melting, this heat treatment is not necessary, because the part is being additively manufactured at an elevated temperature, between 700°C and 1,000°C (Faning, 2013).

Even if the machine itself could not be considered simple, it enables the user to produce more complex parts in a simpler way. These machines give users a simpler process when working with complexity. If we look at parts being additively manufactured, we can also observe that these parts can replace complex assemblies with the use of AM: a good example is GE's fuel nozzle. This component required the assembly of 18 different parts, and with the use of additive manufacturing, GE managed to manufacture a one-part fuel nozzle, thus simpler.

Finally, additive manufacturing gives new design rules for manufacturing and assembly. The novelty of these rules can be harder to handle for designers, who have been working with traditional DFM/A rules for a long time, but the tool itself gives simpler solutions to designers when they need to manufacture one part that has to fulfil specifications. These new rules are less constraining and allow designers for more freedom in their designs.

4.1.2 Cheaper

Only comparing prices of different machines provide an incomplete picture. When assessing costs, we should take into several aspects of the aviation industry. Additive manufacturing machines are very expensive and can cost up to $500,000. But these machines can offer in some cases reduction in long-term manufacturing costs. As we saw previously, the technology can reduce the costs of manufacturing low-volume parts. Without the need for production tooling, companies do not need to produce a certain amount of parts to reach the break-even point. Therefore, the technology is cheaper when it comes to low-volume production.

The price of raw material should also be considered. By using additive manufacturing, aircraft manufacturers can in some cases largely reduce the "buy-to-fly ratio" mentioned previously, and therefore reduce the amount of raw material wasted. Titanium is a very expensive material and this ratio is consequently very important for part producers. It is also very hard to shape, and has a high-embedded energy (in other words, shaping titanium requires a lot of energy). From an energetic point of view, the process of depositing fewer material results in energy savings, and therefore, in cost savings.

4.1.3 Lower Performing

Historically, additive manufacturing was born from rapid prototyping technologies in the 1980s. It was first capable of producing models for research offices to validate designs using a solidifying photopolymer (a liquid polymer that solidifies when exposed to ultraviolet). At that time, mechanical properties of these models being additively manufactured were not good enough to be introduced as end-use parts.

With the development of the technology, additive manufacturing tools could reach better performance and are now taken into consideration by the aviation industry to manufacture non-structural parts (parts that do not have to support any effort). Further researches and certifications on the additive manufacturing processes are still needed to see a technology capable of manufacturing structural parts.

The AM powder market also has to develop: these machines require powder with a certain degree of quality, but only some suppliers are ready to produce such powders. In the same time, there are fewer alloys available for additive manufacturing than for traditional manufacturing.

Finally, when it comes to high-volume production, traditional manufacturing is still more compelling in part because the additive manufacturing technology is not fast enough and has a high-energy consumption.

4.2 Disruptive innovations generally promise lower margins

From this research, I am not able to quantify with accuracy margins made with traditional CNC tooling versus additive manufacturing machines.

Nevertheless, because of their flexibility, re-configurability and capability to produce different parts in the same time or sequentially, we can imagine that a part additively manufactured would have a lower unit contribution margin as the additive manufacturing tool could be used more often and longer (e.g. when comparing to the use of a mould). In the same time, we can imagine that the elimination of tooling induced by the use of additive manufacturing could also lead in some case to lower margins, due to lower costs.

These are only high-level observations and I would need to go further in the research to be able to clearly attest of these hypotheses.

4.3 Leading firms' most profitable customers generally can't use and don't want them

Some parts manufactured with traditional CNC machines cannot be produced with additive manufacturing tools. This can be due to several reasons. First the mechanical properties of the final part might not meet the performances needed. At the same time, every process has to be certified by aviation regulation organisations before being introduced to aircraft part manufacturers. As said earlier, these certifications take time. The AM technology, as well as the powders and the parts being additively manufactured, still need some certifications.

The aviation industry is characterised by high safety standards, therefore some industry actors can be reluctant to change, because it always presents a risk. Educating manufacturers with the technology seems also to be important. Indeed, the technology offers a new set of opportunities and solutions, but users and designers should be aware of its strengths and weaknesses before starting to produce parts.
For these reasons, not all aircraft part manufacturers are willing to use additive manufacturing tools.

4.4 Disruptive innovations are first commercialized in emerging or insignificant markets

AM technology was first commercialized as a rapid prototyping tool. The machine was useful to rapidly validate first designs of a part. These models were first made with liquid photopolymer and their use was restricted to models. With successive technological improvements, additive manufacturing tools could be used as rapid tooling machines. Rapid tooling is the process of using rapid prototyping machines to produce manufacturing tools. For example, rapid tooling could be the rapid production of a mould with rapid prototyping techniques. The rapid tooling technics have the advantage of producing tools much faster and cheaper, but the lifespan of the "rapid tool" is shorter.

The AM technology went from the rapid prototyping market to the rapid tooling market, and is now entering the aircraft parts market with the manufacture of non-structural parts such as brackets, seatbelt buckles, etc.

Using Christensen's criteria, based in our analysis we can consider additive manufacturing as a disruptive technology.

5 How could additive manufacturing likely impact the aviation industry in terms of manufacture and design?

We just qualified additive manufacturing as a disruptive technology. Using Christensen's theories and data from the interviews, we will now analyse how this technology could likely impact the aviation industry, from the manufacturing & design point of view.

According to Christensen and as explained earlier, a disruptive technology starts in the low-end of the market to invade it with its successive improvements. Once the technology reaches the level of performance needed to satisfy mainstream clients' demand, in our case the aviation manufacturers, there is a shift in the choosing criteria, which plays usually in favour of the disruptive technology.

With the increase of the price of oil and of passenger demand airline companies will need more fuel-efficient aircrafts, as explained earlier. This need will make AM interesting for aircraft manufacturers and their suppliers. Due to the interest in the technology, certification organizations will recognize the importance of additive manufacturing, and will agree on specifying more processes and materials. Finally, a common set of certification standards will be created.

The example of the adoption of composites in the aviation industry gives a clue on how this technology could spread in the market. Composites were first introduced on a small amount of parts on aircrafts in the 1970's, to constitute half of the composition of an aircraft produced nowadays, (e.g. the A350XWB). This step-by-step approach is also being adopted with the progression of electric systems that are usually coupled to pneumatic and hydraulics systems (Dassault Falcon, 2011). A good example of this trend is the B-787: one of the objectives while manufacturing the aircraft was to increase the part of electrical systems, for energy consumption concerns (Boeing, n.d.).

As we said earlier, some parts of aircrafts and engines can now be made using AM. We believe that additively manufactured part will follow the same step-by-step approach used with composites or electric systems.
Because of a clear gain in mass and therefore in fuel consumption, these additively manufactured parts would be an asset for aircraft manufacturers to respond to airlines needs.

From the manufacturing point of view, the flexibility and reconfigurability of the technology will offer the opportunity for aircraft part manufacturers to simplify their supply chain. They will be able to get rid off of older manufacturing machines that are still kept in use in case they need to repair old aircraft parts. Using AM, they will be able to repair old aircraft without the need of the tool used to manufacture the plane. It will save them a lot of space on the shop floor, which could be used to put other machines producing more profitable products. With advanced AM processes, the need for post-treatments can be mitigated, simplifying the supply chain. They would offer the aircraft manufacturers the opportunity to print parts on demand for maintenance purpose. At the same time, the technology will still be used to build manufacturing or maintenance tools thanks again to its versatility. This will offer more manufacturing solutions to aircraft manufacturers, resulting in more performing aircrafts.

Leaders in the aviation industry have already understood the potential of the technology, and are working at developing it. General Electrics showed its interest in the technology when it bought Morris Technologies, a company specialised in additive manufacturing, in 2012.
After the acquisition of Avio Aero, GE has plan to build the largest factory in the world ($2400m^2$) dedicated to AM in Cameri, Italy (Materialise, 2013). This plant will be able to contain up to 60 AM machines for the manufacture of aircraft components. The space will also enable the installation of two gas atomisers for the production of powders, and two systems for the heat treatment of the components produced. This interest for the technology shows how seriously leaders such as GE are considering AM.

The technology will spread progressively in the aircraft manufacturers' supply chain with a top-down approach: they will ask their suppliers to adopt the technology, and these suppliers will finally ask their own suppliers to adopt it as well. A good example is the collaboration between Airbus Group and a first tier supplier, GKN Aerospace. In 2011, they started a collaboration with the aim of certifying the technology for use in aircraft components (Airbus, 2011).
Aircraft manufacturers such as Airbus are preparing the supply chain for this transformation: they are working with the Centre of Additive Layer Manufacturing (CALM) of Exeter University to introduce the technology to businesses, organising workshops and events to educate the market. "With the growing interests in the subject of additive manufacturing, Airbus wants to ensure that the supply chain would be ready to support them"; said the CALM Co-ordinator during our discussion.

AM will also allow engineers and designers to use topology optimization. In their paper, Brackett, Ashcroft & Hague explained that this approach is powerful for "determining the best distribution of material within a defined design domain" (Brackett, Ashcroft, & Hague, 2011). In many instances, the optimized topology is very complex and needs to be simplified due to manufacturing constraints. AM enables the production of the complex optimized part, without inducing high increase of production cost, resulting in lighter part with a more functional-driven design, and enabling airline companies to make huge savings on their operating costs (one saved kilogram on an aircraft results in 6,000kg savings in fuel over its lifespan). AM will enable simpler, lighter and more robust assemblies driving airlines' operating costs down as well, due to lower needs for maintenance and lower fuel consumption.
The design approach will evolve as well. The technology gives the possibility to modify designs during the product development without inducing tremendous additional costs to produce new tools. A more iterative approach to design could therefore be considered, as the example of Leptron's UAV.

The industry's value, which was $1.3 billion in 2012, is expected to reach $3.1 billion in 2016 and finally $5.2 billion in 2020 (On 3D Printing, 2012). The industry is growing rapidly, offering actors within the aviation supply chain the opportunity to take advantage of the technology, to become more important players in that supply chain.

We believe that more companies will invest in the technology and we will see more clusters around additive manufacturing. Larger companies might also continue to acquire small companies with an expertise in the technology, to be able to stay in the run.

Further development of the technology would enable the use of a broader range of materials and the production of larger parts. Most of the experts being interviewed agreed on the fact that this technology would be another tool for engineers to manufacture parts. Of course AM is a promising technology that opens up new possibilities, but traditional manufacturing machines will still be used since they present advantages as well.

The AM machines will be complementary to traditional CNC machines, and some AM machine manufacturers, such as the German Concept-Laser are working on hybrid systems, combining AM systems with milling systems. This kind of hybrid system is really interesting for the manufacturers in the aviation industry. During one of our interviews, a Cabin Innovation Manager at Airbus said: “when you consider only additive manufacturing, you get these semi-finished parts, and in some cases, a certain kind of post processing is required to create the final component”. This is because the AM machines are not able to produce a surface quality that meets requirements (for example, when attaching a screw, there is a need for a really good surface quality).
This kind of hybrid machines might therefore be the future of AM in the aviation industry, and could replace some of the traditional machinery.
Therefore, traditional machine manufacturers, in order not to be disrupted, should invest in the AM technology: if they do not, they will not have the expertise to produce these hybrid machines, and will not be able to satisfy their customer’s future needs.

Some researches are also aiming at mixing materials in one part, to have customised mechanical properties (e.g. the ability to play on the flexibility of the material inside the same part). The development of new material for AM could also enable the production of more fuel-efficient engines with material that are working at higher temperatures.

The technology played an important role in the design of the concept plane of Airbus (Airbus, n.d.). Using AM and topology optimisation, the team of engineers at Airbus came out with a structure, which mimics the design of skeleton. Inspired by nature, the team imagined using carbon nanotubes to build larger structures, as small cells can be large bones. By growing carbon nanotubes inside a 3D printer embedded in a matrix of plastic, they would be able to build substructures. With morphological optimization, a treatment that orientates the molecular ordering of the polymer, they thought about producing substructures that could transmit electrical energy and data. Finally, a transparent biopolymer membrane would be used to make some part of the fuselage transparent.
According to the Cabin Innovation Manager who worked on this concept plane with his team, it is “the ultimate vision to print an entire aircraft, no one knows in this world if this will become true, but finally we wanted to create the kind of “carrot” we can show to the engineers”.

To conclude, this technology will enable more functional-driven designs, however, designers will still have to take into account the feasibility of the part being designed and its cost. It will lead to a disruption in the designs of aircraft parts and in their manufacture, offering aircraft part manufacturers the opportunity to innovate in new ways.

6 Conclusion

6.1 Conclusion

This thesis has first shortly explained what was AM and why aircraft manufacturers were willing to build lighter and more fuel-efficient aircraft. We also explain the gain and challenges of using AM within the aviation industry, and understood that the technology had a lot of challenges to address yet. We also provided some examples of AM current applications in the aviation industry to give the reader the potential of the technology.

From this thesis, we can consider that additive manufacturing represents a disruptive technology for the aviation industry, competing with traditional CNC machines. We can imagine that we are actually seeing shifts in customers' choosing criteria: the technology starts being used in the low-end aircraft parts market, and will eventually move up market, to manufacture structural parts.

AM will impact the aviation industry in various ways, from the design of an aircraft, the manufacture of its different parts, driving down operation costs of airline companies. From this work, we can understand that AM will disrupt the way we manufacture aircraft components, offering in the same time a disruption in their design and therefore the rules for manufacturing and designing that designers have to follow.

Traditional CNC machine manufacturers might want to investigate additive manufacturing if they do not want to be disrupted by this technology.

6.2 Further research

The findings of this thesis were based only on the Christensen's book: *The Innovator's Dilemma*. It would be interesting to make further researches to address the business model as well by using the disruptive innovation terminology used in *The Innovator's Solution*.

7 References

3D Systems. (2013). The Journey of a Lifetime. *3Dsystems.com*. Retrieved from http://www.3dsystems.com/30-years-innovation

Airbus. (n.d.). The Airbus Concept Plane. *Airbus.com*. Retrieved from http://www.airbus.com/innovation/future-by-airbus/concept-planes/the-airbus-concept-plane/

Airbus. (2011). EADS, GKN AEROSPACE LAUNCH ADDITIVE LAYER MANUFACTURING COLLABORATION. *airbus-group.com*. Retrieved from http://www.airbus-group.com/airbusgroup/int/en/our-innovation/latest-news/EADS--GKN-AEROSPACE-LAUNCH-ADDITIVE-LAYER-MANUFACTURING-COLLABORATION-.html

Airbus. (2013). *Global Market Outlook - Future Journeys*.

ASTM. (n.d.). *Standard Terminology for Additive Manufacturing Technologies*. Retrieved from http://enterprise2.astm.org/DOWNLOAD/F2792.1294924-1.pdf

Ayre, M., & Sarah Fielding. (2012). Design for Selective Laser Melting: No rules or new rules? *TCT Magazine Volume 20, Issue 6*. Retrieved from http://www.crucibleid.com/wp-content/uploads/2013/01/DMLS-no-rules-or-new-rules.pdf

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., & Hague, R. (2011). *ENERGY INPUTS TO ADDITIVE MANUFACTURING: DOES CAPACITY UTILIZATION MATTER?* Loughborough University. Retrieved from http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2011/2011-03-Baumers.pdf

Boeing. (n.d.). 787 Electric System. Retrieved from http://787updates.newairplane.com/787-Electrical-Systems/787-Electrical-System

Boeing. (2013). *Current Market Outlook*. Retrieved from http://www.boeing.com/assets/pdf/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2013.pdf

Brackett, D., Ashcroft, I., & Hague, R. (2011). *TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING*. Retrieved from http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2011/2011-27-Brackett.pdf

Campbell, T., & Ivanova, O. (2013). *Additive Manufacturing as a Disruptive Rechnology: Implications of three-dimensional printing*.

Carpel, G., & Julian, F. (2013). Une révolution industrielle. *Air & Cosmos*, 12–17.

Catts, T. (2013). GE turns to 3D printers for plane parts. *businessweek.com*. Retrieved from http://www.businessweek.com/articles/2013-11-27/general-electric-turns-to-3d-printers-for-plane-parts

Christensen, C. (1997). *The Innovator's Dilemma*. Harvard Business Press.

Colorado State University. (2010). Reliability and Validity. Retrieved from http://writing.colostate.edu/guides/page.cfm?pageid=1388

Crucibleid. Design guidelines for DMLS – a case study of the basic issues. , crucibleid.com (2012). Retrieved from http://www.crucibleid.com/wp-content/uploads/2012/10/Bicycle-pedal-case-study-V2.pdf

Crucibleid. Redesigned airline buckle to save energy (2012). Retrieved from http://www.crucibleid.com/wp-content/uploads/2012/10/TSB-Airline-buckle-V2.pdf

Dassault Falcon. (2011). *The Electric Aircraft*. Retrieved from http://www.dassaultfalcon.com/PublishingImages/IMAGES/Media-center/Media-gallery/Publications/Focus3.pdf

Deloitte. (2013). *2013 Global aerospace and defense industry outlook : Expect defense to shrink while commercial aerospace sets new records* (pp. 1–15). Retrieved from http://www2.deloitte.com/content/dam/Deloitte/global/Documents/Manufacturing/gx_mfg_2013GlobalADIndustryOutlook.pdf

ECORYS. (2009). *FWC Sector Competitiveness Studies - Competitiveness of the EU Aerospace Industry with focus on: Aeronautics Industry*. Retrieved from http://ec.europa.eu/enterprise/sectors/aerospace/files/aerospace_studies/aerospace_study_en.pdf

EOS. Light, Cost and Resource Effective – Researching Sustainability of Direct Metal Laser Sintering (DMLS) (2013). Retrieved from http://ip-saas-eos-cms.s3.amazonaws.com/public/3fb75eeabb786ba7/6bea4ef6e33191ffaf0372fd47e8601a/download.pdf

Flottau, J. (2013). Slowing Demand Leaves Airbus With Challenge To Break-Even On A380 Program In 2015. *aviationweek.com*. Retrieved from http://www.aviationweek.com/Article.aspx?id=/article-xml/avd_05_15_2013_p01-01-578735.xml

Funding universe. (n.d.). Stratatys History. *www.fundinguniverse.com*. Retrieved from http://www.fundinguniverse.com/company-histories/stratasys-inc-history/

General Electrics. (n.d.-a). 3D Printing Creates New Parts for Aircraft Engines. *geglobalresearch.com*. Retrieved from http://www.geglobalresearch.com/innovation/3d-printing-creates-new-parts-aircraft-engines

General Electrics. (n.d.-b). ADDITIVE MANUFACTURING IS REINVENTING THE WAY WE WORK. *ge.com*. Retrieved from https://www.ge.com/stories/additive-manufacturing

Gibson, I., Rosen, D. W., & Stucker, B. (2009). *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (Springers., p. 484).

Harris, I. D. (2011). *Development and Implementation of Metals Additive Manufacturing*. Retrieved from http://ewi.org/eto/wp-content/uploads/2013/06/Additive-Manufacturing-DOT-Paper-2011.pdf

Hellard, G. (2008). Composites in Airbus: a long story of Innovations and Experiences. Retrieved from http://www.airbus-group.com/dms/airbusgroup/int/en/investor-relations/documents/2008/presentations/GIF2008/gif2008_workshop_composites_hellard.pdf

Helms, H., & Lambrecht, U. (2006). *The Potential Contribution of Light-Weighting to Reduce Transport Energy Consumption*. Retrieved from http://ifeu.de/verkehrundumwelt/pdf/Helms(2006)_light-weighting.pdf

Henriques, V. A. R. (2009). *Titanium production for aerospace application*. Institute of Aeronautics and Space - Sao José dos campos. Retrieved from http://www.jatm.com.br/papers/vol1_n1/v01n7a17_titanium_production_for_aerospace_applications.pdf

Herrmann, J. W., Cooper, J., Gupta, S. K., Hayes, C. C., Ishii, K., Kazmer, D., … Wood, W. H. (2004). *NEW DIRECTIONS IN DESIGN FOR MANUFACTURING*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.198.8706&rep=rep1&type=pdf

Hopkinson, N., Hague, R. J. M., & Dickens, P. M. (2006). *Rapid Manufacturing: an industrial revolution for the digital age*.

Hugel, E. (2013). *Industry surveys - Aerospace & Defence*.

IATA. (2013). *IATA Annual Review 2013*. Retrieved from http://www.iata.org/about/Documents/iata-annual-review-2013-en.pdf

ICAO. (2013). *REDUCING EMISSIONS FROM AVIATION THROUGH CARBON- NEUTRAL GROWTH FROM 2020*. Retrieved from https://www.iata.org/policy/environment/Documents/atag-paper-on-cng2020-july2013.pdf

Jarboe, K. (2014). Additive Manufacturing as a Disruptive Technology. Retrieved from http://www.athenaalliance.org/weblog/archives/2014/02/additive-manufacturing-as-a-disruptive-technology.html

Kvale, S. (1996). *Interviews: An Introduction to Qualitative Research Interviewing*.

Mackenzie, N., & Knipe, S. (2006). Research dilemmas: Paradigms, methods & methodology. *iier.org.au*. Retrieved from http://www.iier.org.au/iier16/mackenzie.html

Marks, P. (2011, July). 3D printing takes off with the world's first printed plane. *New Scientist*, *211*(2823), 17–18. doi:10.1016/S0262-4079(11)61817-4

Materialise. (2013). AvioAero truly created the AM Factory of the Future. Retrieved from http://www.materialise.com/AvioAero-AM-factory

McWilliams, J., Hysinger, C., & Beaman, J. J. (1992). *Design of a high temperature process chamber for the selective laser sintering process*. Retrieved from http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/1992/1992-12-McWilliams.pdf

Murman, E. M., Walton, M., & Rebentisch, E. (2000). *CHALLENGES IN THE BETTER, FASTER, CHEAPER ERA OF AERONAUTICAL DESIGN, ENGINEERING AND MANUFACTURING*. Retrieved from http://dspace.mit.edu/bitstream/handle/1721.1/1651/RP00_02_val.pdf?sequence=2

On 3D Printing. (2012). 3D Printing Industry Growth. *on3dprinting.com*. Retrieved from http://on3dprinting.com/2012/11/01/3d-printing-industry-growth-forbes-incorrectly-says-52b-by-2020/

Park, R. (2014). Research At Cranfield Yields Large Scale 3D Printing Metal Process. *3dprintingindustry.com*. Retrieved from http://3dprintingindustry.com/2014/01/02/research-cranfield-yields-large-scale-3d-printing-metal-process/

Pham, D. T., & Gault, R. S. (1998). *A comparison of rapid prototyping technologies*.

RolandBerger. (2013). Additive manufacturing A game changer for the manufacturing industry? Retrieved from http://www.rolandberger.com/media/pdf/Roland_Berger_Additive_Manufacturing_20131129.pdf

Royal Academy of Engineering. (2013). Additive manufacturing: opportunities and constraints. Retrieved from https://www.raeng.org.uk/news/publications/list/reports/Additive_Manufacturing.pdf

Sealy, W. (2012). *ADDITIVE MANUFACTURING AS A DISRUPTIVE TECHNOLOGY: HOW TO AVOID THE PITFALL*. Retrieved from http://www.ajetr.org/vol12/no1/vol12no110.pdf

Stratatys. (2013a). Additive Manufacturing Reduces Tooling Cost and Lead Time to Produce Composite Aerospace Parts. *Stratatys.com*. Retrieved from http://www.stratasys.com/~/media/Case Studies/Aerospace/SSYS-CS_Fortus-ACS-05-13.ashx

Stratatys. (2013b). FDM Reduces the Time and Cost Required to Develop Unmanned Aerial Vehicle. *Stratatys.com*. Retrieved from http://www.stratasys.com/~/media/Case Studies/Aerospace/SSYS-CS-Dimension-Leptron-05-13.ashx

T.Rowe Price. (2012). A brief history of 3D printing. *troweprice.com*. Retrieved from http://individual.troweprice.com/staticFiles/Retail/Shared/PDFs/3D_Printing_Infographic_FINAL.pdf

Tracy, J. (2004). Drivers and Challenges for US Aerospace Manufacturing. In *New directions in Manufacturing: Report of a Workshop* (pp. 49–54).

Trotman, A. (2013). Rolls-Royce looks to make jet engine parts with 3D printers. *telegraph.co.uk*. Retrieved from http://www.telegraph.co.uk/finance/newsbysector/industry/10448147/Rolls-Royce-looks-to-make-jet-engine-parts-with-3D-printers.html

Wohler, T., & Caffrey, T. (2014). Top 3D Printing Developments in 2013. *wohlerassociates.com*. Retrieved from http://wohlersassociates.com/blog/2014/01/top-3d-printing-developments-in-2013/

Wohlers, T., & Gornet, T. (2011). History of Additive Manufacturing. *wohlerassociates.com*.

Yahoo. (2013). Stratasys to Acquire MakerBot, Merging Two Global 3D Printing Industry Leaders. *Yahoo Finance*. Retrieved from http://finance.yahoo.com/news/stratasys-acquire-makerbot-merging-two-201500565.html