Quynh Trang Nguyen

Environmental Impact Of Additive Manufacturing On The Global Supply Chain

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Additive manufacturing or more commonly known as 3D printing, has recently gain attention and praises to become one of the most disruptive technology, that will greatly impact the global supply chain and logistics industry. In the era of increasing globalization, movement of goods across the globe continuously shows sign of increasing; it is worthy to take into account of environmental impact of the rising volume of goods transported.

With the drastic improvement of the technology and rising accessibility of 3D printers, gradually, not only manufacturers but also their customer should considering integrating the technology in their supply chains to reduce their environmental footprint. As 3D printing has the capability to bring manufacturing back to the local market, on-shoring, this reduction in transportation of goods could help reduce the emission.

The first part of the thesis will give an overview on the technology: how does it works, its implication on the global supply chain, and what does the future hold for 3D printing.

The second part of this paper will focus in finding the link between 3D printing implications and its benefits on the supply chain and the environmental impact it could yield, specifically on the highly customizable products market and the spare parts sector.

The research found out that 3D printing has a vast range of applications and each could have a positive impact on the environment. However, under the current level of maturity and adoption, 3D printing has the most positive environmental impact, specifically reducing emission and environmental cost on the spare parts supply chain.

Keywords	Additive manufacturing, 3D Printing, Supply Chain Management, Environmental costs

Contents

1 Introduction

Additive Manufacturing (AM) or more widely known as 3D printing though is not a newly developed technology and has been existing for nearly three decades but have only been gathering attention from the mass common consumers just for a couple of recent years. Briefly described, 3D printing is a method of manufacturing that in theoretically is similar to common prevailing commercial 2D printing method but with another dimension added to build a complete object out of a digital 3D model. In practice, 2D printing and 3D printing are two different fields; the methods of "printing" are different and the end result is direct to different purposes and users. While 2D printing deposit one layer of ink on to the surface of the paper, 3D printing deposit many layers of material onto each other to build a multi dimensional object that can serve multiple purposes and could even possess several characteristics similar or even superior compare to objects made by traditional manufacturing methods.

3D printing has a range of applications stretches across several industries and have been promised by enthusiast to not only revolutionize the manufacturing techniques but also simplify the supply chain for numerous industry sectors and may have positive impact on the environment especially in the context of growing goods movement around the globe. In the era when an not only a small business but also an individual consumer can place an order for an item across the continent and have it shipped directly home, it is worth to consider a better solution for a more efficient way to reduce the environmental impact of goods transportation but does not limit the free flow of goods across borders.

3D printing is also believed to be able to bring manufacturing back to developed countries and close to the consumers. With this new method, from the simplest to very complex product can be made and delivered to the customer in the closest distance possible. The concept is that the customer can have the product's design, printing machine and raw material already on hand and have the product be ready after just only a few hours or for less experienced consumers, have the product be made by a professional printing service so called "fab-lab" (Fabrication lab) nearby. The new model enable flexibility and agility in the supply chain as well as it would cut out unnecessary loop in the supply chain and shorten the time for the product to reach its customer.

Choosing between decentralized or centralized manufacturing and distribution is also a recurrent problem for many manufacturers and finding a balance between the two strategies as well as maintaining the balance accordingly to the company's business model are tough problems for growing companies or those with expansion plans. With 3D printing, decentralized production could open a road to a greener supply chain without increase in several costs like infrastructure, planning, production, transportation, warehousing, etc.

With many promising opportunities opened up with the adoption of additive manufacturing together with doubts of its possibilities from the skeptics, this thesis aim to find a link between the impact of 3D printing application not only on the simplicity it will bring to the global supply chain but especially also on the environmental impact the technology might help by reducing the unnecessary flows of goods globally.

2 Research question and methodology

2.1 Thesis Question

Additive manufacturing is not a recent technology but it has just gained attention recently and promises a great disruptive effect on several industry sectors. Once widely evaluated and carefully studied, the implementation of this technology could bring significant impact not only to the way company manufacturing goods but also on companies' logistics and supply chain strategy and approach.

This research focuses on answering the question whether 3D printing can bring any environmental benefit by restructuring and simplifying the logistics process of several companies and industry sectors. In certain business sectors and areas like the spare parts industry, where rapid respond to demand is necessary; or in the category of product with high degree of specialization/ customization like personal medical devices, it is revolutionary to have the supply chain be simplified and the product to have quality and complexity far more superior to product made by traditional manufacturing methods.

This research will give a description about most common methods of additive manufacturing that is currently been used by many manufacturers and the application of these methods on how it can simplify the supply chain. There are a variety of users of this technology and each method/equipment is developed for a certain range of applications, from personal uses of recreational hobbies to professional application even in the space industry.

The research will compare between the supply chain of traditional manufacturing method and the newer approach of 3D printing integrated supply chain in terms of effectiveness on several aspects like cost, time and especially environmental issues generated during the logistics processes. As transportation takes up a fairly significant amount of greenhouse gas emission around the world, 3D printing offer an alternative path with the actual transportation occurs only with the raw material itself and the design could be sent and received virtually. This would reduce the need for transportation and inventory for unnecessary finished goods or express shipping for some item in emergency situations. To further demonstrate the benefit of 3D printing, the research will also examine and analyse cases of companies with their adoption of 3D printing in their supply chain and how the technology has transformed or resolved the problems.

This research also looking to answer whether companies should invest in 3D printing in their supply chain to reduce their logistics activity ecological footprint. Finding the links between the shortened logistics process and environmental benefits is the main objective of thesis. Therefore, by the end of the research, companies should be able to decide whether to adopt and implement additive manufacturing and how should it be used according to the nature of the technology and companies' strategy.

2.2 Methodology and limitations

As the current rate of adoption of additive manufacturing among companies are still relatively low and mostly stays at prototyping and tooling process, to be able to find the answer whether or not 3D printing could bring significant environmental impact, this research will use a qualitative approach to find out connection and correlation between the benefits 3D printing brings to supply chain in general and how those benefits reflect from an environmental perspective, whether it is going to be positive or negative.

This research will serve as an extended literature review that combines both previous qualitative and quantitative research as well as concept papers to form a clearer idea of the area of supply chain where additive manufacturing will have the most impact on. Currently, existing literatures have only tapped on how 3D printing can reconfigure supply chain but there has been no clear link between its benefits and environmental impacts it might bring, considering other trade-offs. Results for centralized versus de-centralized distribution strategy also varied and inconsistent as they have been mostly focus on the conventional supply chain.

This research will not be discussing or presenting heavy numerical data or calculation related to the simplification of the supply chain resulted in the adoption of 3D printing as the technology has numerous application throughout the whole supply chain. And depending on the industry sector, companies' business strategy, operating market and other circumstances, it is very difficult to present a clear measure of how additive manufacturing can produce positive environmental impact if it's unclear about the direction and magnitude of the application.

3 Additive manufacturing overview

3.1 History of Additive manufacturing

3D Systems was the first to develop Stereolithography (SL) in 1987, the process that uses laser to solidify thin layers of ultraviolet (UV) light-sensitive liquid polymer. Each layer was built upon another therefore layers after layers a complete 3D object could be "printed" without having the need for using a mould or using a subtractive method like carving or cutting like traditional manufacturing methods. The first commercial additive manufacturing machine available was SLA-1 and later was succeeded by SLA 250, a more popular model by 3D Systems (Wohlers Report 2014). Respectively, the technology was adopted and commercialized in other industrial giants like Japan and Germany. Later in the 1990s, others method of additive manufacturing was developed and introduced to the market, each feature different types of base materials and printing methods, but the idea of the manufacturing stayed the same, depositing one layer after another and repeat the process many times to build up a complete object.

During the first decade since additive manufacturing development, stereolithography was only known to expert in the industry, as this was the most popular one and it was fairly costly and required users to have an extensive knowledge about the complete process/ materials/ equipment etc. Eight years after the first commercialization of SL machines, Stratasys introduced Genisys, and later on the same years, 3D Systems launched Actua 2100, which used the technology similar to fused deposition modelling (FDM) to melt and deposit layers of wax material using an inkjet printing mechanism. These were the first low-cost machines introduced and opened up many new solutions for companies with its versatile applications and laid the foundation for many personal 3D printers that an individual can easily afford and use as we see today. According to Thomas, D.S. and Gilbert, S.W., (2014) cost of 3D printing system between the period 2001-2011 have decreased by 51% adjusted for inflation.

From the period of late 2000s, 3D printing machine manufacturers started to target toward the segment of individual users, and started to introduce machine with the price tag below USD $1000, opened up a whole new category of customers and different possibilities. As the cost of 3D printers was drastically reduced, additive manufacturing began to gain popularity not only among manufacturing expert but also individual users like hobbyists have found the technology has useful applications. With the rise in adoption rate, cost of 3D printing machines, equipment and material also has been significantly reduced and designing software and platform for personal users were also popularized.

3.2 The 3D Printing Industry and its potential

The worldwide 3D printing industry is expected to grow from USD 3,07 billion in revenue from 2013 to USD 12,8 billions by 2018, and expected to surpass total revenue globally of USD 21 Billions by 2020. The 3D printing revolution is expected to transform almost every major industry and change the way we live, work, and experience in the future (Wohlers Report 2015)

Sculpteo’s state of 3D printing (2017) reported its respondent were in industrial sectors of: Consumer Goods (17%), Industrial Goods (17%) High Tech (13%) Services (9%) and followed by Healthcare sectors (7%) (Sculpteo, 2017)

A hefty amount of these respondents (47%) saw a greater return on investment than last year and most expect a 55% rise in spending for 3D printing 2017. So far, most companies are still largely focusing on using 3D printing on research and development and prototyping though 90% of the respondent positively believed and considered that 3D printing is going to be a competitive advantage in their business strategy. These responses showed that respondents are still having a strong belief and loyalty for additive manufacturing and the market show a strong sign of maturity and stability.

Gartner hype cycles research movements and maturity and adoption of a particular technology in graphical form by dividing the its trend into 5 stages: innovation trigger, being at the peak of expectations, sliding into a trough, climbing a ‘slope of enlightenment’, and finally reaching a plateau of productivity. Trends that are on the rise tend to gather a lot of interest due to their potential applications, but the majority is conceptualized application, not yet usable technology. (Gartner, 2017)

Gartner 2017’s hype cycle of 3D printing showed a notably strong interest toward 3D Printing in Supply Chain, Manufacturing Operation, Retail and other industries where the supply chain is different from other mainstream products like Tooling, Medical devices, Aerospace, Automotive, Electronics and Fabrication. The market for these applications are considered to becoming more professional and B2B 3D printing is used more frequently than B2C printing.

Figure 1: Gartner’s 2017 3D printing Hype cycle. Source: Gartner 2017

In PwC’s 2016 survey regarding the disruptive effects of 3D printing on the US Manufacturing, it is notable that more than two third of US manufacturers has already adopted 3D printing in some way and the majority of manufacturers anticipate greater use of 3D printing for high-volume production More manufacturers (42%) now believe positively that, in the next term of 5 years, 3D printing will likely be implementing for larger batch manufacturing, up slightly by 4% from statistics of 2014. Most still have strong belief in the application of 3D printing will be mainly be used primarily low-volume, specialized products (67%)—although that percentage decrease slightly from 74% in the same survey in 2014. (PwC, 2016)

Area where manufacturer see that additive manufacturing could create the most disruptive effects if 3D printing was widely adopted is restructured supply chain (22.3% of respondents), especially the reduced need for transportation and logistics (14% of respondents) as this area was not a significant effect to manufacturer in the survey of 2014. (PwC, 2016)

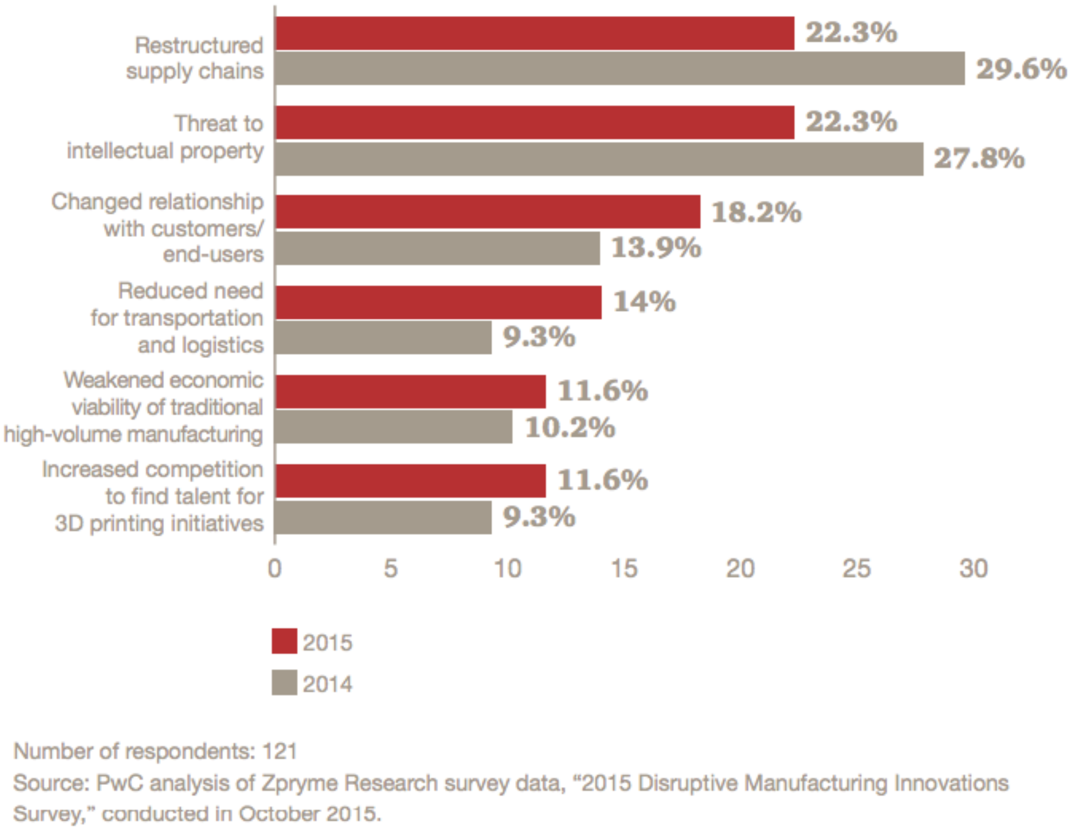

Figure 2 If and when 3D printing is widely adopted, what will be the most disruptive effect on US manufacturing? Source: PwC

It is also worth to note that manufacturers see great potentials of additive manufacturing in the after-market parts production: over half of US manufacturers (52.8%) believe that, in the upcoming 5 years period, 3D printing will become more beneficial for after-market parts sector. 64% of respondents also believe that 3D printing will potentially be implemented to manufacture parts that no longer have the visible immediate value. Therefore there will be no need for planning and keeping in stock parts that might become waste in the future. (PwC, 2016)

3.3 Implications of 3D printing on the logistics industry

Not only does the technology has impact on the production but the logistics of these manufacturing company has to adjust and even restructure to cope with changes in the completely new process as well. Logistics companies, in cooperation with their manufacturing clients, need to be proactive if not taking the initiative to provide suitable and optimized solutions that implementing 3D printing in it.

Major impacts that directly affected the operation of each party in the supply chain, from the supplier to manufacturer, logistics provider and consumer are:

- A greater proportion of goods, which was previously produced in developing countries in Asia would be relocated and sourced directly from the local market of North America and Europe. Manufacturing cost in China in recent years has not been as cheaply as it used to be a decade earlier and beside shifting to even lower cost countries, companies are considering moving production back closer to local market for products that are in the higher end spectrum. The shifting could greatly reduce shipping volumes and increase flexibility in the supply chain.

- Downstream logistics would also take a toll from the viewpoint of the logistics service provider. The manufacturer – wholesaler – retailer relationship could be fundamentally impact by made-to-order production and distribution strategy. The shopping experience since the introduction of internet to the public has already been revolutionized greatly and now with the potential of even have the product manufactured locally, it is promised to elevated to another level. In some sectors, retailers will either cease to exist or become the showrooms for manufacturers, keeping very little or no inventory of their own. Orders are fulfilled directly from the manufacturer to the home or desired shipping place of the consumer.

- Logistics service providers' level of involvement in firm's upstream logistics might be diminished intensively and extensively and there might be less chance to take advantage of the supply chain's complexity, as manufacturing processes are increasingly incorporated inside a single facility.

- The mass customization of products is rising as customers have always been demanding a wider range of products and this technology opened up a whole new era of customization like never before. This would mean that inventory levels will fall, as goods are made to order in return reducing warehousing requirements as well as reducing the complication of inventory planning for company with wide range of product and complex distribution system

- If the number of purchase of personal 3D printer rises as envisioned by the 3D printer makers, a major new sector of the logistics industry would arise focusing on the storage and distribution of 3D printers' feeding materials. As 3D Printer manufacturers have started to introduce more affordable desktop 3D printers, the home delivery market of these raw materials would increase.

- The service parts industry, from manufacturing to logistics would be one of the areas where additive manufacturing will have the most impact on. Currently in some sectors, billions are spent on keeping stock to supply parts for products from all different categories. In some occasions, large quantity of stock is forced into supply chains to allow the chain to operate smoothly as spare parts could be shipped and received in a very short time period to get machines up and function again and/ or to meet customer needs as soon as possible. It would be not far from the reality when consumers can buy and download designs of parts from an online database, 3D Print it and replace the faulty part within a much shorter time window or have it delivered by a service part logistics provider who double up as manufacturer. This would make a large proportion of warehouse reserved for spare parts as well as forecasting demand and manufacturing become redundant. (Manners-Bell, J., Lyon, K., 2014)

In the context of 3D printing may have the possibility to take away the work of traditional logistics providers, these threats could be considered and reverse to be 3PLs' opportunities. For small and medium manufacturers with the large customer base or the customer net work is wide spread, logistics provider could provide the solution of even becoming the manufacturers for its clients. Briefly speaking, logistics provider will not only offer transportation, inventory, warehousing and other value added services like before but also 3PLs could even do the work of demand planning, material handling, manufacturing, spare parts producing and distributing, and return and recycling logistics. In short, 3PLs would become Product Life-Cycle Management service providers. (Manners-Bell, J., Lyon, K., 2014)

> Companies can also make use of their logistics providers' future end-to-end spare parts on-demand solutions. Each logistics provider can achieve economies of scale by building up an owned network of shared 3D printers located in warehouses and distribution centers around the world. In the same way as many companies today provision spare parts to a third-party logistics provider, in future companies will be able to entrust their logistics provider to efficiently process, print, and deliver spare parts orders in a fast, low-cost manner.
> (DHL, 2016)

Several giants in the logistics industry have taken steps toward a 3D printing integrated supply chain, providing solutions for not only large business partners but also individual customers with request for manufacturing smaller and highly customized products. Although the technology still have many limitations regarding production time, limited materials, high production cost for the lack of economy of scale, it could be considered ground breaking to see companies take initiative steps that could further accelerate the rate of growth for 3D printing.

TNT Express has been working to incorporate additive manufacturing in its business portfolio by establishing a number of 3D printing facilities right in its distribution centers throughout the whole Germany to examine how to be able to implement the technology to best suit its strategy as well as its clients'. United Kingdom's Dynamic Parcel Distribution (DPD) has also partner up with 3YOURMIND, a platform for industrial 3D printing, to develop mobile 3D printing factories. The partnership is a vision of a network of a mobilized additive manufacturing hubs with the ability to service a variety of companies from many industries; these facilities could also be leased to manufacturing companies to maximize their production volume in peak times. (3DPrint.com, 2015)

Earlier in 2016, UPS update its business model with the introduction of 3D printing in its UPS stores across the US. These facilities can print simple production prototypes, accessories, and providing solution for small business owners. UPS also has made a large investment in a company called CloudDDM (now Fast Radius), to set up industrial 3D printers inside one of UPS facility in Kentucky. The two companies' collaboration aim to build a supply chain in the cloud, that is able to produce parts at the right time, right place, and right amount. Later in 2016, UPS also announced expansion of the partnership with Fast Radius to Singapore, being the first logistics provider that offer on-demand 3D printing network in Asia. UPS also partnered with SAP in a project to offer on-demand 3D printing service. SAP's responsibility is to create an end-to-end system that will be able to handle the entire manufacturing process from the taking order, manufacturing to the final product shipment within a time frame of 24 hours.

3.4 How does Additive Manufacturing work?

Additive manufacturing, or 3D printing works in a similar manner like the conventional inkjet 2D printer as we are all familiar of but instead of depositing only one layer of ink onto the paper, 3D printing added another dimension by injecting multiple layers of material to build up a complete object. There are multiple ways to build up the material onto one another but most commonly used and easy to understand methods are i) liquefy feeding material and use room temperature to slowly solidify the layers ii) solidify feeding material which is already in liquid or powder form.

Conventional manufacturing methods often require specific tooling for specific parts or modification to equipment when switching to produce similar parts on the same machine. Traditional manufacturing also produces a lot of waste such as method of cutting or carving and these techniques are also often labour-intensive.

The basic requirements to manufacturing 3D printed objects are:

- 3D digital design or model: the blueprint for the final product. There are 3D scanners available that can scan an actual part and produce a 3D image of it or the model could also be design with common computer aided program (CAD). Apart from the design, there is also need for software to adjust and modify as well as giving directions to the 3D printer on how to print the part with the desired characteristics.
- Raw material: depending on the final product requirements that there are suitable materials to feed the machine. Most common for its cost and ease to handle as well as availability are plastics or plastic based filaments. Metal powder is also commonly used as it’s highly durable but the material is only suitable for a certain types of printer. Gradually companies are developing and introducing several other material with characteristics that are no different from traditionally produced product. These materials could be flexible, elastic, transparent or have biological properties, etc.
- 3D printer: using direction from the 3D digital design, 3D printer transforms feeding material into object with the exact design like the digital model. Using different printing techniques, the machine either melt and extrude plastics onto a printing platform or using lasers/ ultraviolet light to solidify powder/liquid material layers upon layers. Depending on the users, commercial industrial printers could have the price tag of a million dollars, while simple desktop personal used printer could go as cheap as 200 dollars.

Figure 3: The 3D printing process. Source: DHL

3.5 Additive manufacturing methods

Although the term “additive manufacturing” and “3D printing” are usually used interchangeably, additive manufacturing is a more accurate and descriptive term for the method. The term 3D printing might give an impression of common desktop printer that we often see nowadays though it cover a wide range of building methods. As there are several types of material and desired finished product, each required a different manufacturing method but listed below are some of the most common one. From 2010, the American Society for Testing and Materials (ASTM) group has established a set of standards that categorize the Additive Manufacturing processes into seven categories.

- Fused Deposition Modelling (FDM): this technique is the most common and well-known technique as it is the base for most advertised desktop personal 3D printer. FDM is one of the techniques that are included in a broader category of the Material Extrusion Method. Other methods under Material Extrusion are: Fused Filament Fabrication (FFF) (which is basically the same as FDM but are used to be legally unconstrained) and Contour Crafting. The term Fused Deposition Modeling and its abbreviation to FDM are trademarked by Stratasys Inc.

> The FDM technology works using a plastic filament or metal wire which is unwound from a coil and supplying material to an extrusion nozzle which can turn the flow on and off. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The object is produced by extruding melted material to form layers as the material hardens immediately after extrusion from the nozzle. This technology is most widely used with two plastic filament material types: ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic acid). Though many other materials are available ranging in properties from wood fill to flexible and even conductive materials.
>
> (3DPrinting.com)

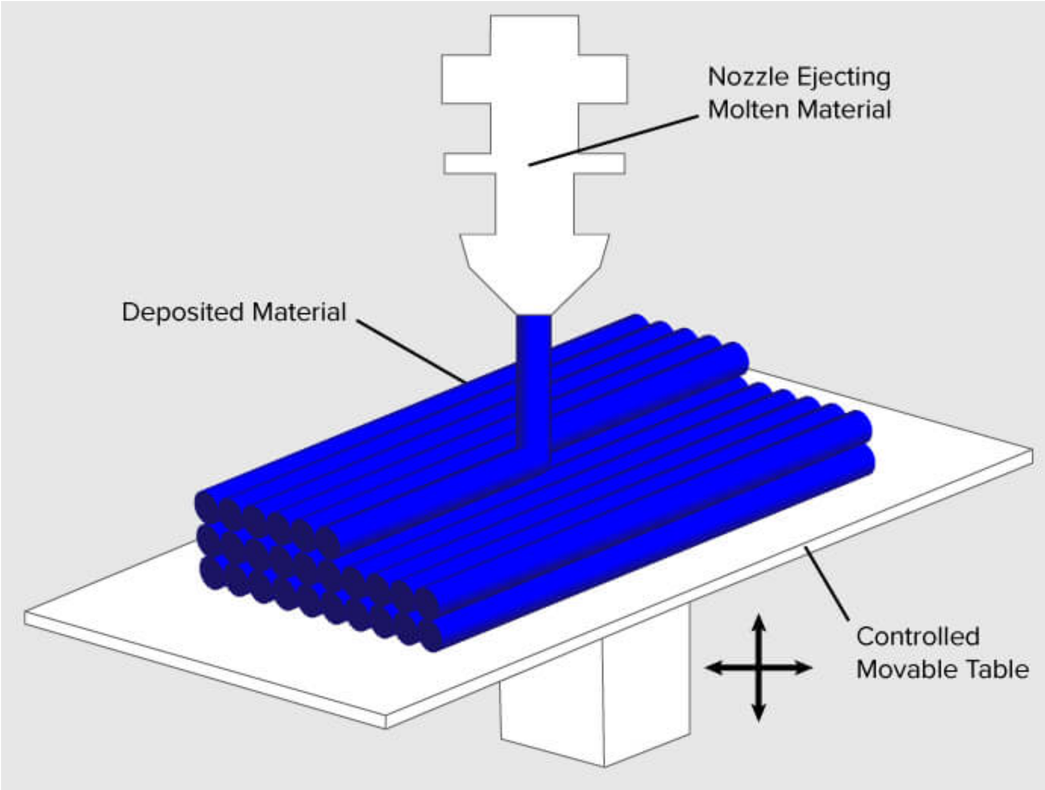

Figure 4: Fused Deposition Modelling (FDM process) Source: Wikipedia, made by user Zureks under CC Attribution-Share Alike 4.0 International license

- Selective Laser Sintering (SLS): this technique is far less common amongst the individual users as the availability of the feeding material are limited as well as the printer itself is priced with a different price category. The majority of user are experts in the manufacturing industry as these type of printers require users to have a solid knowledge about the process and product itself. SLS uses very high power laser to melt small particles of metal, ceramic or glass powders into the desired shape. After each layer gets processed with laser, the building platform/ powder bed is lowered by one layer thickness. Then a new layer of powder is laid on top and similar to other additive manufacturing method, the process is repetitive until the object is finished.

  SLS is one of the techniques that are included in a broader category of the Powder Bed Fusion Method. Other method under this categories is Direct Metal Laser Sintering (DMLS)

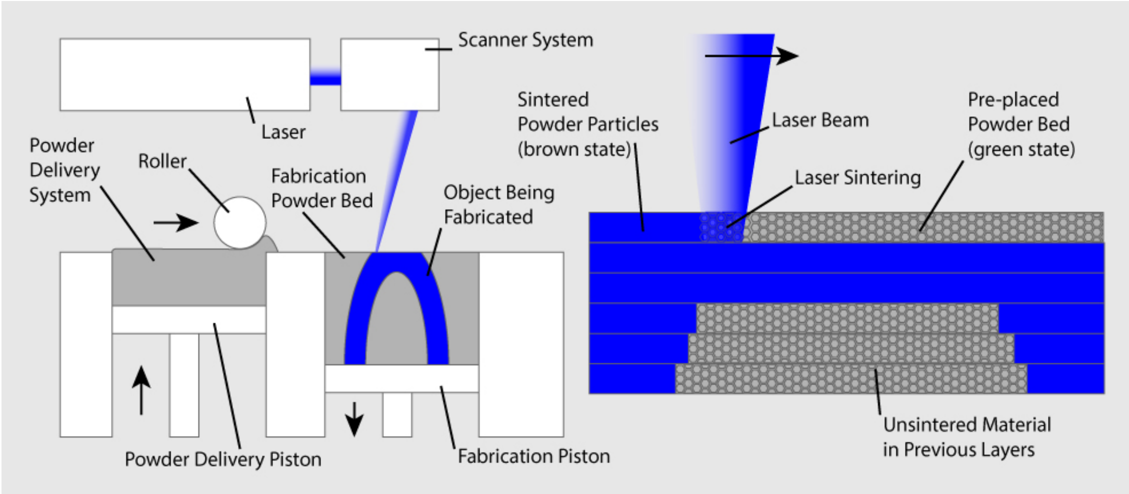

Figure 5: Selective Laser Sintering (SLS) process. Source: Wikipedia from user Materialgeeza under Creative Commons Attribution-Share Alike 3.0 Unported license.

- Stereolithography (SLA): is one of the first additive manufacturing methods ever developed and commercialized and still being used widely nowadays for not only for its superior quality but also the ability to produce aesthetically pleasing final product. The speed of production as well as its versatility regarding raw materials, design and finish of final product still make SLA stand out and remain competitive compare to other methods like FDM

  SLA is one of the techniques that are included in a broader category of the Vat Photopolymerisation. Other lesser-known methods under this category are Digital Light Processing (DLP) and Continuous Liquid Interface Production (CLIP)

> This technology (SLA) employs a vat of liquid ultraviolet curable photopolymer resin and an ultraviolet laser to build the object's layers one at a time. For each layer, the laser beam traces a cross-section of the part pattern on the surface of the liquid resin. Exposure to the ultraviolet laser light cures and solidifies the pattern traced on the resin and joins it to the layer below.
> After the pattern has been traced, the SLA's elevator platform descends by a distance equal to the thickness of a single layer, typically 0.05 mm to 0.15 mm (0.002″ to 0.006″). Then, a resin-filled blade sweeps across the cross section of the part, re-coating it with fresh material. On this new liquid surface, the subsequent layer pattern is traced, joining the previous layer. The complete three dimensional object is formed by this project. Stereolithography requires the use of supporting structures which serve to attach the part to the elevator platform and to hold the object because it floats in the basin filled with liquid resin. These are removed manually after the object is finished
>
> (3DPrinting.com)

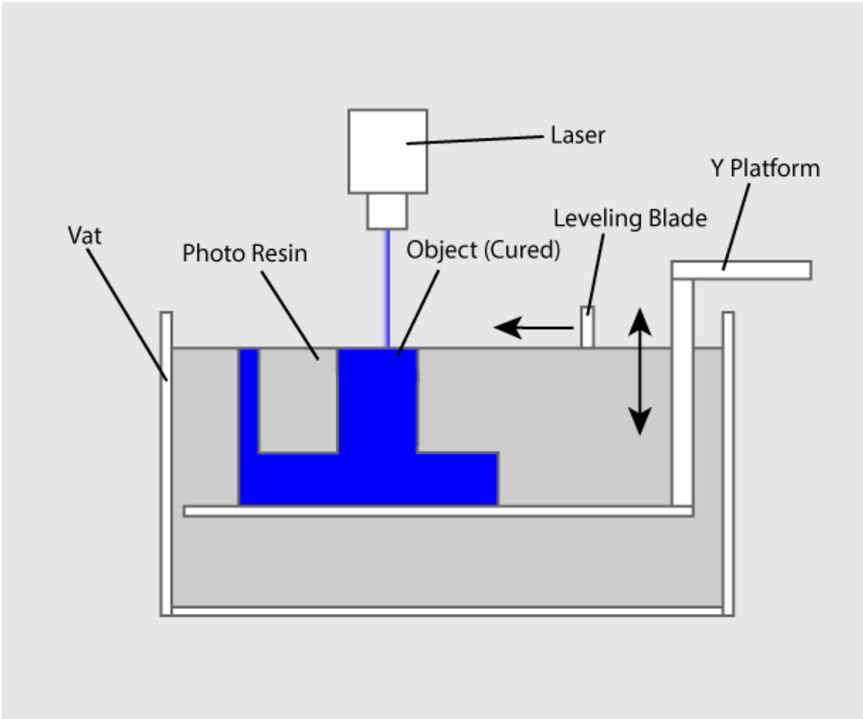

Figure 6: Stereolithography (SLA) process. Source: lboro.ac.uk

- Other manufacturing method that are under the term Additive manufacturing that worth mentioning are:
    - Material Jetting
    - Binder Jetting
    - Sheet Lamination
    - Directed Energy Deposition

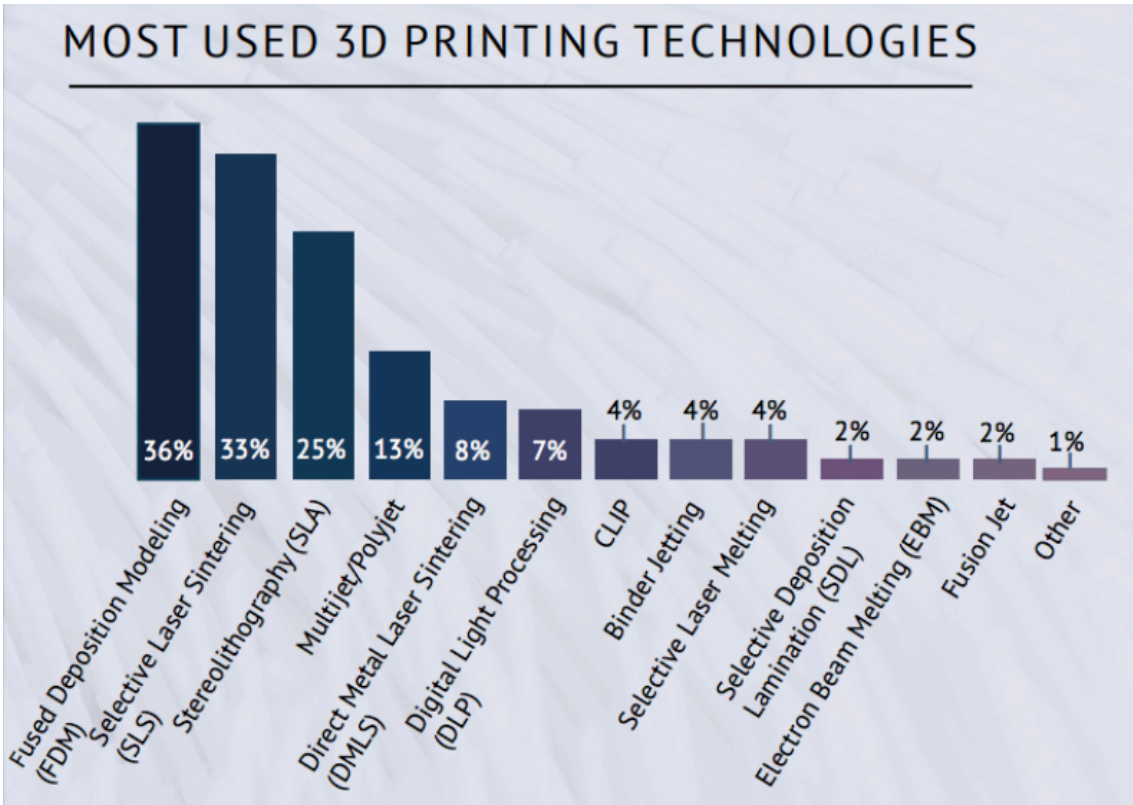

Figure 7: Most used 3D Printing technology, Source: Sculpteo

3.6 Major implications of 3D printing

3D printing not only found the stand in the industrial context but also it has gained popularity among individual users as the technology enables users to take charge in the manufacturing process and even gives the customers opportunity to influence the downstream supply chain of their products as well. 3D printed product are not only fast and easy to produce, it's also highly customizable. Therefore major applications or where 3D printing could create the most influence to the products and process are where there's always need for customization, or speedy and flexible respond to changes.

3.6.1 Individualized production

In the rising of do-it-yourself culture as well as the higher demand for customizable products, the distinction between manufacturer and consumer is no longer a fine line. Customer wanted to be in the driving seat of what, when, where and how they want there product to be like.

Personalized products that 3D printing could have major impact on that worth mentioning are

- Customized health care industry: Medical devices or prosthetic limbs, dental
- Jewellery and fashion
- Hobbyist’s toys and gadgets
- Education: classroom’s illustrations can now become physical demonstrations

3.6.2 Complex parts and products

Selective Laser Sintering (SLS) and Stereolithography (SLA) as mention earlier are the two of the most common method of additive manufacturing not only because of its ease to use, but the being majority of user preferred choice for its ability to produce product with high level of complexity and durability.

Automotive industry and Aviation as well as Aerospace industry is the area that are mostly benefit from the technology the most. Less time needed for prototyping and customizing tooling, product development speed is shorted and the final product could roll out in the market and receive feedback in a drastically shorter time frame

3.6.3 Decentralized and on-demand manufacturing

3D printing is very likely to thrive in the area where the traditional supply chain is problematic. Most notably could be bringing manufacturing to remote, hard to access area or manufacturing products that are no longer having the need to keep stock of.

Inventory management could be a costly operation for companies with the widespread network of distribution. For the product in which company don’t want to hold stock on or spare parts, it is also a burden to do forecasting demand or maintaining stock of unnecessary items.

Both decentralized production and decentralized distribution has become the preferred strategic move for companies nowadays as in this digital age, being able to respond to customer demand and requirement in a timely and effective manners is the direction that companies should and currently aiming for.

3.6.4 Rapid prototyping and shortened R&D cycle

Traditionally the R&D cycle for a design goes with designing – producing prototypes, typically in house or commissioning another producer – testing – make changes.
Having a 3D printer in possession or having access to one within the vicinity, designers and companies can cut out the intermediaries from their prototyping cycles and create prototypes that are not only demonstration of the design but also a complete working product and even mass manufacture their products completely in-house. This puts companies in charge over digital manufacture processes as well as materials being used and enables them to rapidly make adjustment and modification on the design based on the results.

Prototypes that are printed directly from CAD data allow quick, accurate and frequent amendments based on actual testing, analyzing response and reactions. Other advantages of rapid prototyping with the integration of 3D printing are design iterative, reduction in scrap and rework, easily communicating ideas, testing in the real world condition. In a survey by PwC (2016), a large amount of producers and manufacturers (31,4%) have already implementing 3D printing in their R&D cycle. (PwC, 2016)

3.6.5 Development of new business model

Not everyone would have the need to own a 3D printer or know someone who could lend him or her one or having the expertise to operate a printer. Taking advantage of this, fabshop (fabrication shops) is new type of business where people who lack the production capability – printer, can just come or made an online order to have their design manufactured and handle by professional. These sites are also a place where hobbyists, designers and amateurs could use to design, receiving consultations from professionals, and have it printed in just a few hours.

Nowadays in the digital age, for everything that available virtually, there will always be a platform for sharing the works with others. Thingiverse is an online open platform dedicated for designers to upload and share their work with others. These designs are often in creative commons terms and available for everyone. This enables a user from across the globe away from the designer to have a product printed and be ready in a local fabshop in within a fraction of the time compare to the other traditional ordering-manufacturing-delivery process (Thingiverse.com). Other more advanced platforms for designers that are currently on the rise are Shapeways and Sculpteo. These professional fabshops is the platform for pro-designers to sell their designs to customer without having to deal with the hassle of finding suppliers/ manufacturers/ delivery options. Designers are free to price the design and can just focus on designing and branding their shops while these providers will take care of production, payment, customer service and shipping. (Shapeways, 2017) (DHL, 2016)

4 Traditional vs. 3D integrated supply chain

4.1 Framework of Supply Chain Management

The definition of Supply Chain Management according to Council of Supply Chain Management Professionals:

> Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies.
>
> (Council of Supply Chain Management Professionals, 2017)

The Supply Chain Operations Reference model (SCOR) is the standardize reference model for supply chain management developed by the Supply Chain Council. It is a management tool used to address, improve, and communicate supply chain management decisions within a company and with suppliers and customers of a company (Scott Hudson, SCRC, 2004). The framework define the six processes required to satisfy the customer demands and the processes of the whole supply chain, from the first chain of raw material to the end where the product meets the final consumer. These 5 processes are:

1. Make: Procedures of manufacturing a product to a completed state from raw materials using available equipment to meet actual or planned demand. This part emphasizes the strategy of production and determines whether it is going to be make-to-order, make-to-stock, or engineer-to-order.

2. Source: processes of infrastructure and material procurements to meet actual or planned demand. These processes also comprise of inventory and supplier management.
3. Deliver: Deliver starts with receiving orders to order management, warehousing, and transportation and distribution managements that ensure the right products get to the right place at the right time.
4. Return: this does not only comprise of returning or receiving returned products but also the container, packaging etc. as. It also encompasses post-delivery customer support as well as regulatory requirements.
5. Plan: Include demand and supply planning and management actions that would measure and improve supply chain efficiency and maximize sourcing, production and delivery requirements along the entire chain.

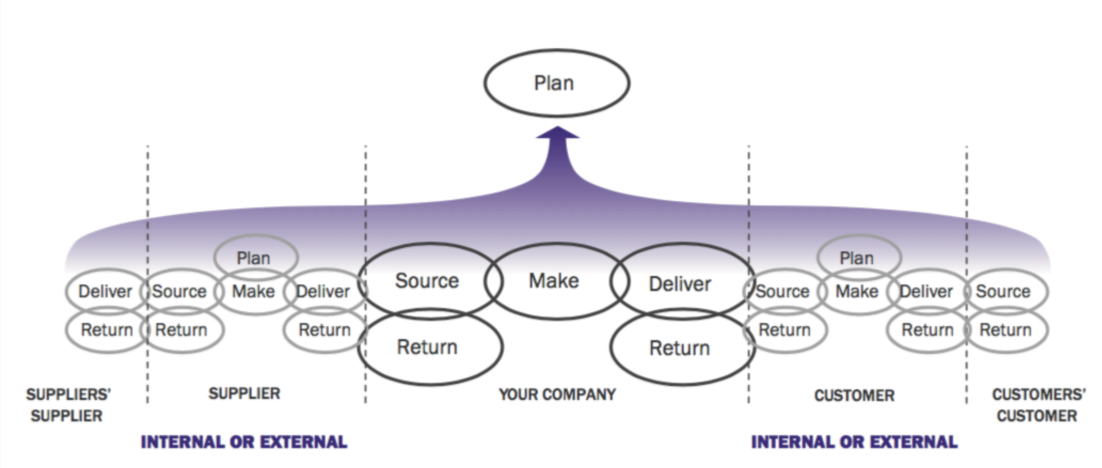

Figure 8: SCOR reference model “Supply Chain” (Source: the Supply Chain Council)

Supply chain management, according to the Supply Chain council, could be briefly defined as an integrating function with primary responsibility is to connect primary business functions and business processes within and across. It addresses manufacturing operations, sourcing, distribution, returns, planning and it enables coordination of processes and activities with and across marketing, sales, product design, finance and information technology. (Council of Supply Chain Management Professionals, 2017)

4.2 3D printing integration on the entire supply chain

As previously addressed above, the 3D printing industry could have a remarkable impact on many level across the entire supply chain. This part of the research would investigate the implication and application of additive manufacturing on the supply chain using the previously explained SCOR model. It is important to look at how additive manufacturing could simplify the supply chain and produce positive environmental impact. The SCOR model would be used to create a supply chain road map that aligns with companies' business functions and identify how companies can utilize the advantages of 3D printing in their supply chain to solve their problems or maximize their potentials and expand accordingly to the business plan.

The entire "Plan" for 3D printing integration could comprise of adoption and implementation of additive manufacturing on one or several chain of the SCOR model: Make, Source, Delivery, Return. As the applications of 3D printing stretch across the entire value chain, it is revolutionary to be able to utilize its versatility to not only one but also several aspect of the value chain. This part of the analysis will place an emphasis on how these applications could overall improve all the ecological impact of companies on the global trade.

4.2.1 Make: Manufacturing and operations

Ecological mass customization: traditional manufacturing achieved low manufacturing and operation cost using the economies of scales. Cost of each batch is relatively high but for most traditional "subtractive" manufacturing techniques like injection moulding, the higher the production volume, the lower the cost of each batch. Using 3D printing, this reduces and even eliminates the need for tooling and making huge calibration between batches. Production cost and time per each unit is the same, therefore, open up more rooms and flexibility for mass customization. This is cost effective in the case of mass customization, which primarily means that custom made products are less costly and take less time to produce. Each and every single products and parts can be customized to the customer's requires specification without huge extra cost. The application of this for companies could be in production for small test or trial products or so-called bridge manufacturing. This is used mainly for initial introduction of the product for its real use/ end consumers. When demand is high enough for investment in tooling for traditional manufacturing methods then production will get shifted back. (TNO, 2014) Major drawback of using 3D printing is the cost of producing a unit is the same no matter the batch size. The balance for Additive manufacturing and Traditional manufacturing when the batch size is small to medium is using Additive manufacturing to create tools and molds to use for traditional methods. 3D printed molds take less time to produce and will surely also reduce visits to mold-manufacturers.

Low production waste: only the exact amount of raw material is used in contrary with the usual methods when material is mild, scrapped or cut away. This does not only cut cost and waste for excess material but also eliminate the step of post-processing the excess materials generated during the manufacture process. A study comparing environmental impacts of additive manufacturing and traditional machining via life-cycle assessment by University of California, Berkeley confirm that the 3D printing machine using Fused Deposition Modeling methods produce less waste compare to traditional Computer numerical control (CNC) milling machine. (Faludi et al., 2015) The overall environmental impact of each machine and method is depending on the settings and percent usage of each.

Better production capacity through open networks: As most machines could share the same characteristics and setting given that they have the same settings and materials and the original blue print for production. This mean that the factory from across the country or near by in the vicinity can produce the same product at the same time, double the capacity produced. This could be benefitted for existing manufacturers that have invested in additive manufacturing, who would be able to satisfy others nearby manufacturers' demand. These companies will accumulate competence advantages, and profited from economies of scope for using the same raw material. (TNO, 2014) (Sasson, A., Johnson, J.C., 2016)

Manufacturing outsourcing: as previously discussed above, instead of having own 3D printers and let the machine stay in idle state of low capacity, companies could outsources the entire logistics to others producer with excess capacity or even advanced logistics service providers. Demand consolidation is a promising tool for logistics service providers in terms of supporting the multiple manufacturers by combining generic additive manufacturing and conventional logistics (ManRM, 2005) (Holmström, J., Partanen, J., 2014) The consolidation of demand from a number of clients enables these logistics service providers to invest in an additive manufacturing strategy that is less uncertain than traditional producers. These upgraded logistics providers can bring maintenance locations closer to consumers and provide emergency services in a timely manner. (Holmström, J., Partanen, J., 2014) Using 3D printing also enables commoditization of manufacturing infrastructure. With the possession of additive manufacturing infrastructures and equipment, incase of demand for manufacturing center A go over its printing capacity, orders could be redirected to another center nearby as long as the additional distribution costs from center B are lower than customer queuing costs thus cut time as well as transportation cost and emissions. (Sasson, A., Johnson, J.C., 2016) (Holmström et al., 2010)

Direct Digital Manufacturing: According to McKinsey report (2013), even until 2025, traditional manufacturing methods would still have a large cost advantage over additive manufacturing for most high-volume commonly used and stocked products. However, Additive manufacturing has already become an increasingly common approach for low-volume, complex and customizable components and complete products, starting with molding and tooling and could later on expand to medical implants and engine components. It is estimated that 30 to 50 percent of these products could be manufactured directly and digitally. (McKinsey, 2013) Customization is not always available and in case of there is access to certain degree of customization, options are often limited and cost for customization is often too high that inhibit demands and product development. Direct digital manufacturing enables small batch manufacturing of customized products and parts.

4.2.2 Source: Procurement and Outsourcing

Lowered supply risks due to abundant availability of material: Traditional manufacturing normally requires combination of a number of parts or semi-finished products and raw materials. With 3D printing, hypothetically, a product can be made out from a single type of raw material or a mixture of multiple types, all can be made within the same site, even on the same machine eliminates the need for purchasing expensive sub-assemblies and components and runs into severe shortage if there’s an error in planning. Basic materials for additive manufacturing so far has been developed to include plastics, nylons, metals, and even clay, porcelain and silicone. This combination promised to be broadened soon as the rate of development for 3D printing is still constantly rising. These materials are readily available thus could decrease supply risks as there would be suppliers available for these materials, no matter where. (TNO, 2014) This enables simplicity of the supply chain as well as reducing the need for a complex network of suppliers, improving production efficiency and reducing wastage for inventory as well as transportation.

Source and manufacture at or near the home market: traditionally and currently, production is put offshore, to lower cost countries to take advantage of low cost labourers and material to compensate for the transportation and handling costs as well as providing foundation to enter the market. This is the case for production of relatively simple products or small components using cheap manual worker. Yet, 3D printing is a highly computerized and standardized process, thus doesn't need a high proportion of low-skilled workers in the overall production process. This results in production centre being relocated to local manufacturers that are equipped with additive manufacturing capability in close proximity to home markets of high-wage, developed countries of Europe and the U.S., shortening the length and complexity of the supply chain, improving the launch time to market and reducing the tremendous amount of movements of goods. (TNO, 2014) It is estimated that with the current rate of development, half of the goods will be printed in 40 years, according to a report by ING (2017). It is also notable that estimated 25% of world trade would be wiped out by 2060, most affected are manufacturer of the automotive industry (White, E. 2017)

4.2.3 Deliver: Sales and Distribution

Customized and tailor-made products: putting the consumer at the driver seat. Consumer will be the one who decided what would be made, how it’s made, how it’s delivered. Customers can modify to the products and choose who will manufacture and deliver to them themselves. This additional experience could be available with a premium price but compare to the traditional manufacturing procedures, 3D printing integrated manufacturing chain would be much simpler and cost for customization would also be a less significant factor that prevent consumer experiences (TNO, 2014) This could ensure lower product return and minimize impact of the reverse logistics on the environment when the defective products have to be collected and processed as well as distributing new replacement products.

Lower supply chain complexity: perhaps the most disruptive impact that additive manufacturing has on the supply chain is drastically simplifying the supply chain complexity.
3D printing has a high potential to to significantly decrease the complexity of existing supply chain networks. The traditional supply chain often involve several parties, each plays a role in the long logistics process. One complete product is built up from several components; each could come from a different supplier, along with that is a different

logistics provider. Distributing the finished product may as well involve many parties, from distributing partners (wholesalers, retailers) to logistics provider as well as managing the storage facility. By implementing 3D printing, no matter in which logistics process AM was implemented, a large part of the logistics has already happened virtually. The most optimized scenarios for supply chain would be companies could directly source materials, receiving orders and produce every components in-house at the facility closest to the customer, and have it shipped directly to the end user. By cutting out the middlemen and the long await processes along the way, such significantly shorter supply chain may incur lower transactions costs, lower logistics costs and time and environmental impact as most of the logistics have already happened online. (TNO, 2014) (DHL, 2014)

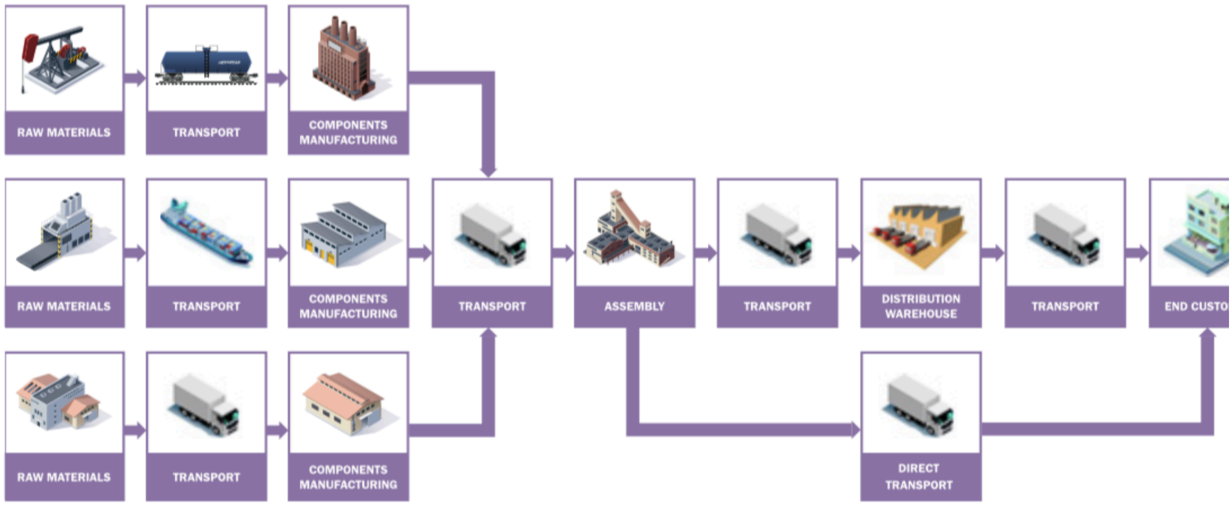

Figure 9: Simplified traditional supply chain network structure (TNO, 2014)

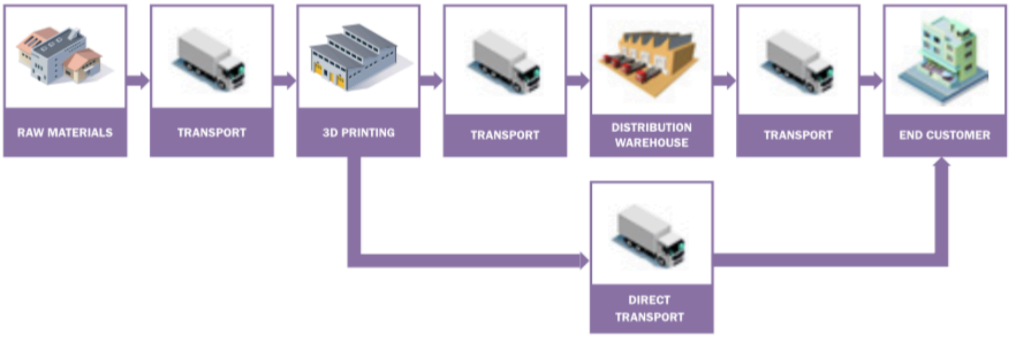

Figure 10: Supply chain network structure with 3-D printing competence (TNO, 2014)

It is clear from the two figures 9 and 10 comparing supply chain of traditional manufacturing method and 3D printing integrated that there will be less transportation between each process of the supply chain as there are processes that are no longer existed. And the movement of goods between remaining processes is likely to be only one way, as efficiency in manufacturing would be improved. On-demand manufacturing is going to be advantageous, especially from an environmental perspective. Waiting for a delivery is unnecessary if it can be printed onsite. (Hardcastle, 2015)

4.2.4 Return: Reverse logistics and aftersales

Improved order fulfillment and reduced returns: Usually lead-time for customizable or highly complex products are relatively long; the waits for a products from the moment the demand was generated to the time when it was satisfied. Orders are initiated and made according to the customer’s demand to reduce the need for inventory and warehousing as well as improve customer satisfactory and reduce return but this also mean that order fulfillment takes longer than for usual made-to-stock products. For products in this category, numerous adjustments need to be made and the manufacturer who has the expertise to execute such large degree of customization is often not located nearby. Customization was shown to have significant negative environmental effects, for example, manufacturer of individualized shoes the individual shipment of products from the production site in China to the customers in Europe makes up a substantial amount of the overall carbon emissions of this individualized and custom-made business model (Kleer & Steiner, 2013). However, this study also showed that mass customization is best suited with the setting of localized production, the environment effect of individualized production is strongly diminished. (Pourabdollahian G., Steiner F. 2014) This advantage was made available by the implementation of 3D printing in the supply chain by bringing production back to local, result in lower energy consumption and less emissions from the distribution.

Decentralized production of spare parts: The service parts industry is among the area that will be most affected as estimated. Logistics costs, inventory holding, stock out and material handling would be reduced by scheduling and consolidating parts when demand and order for parts are received (Ruffo *et al.*, 2007). Manufacturing postponement in this after sales sectors would result is a reduction in inventory management cost throughout the supply chain as well as reduction of risks from fluctuation of demand. These effects would to encourage manufacturing postponement, especially for rare spare parts that has unclear demand and might run into either state of obsolete and or unpredicted shortage or high shortage cost. (Holmström, J., Partanen, J 2014)

With convention manufacturing and distributing method, firms usually need to keep a limited amount of stock for spare parts at a central warehouse that is distant to most customers, because keeping and managing inventory for spare parts at multiple decentralized location is more expensive than having customer demand met in a timely manner. Given the right manufacturing instrument and material, even the customer can become the manufacturer, completely cut the waiting time from ordering to delivery and receiving of the products. Globalization has made it easier to make a purchase from across the globe, and 3D printing now made it even easier and faster to receive after sale service directly and completely virtually. Because the product design could be shared via the Internet easily nowadays, spare parts fulfillment cost will go down in spite of currently higher cost to produce using 3D printers. The lower cost and environmental effect would also be positively affected by the fact that expensive warehouse management cost for redundant or low demand spare parts will not be necessary anymore. (TNO, 2014)

5 Additive Manufacturing: an optimal solution for the spare parts supply chain – An environmental perspective

5.1 The spare part supply chain

Supply chain management is integration of the whole business processes and supply chain participants to satisfy the end consumer. The spare parts market, or aftermarket supply chain, on the contrary, provides after sales services of the product and differ greatly from the supply chain of regular products (Aminimoghadamfarooj, N., Shcherbakova, M., 2010) Recently, the spare parts industry and predominantly the need for service parts management and aftermarket logistics innovations have began to gain more consideration as customers has been more conscious and taking consideration of the aftersales services when making buying decision. The maintenance services and especially quick problem-solving response play a significant role and add exceptional value to the product, increase trust and improve loyalty towards the product and service provider.

Greening the supply chain also means that firms has to take actions in the aftersales market to help minimize the environmental impact it create from the supply chain of this market. It is very likely that the area where the environmental footprint could be cut is transportation. In the most countries and area, transportation accounts for a significant amount of emission, plays as a major source of pollution. In developed countries, where emission has been cut drastically by moving manufacturing to other lower cost countries, transportation of those goods back to the countries is still a huge source of pollutions that is become harder to cut back, especially in the era of globalization. In Europe, transportations accounts for 23 percent of green house gas (GHG) emission (Eurostat, 2017) while in the U.S. the figure was 27 percent in 2015 (United States Environmental Protection Agency, 2017)

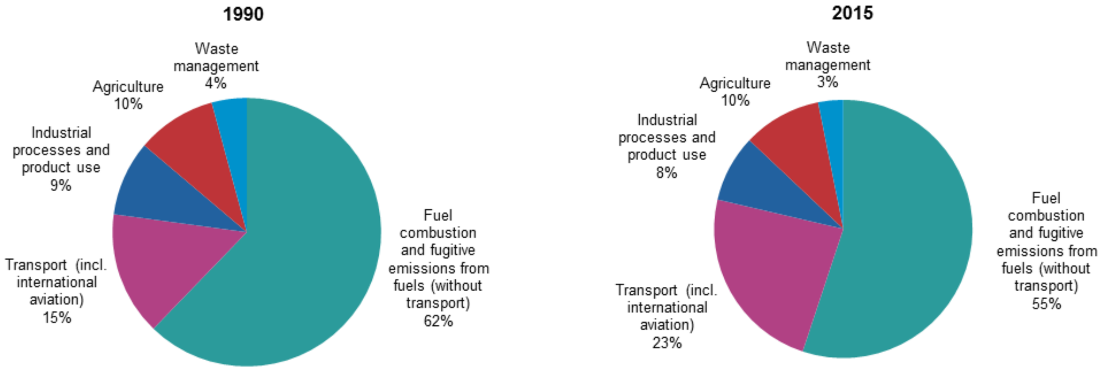

Figure 11: Greenhouse gas emissions, by source sector, EU-28, 1990 and 2015 (percentage of total) (Eurostat, 2017)

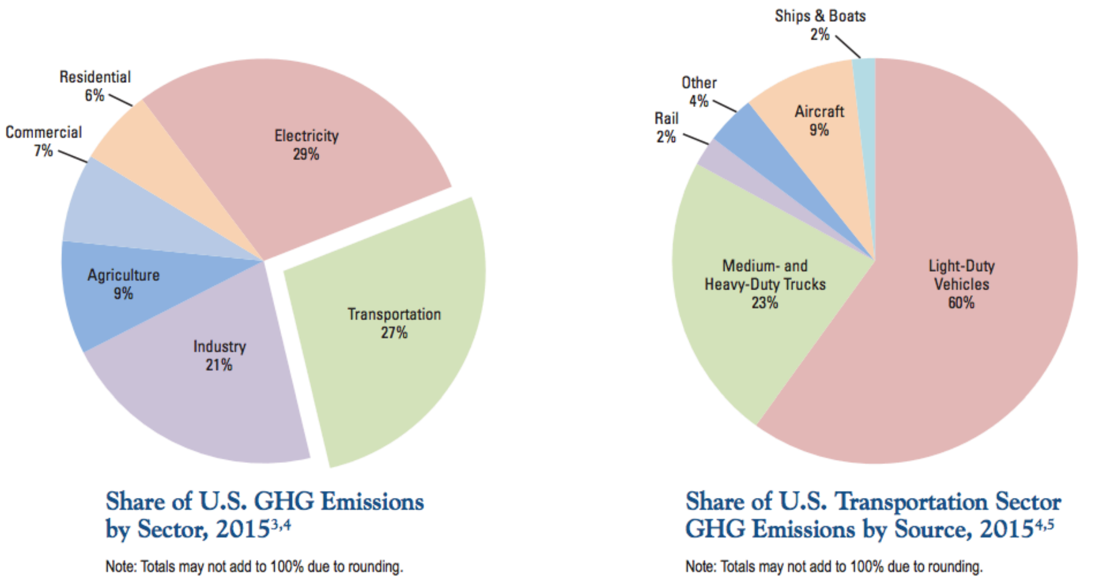

Figure 12: U.S. GHG Emissions by Sector (2015) and U.S. Transportation Sector GHG Emissions by Source (2015) (United States Environmental Protection Agency, 2017)

Reducing transportation does not only mean cutting emission from the activity of moving goods from place to place but also reducing cost and labor and other management activities. In the aftermarket industry, though transportation is not only the responsible factors, it is one of the major causes of pollution in inbound, outbound and as well as reverse logistics.

5.2 Opportunities and challenges for an environmental friendly spare parts supply chain

Manufacturing, material planning and warehousing could also be considered to be area where “greening” is highly possible. And with the wide-stretched application of 3D printing, if applied extensively throughout the supply chain, the technology could potentially bring significant impact not only on cost saving and improve efficiency and productivity but also reducing environmental impact. Companies often neglect services parts supply chains because they’re more difficult to manage than regular supply chain (Cohen et al, 2006). Table 1 compares the difference between the two supply chains

Table 1: Manufacturing and aftersales services supply chains compared (Cohen, 2006)

Parameter	**Manufacturing Supply Chain**	**Aftersales Service Supply Chain**
Nature of demand	Predictable	Unpredictable
Required response	Scheduled	ASAP (Same day or next day)
Stock Units	Limited	Up to 20 times more
Product portfolio	Homogeneous	Heterogeneous
Delivery network	Depend on nature of product, multiple networks necessary	Single network, capable of delivering different service products
Reverse logistics	Doesn't handle	Handles returns, repair, disposal, failed components
Performance metric	Fill rate	Uptime (availability)
Inventory management aim	Maximize velocity of resources	Pre-position resources
Inventory turns	6 to 50 a year	1 to 4 a year

The flexibility-enabled 3D printing integrated supply chain suits the best for the Aftersales service supply chain that traditional supply chain struggle to satisfy. As demand for spare parts are unpredictable, it is costly not only for companies to keep in stock product that might be obsolete but also the environment take a toll for the energy needed for warehousing. Additive manufacturing is also responsive to demands in a rapid way, able to manufacture the needed parts immediately after the order has been made. Product portfolio are heterogeneous and distribution network is simple and could be close to the customer as 3D printers can manufacture almost every parts needed in the same factory. Assembly for replacement product could also be less necessary because 3D printers are capable of producing monolithic product that required very little or not at all assembling, given that the model was designed specifically for 3D printing.

According to Cohen (2006) though the spare parts sector is a profitable area, companies often find it challenging to decide which resources to deploy and where to deploy them because both parts and locations are hierarchical. The hierarchy for products can be determined by its the level of complexity, with the lowest ranking are simple and low cost parts, while the higher ranking are more completed parts and modules. Replacing a module is faster and more expensive than replacing a simple parts. Geographical hierarchy ranks the distance of the distributing location to customers; with the higher rank are the most central distribution centers. The further inventory is from consumers, the lower their costs will be and the slower firms' responses (Cohen et al, 2006)

5.3 Spare parts supply chain: Decentralized or Centralized as optimal sustainability strategy

Responding to the question of suitable distribution strategy is suitable for the spare parts market of Cohen (2006), Holmström et al. (2009) proposed two alternative deployment strategies of rapid manufacturing in the spare parts supply chain: Centralized rapid manufacturing to replace inventory holding or distributed rapid manufacturing to replace inventory holding and conventional distribution.

- Centralization not only lessens the need to keep safety stocks but also increases inventory turnover, in return, response time are longer and, and does not significantly eliminate the need to keep stock of low demand parts. A combination of centralized warehousing and centralized rapid manufacturing is recommended if the number of parts suitable for rapid manufacturing is not too high. This deployment strategy would reduce logistics costs and volume of low demand parts, as well as the need to back the high inventory costs of seemingly obsolete parts with revenues from faster moving parts. (Holmström et al., 2009) Thus reduce in environmental cost of inventory and warehouse management.

- Rapid manufacturing combined with decentralized distribution eliminates inventory holding and transportation costs, as well as theoretically reduces the delivery time, given the right batch size. Distribution of products is now heavily relied on the physical delivery of required raw materials, which could be easily sourced locally. The rest of the distribution was done virtually with computerized model. For parts with high risks and cost for shortage, distributed rapid manufacturing can significantly shorten the response time. Capacity maximization is the critical key for implementing decentralized rapid manufacturing. Even as rapid manufacturing capacity becomes less costly, demand in every manufacturing location needs to be high enough to meet the breakeven point and balance out the investment of a 3D printing machine.

Considering the trade-offs involved with both approaches, Holmström (2009) concludes that on demand and centralized production of spare parts is the more probable approach that surpass distributed manufacturing though the line is not clearly drawn. Decentralized distributed rapid manufacturing could succeed if 3D printing becomes more affordable and developed into a general-purpose strategy. Local manufacturers or even logistics service providers could produce spare parts on demand and close to the point of use. (Holmström et al., 2009)

There were also researches attempt to draw the line between decentralization and centralization distribution strategy. Each strategy has its own advantages and trade-offs that companies have to consider so that it would align with their business model. Centralization reduced cost but compromised by a higher environmental impact. Meanwhile decentralization of supply chain could potentially reduce the impact of transportation of the environment poses a higher capital cost if not optimized.

> Great economies of scale tend to promote a highly centralized system of facilities. High need for transportation can decentralize either facilities or certain operations. When less product recovery is needed, centralization is optimal; the opposite is true for high product recovery rates where more transport is needed. (Clarke-Sather, A.R., 2009)

Rauch et al. (2015) discussed how Distributed Manufacturing Systems are suitable trends that companies need to adopt for more sustainable manufacturing. Centralization used to be the norm as economies of scale has been always perceived as the most profitable and suitable strategy. However, nowadays companies are facing pressure to switch to a more sustainable supply chain. The author promotes the idea of a smaller, more flexible and scalable manufacturing units, which could potentially double up as distribution center, to fulfill requirements for just in time delivery of and individual customer needs.

Sustainability is an optimization strategy that target overall efficiency of enterprises, products and processes. The three dimensions or triple bottom line that made up sustainability manufacturing are: economy, ecology and socials. Rauch (2014) also proposed another dimension that is Institutional, where politics could play a major role in improving sustainability in manufacturing and distribution.

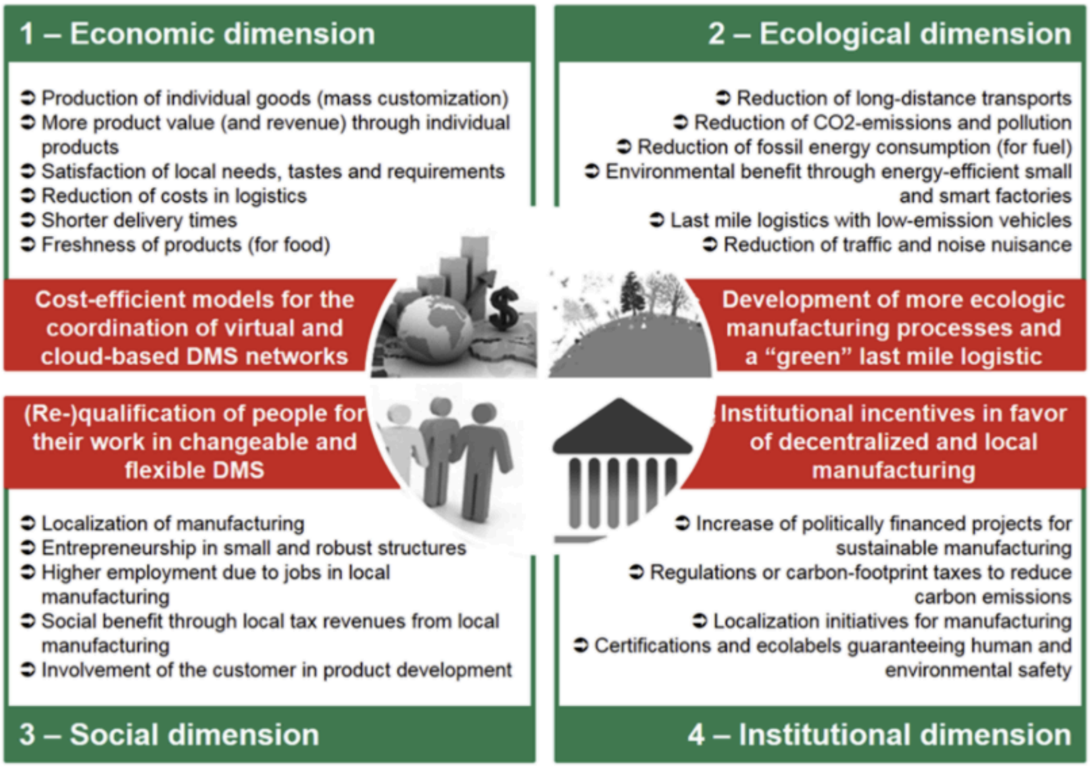

Figure 13: Sustainability in manufacturing through distributed manufacturing and related challenge in the future (Rauch et al., 2016)

Spare parts manufacturing and distributing are in many sense very similar to personalized customized products. These product categories follow a pull system rather than push system like common products. Under highly diverse product demand, a study by Mourtzis et al. (2013) investigate on the optimal configuration of the supply chain, to find out the ideal degree of centralization of the production network while taking into consideration criteria of energy requirements, consumption of natural resources and toxic emission. The study confirmed that the higher the level of customization of a product, the greater the carbon dioxide emitted and higher energy required for its production and transportation (transportation is also accounted for energy consumption) (Mourtzis et al., 2013) However, compared to the centralized strategy, decentralized network configuration exhibited reduced in overall emissions and energy consumption values, for the production and transportation of the same product variant. This configuration could vary depending on the product under investigation. In the case where the assemble could be perform at any distribution center instead of only at original equipment manufacturer's plant, environmental impact are greatly reduce thanks to the decreased transportation distance (Mourtzis et al., 2013)

The only constraint for this deployment strategy to success is the lack of expertise at the final distribution/manufacturing point. This could make businesses hesitate to invest in 3D printing machine and this slow rate of adoption is one of the reason why 3D printed parts are still costly and less accessible to most.

There are still skepticisms around the overall environmental impact of adopting 3D printing, as the technology is still in its development stage. Depending on the batch size, energy consumption for 3D printing per piece is higher than traditional manufacturing methods because it lacks the economies of scale. The process of heating material of FDM or SLS could also produce toxic emissions. The greatest environmental impact rely heavily on the behavior of manufacturer and the now empowered-consumer. Convenience, simplicity and especially is becoming more affordable, could tempt businesses and consumers to overuse and be more wasteful. (Bordoff, 2016)

But from the supply chain management viewpoint, especially in the spare parts industry, 3D printing could bring a total supply chain cost savings of 90 percent for the automotive aftersales market (Bhasin, V., & Bodla, M.R., 2014) This is achieved by eliminating all inventory holding cost and a big reduction in transportation cost because most of the stocks are now stored in digital form and in raw material with high flexibility in production capability. Aviation industry is also a sector that implementing 3D printing for spare parts fulfillment yield positive environmental impacts. Study has shown that in three different approaches: conventional supply chain, centralized supply chain with of 3D printing, and decentralized supply chain with 3D printing, the two approaches that use additive manufacturing yield significantly less carbon emission (Li et al., 2016) The study conclude that with adoption of 3D printing, in both centralized and decentralized option, total carbon emission is significantly lower compare to traditional supply chain. This is largely due to the fact that the complexity of the supply chain was reduced resulting in less transportation needed. Though energy consumption and emission for manufacturing process itself yield 4 times more impacts but this effect is still lower compare to the huge reduction in material and transportation emission (Li et al., 2016)

In the case of spare parts supply chain, it is clearly that additive manufacturing will have a sustainable advantage for companies. The optimal solution for distribution of service parts is when 3D printing is implemented on a decentralized supply chain, as reduction in transportation would result in decrease in the total carbon emissions from a supply chain perspective. However, when taken into consideration the fixed costs such as the purchasing cost of 3D printing equipment, these costs could offset the environmental effect of AM to become less cost effective than the conventional one (Li et al., 2016). It is recommended that businesses should weigh in both environmental and economic benefits when decided to invest in AM. While executives might still be hesitant to adopt 3D printing, survey by Strategy& shows that the earlier companies invest in 3D printing of spare parts the greater sustainable competitive advantage they may gain (Geissbauer et al., 2017)

> 3D printing will not transform the spare parts business immediately. But companies that don't begin investing in the capabilities and technologies needed, including in the supply chain, will find it difficult to catch up with first-moving competitors in the future (Geissbauer et al., 2017)

6 Summary and Conclusion

It is clearly that the introduction of 3D printing in the supply chain, no matter at any process would have a positive impact on the companies overall supply chain practices. Reducing complexity, improving responding time, eliminate obsolete inventory, improving inventory turnover rate, as especially bringing manufacturing closer to the customer, which would certainly reduce the need for transportation or costly emergency delivery. As most of the transportation happens virtually, distance would be shortened, this reduction would result in a less need for transportation, for both raw material and finished product, thus result in less emission by transportation created.

Current additive manufacturing has not yet matured and still promise to become more efficient in the future, in terms of energy consumption, manufacturing time, utilization value, and especially procurement cost. These improvements would promise a wider adoption of the technology both from businesses and consumers. In the upcoming near future, the spare parts industry is the area where 3D printing could thrive the most. The introduction of digital rapid manufacturing should result in hybrid solutions of a both 3D printing integrated supply chain and traditional supply chain. 3D printing based service part supply chain scored better than conventional supply chain in terms of total environmental costs for being able to simplify and shortened transportation network.

Being an active and responsible player in the industry, Logistics service providers should be proactive in finding suitable strategy that integrate additive manufacturing, as the introduction of 3D printers could be seen as a threat to the role of traditional logistics partners. Adopting new roles, for example, not only being the “transporter” but also LSPs can also take the role of the “maker” by having the distribution facility equipped with 3D printers, and double themselves as manufacturers. LSPs already have the advantage of the extensive distribution system, both in facility, instruments and partner networks. Taking the role of the manufacturer now only require the investment in the equipment and technological know-how, which would be a competitive advantage for early adopter. 3D printing integrated supply chain also proven to be the sustainable solution for both business and service provider, in all four dimensions of sustainable development.

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