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THE IMPACT OF 3D PRINTING TECHNOLOGY ON SUPPLY CHAINS

Carolina Pereira Lourenço, 3799

A Project carried out on the Master in Management Program, under the supervision of:

Professor José Crespo de Carvalho

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Disclaimer

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Abstract

3D Printing, also known as Additive Manufacturing has the potential to be one of the most disruptive technologies to impact global Supply Chains. In some sectors, the technology boosts some aspects of the production process, while for others it may replace the traditional manufacturing methods. This work project explores 3D Printing technology, its pros, and cons presents some real cases and identifies possible impacts of the technology in Supply Chains.

KEYWORDS:

3D Printing, Additive Manufacturing, Supply Chain Management, Impact

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List of Abbreviations & Glossary

3D - Three Dimensional

3DP - Three-Dimensional Printing

AM – Additive Manufacturing

ASTM defines Additive Manufacturing as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Standard Terminology for Additive Manufacturing Technologies, ASTM F2792-10, 2010)

c3Dp – 3D Printing for Construction

CAD - Computer Aided Design

CAM – Computer-Aided Manufacturing

CAGR – Compound Annual Growth Rate

CLIP – Continuous Liquid Interface Production

CSCMP - Council of Supply Chain Management Professionals

DPL – Digital Light Processing

FC - Fixed Costs

IDC – International Data Corporation

ISIS - Islamic State of Iraq and Syria

Push Principle - Describe how goods/ services are delivered to the market

Push aims that taking the product directly to the consumer.

Pull Principle - Describe how goods/ services are delivered to the market

Pull aims at motivating customers to seek for a specific good/ service.

SCM – Supply Chain Management

SCRC – Supply Chain Resource Cooperative

SLA - Stereolithography Fabrication System

SLS – Selective Laser Sintering

TPU – Thermoplastic Filament

UV - Ultraviolet

VC – Variable Costs

WIP – Work-in-Progress

Introduction

The Fourth Industrial Revolution, or Industry 4.0. (Marr, 2018) has been rapidly changing the way people create, exchange and distribute value by introducing technology breakthroughs across different fields - artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3DP, nanotechnology, biotechnology, materials science, energy storage, and quantum computing (Schwab, 2018). According to the Klaus Schwab (2018), this revolution was built on the digital technologies that result from the Third Industrial Revolution - Digital Revolution. Although, it is not an extension of it. The velocity, the scope, and the system's impact have no historical precedent (World Economic Forum, 2016). It imposes a systematic change along different sectors and aspects of people life. Also, as a result, all of this creates a societal transformation on a global scale.

Industry 4.0. has been reinventing how goods are produced and distributed challenging Traditional Manufacturing methods. The full potential of Digital Manufacturing methods such as 3DP was realised, meaning that “the digital” is now becoming “the physical” with just a touch of a button (DevicePlus, 2017). Digital design files are transferred to any part of the world to manufacture products. Before going to production, the data can be adjusted to fit local and personal needs of each population. For the first time in history, a manufacturing process enables mass personalisation (DevicePlus, 2017), introducing a new paradigm for manufacturing which has an economic, demographic, environment, security and geopolitical implications (Campbell et al., 2011).

Additive Manufacturing is the best definition to describe the technology that creates 3D objects by adding successive layers of material based on the information from a digital model (Dehue, 2016). By contrasting with Traditional “Subtractive” manufacturing processes which create objects by eliminating material from a workpiece, it creates a sense of the game-changing impact in logistics. (Campbell et al., 2011). It is expected to have a powerful effect when combined with efficient manufacturing processes revolutionising the principles established in previous Industrial Revolution (Manners-Bell, 2012). Initially, 3DP was created for rapid prototyping. Nowadays, it evolved and had been used for things we once only dreamed of (Forbes Technology Council, 2018). According to Sculpteo's report (2018) - The state of 3DP- Prototyping (55%), Production (43%) and Proof of Concept models (41%) are the most common 3D printing applications in 2018 with R&D departments being the most active adopters. In the future, technological advancements will lead to a supply-side miracle, with long-term benefits in productivity and efficiency. It brings flexibility and customisation to manufacturing enhancing decentralisation of production with smaller factories in different parts of the world. It is expected the costs of transportation and communication to decrease, and logistics and global supply chains to become more agile and effective. All in all, it will create new markets and boost economic growth (Schwab, 2016).

Research Question and Methodology

In this section are described the methods followed to explore the research problem and objectives, presenting how the data was collected and analysed.

Research Problem	How can 3DP technology impact while being innovative in Supply Chains?
Research Objective	To understand what 3DP technology is To find out what specifications of the technology create value in Supply Chain To find the main advantages and disadvantages of 3DP technology

To approach the problem, an analytical model was developed, taking into consideration the background presented in the introduction section.

Analytical Model	*The impact of 3DP technology is going to depend on the easiness of usage, its added value in the supply chain, the variety of materials that can be used to print, and companies' level of acceptance.*

Based on the research problem, research questions and sub-questions (**Appendix D.1**) were designed to further understanding of factors that can affect the relevance of 3DP in Supply Chain.

Research Questions	What is the 3DP technology and where to apply it? What are the applications of the 3DP technology in Supply Chains and major pros and cons?

The research design was formulated and comprises an Exploratory Research followed by a Conclusive Research. The Exploratory Research – Qualitative Research – aiming at getting insights and understanding about the technology – what 3DP is, where it can be applied, its pro and cons, its evolution along the years and how it can impact supply chain – from Primary and Secondary Data. The secondary data was collected from a literature review including information from books, articles and other external sources relevant to the topic. Based on the problem formulation, the consistent findings were found out – literature search – and then evaluated to determine which literature has a significant contribution to this paper based on the research problem and objectives – Data Evaluation. It enriched the approach and allowed for a more insightful interpretation. The primary data was collected directly through depth-interviews with five experts (**Appendix A**). The Conclusive Research – Quantitative Research – enriched the approach and allowed for a more insightful interpretation. A survey was conducted to get statistical evidence from variables found in exploratory research about the topic. An itemised rating scale - non-comparative scale techniques - was used and respondents were provided with a scale that has a short description associated with the category. The categories were ordered in terms of scale position, and individuals selected the category that fits better the topic being evaluated. The type of itemised rating used was a Likert Scale which requires the respondents to reveal the degree of agreement or disagreement with each statement. It was conducted online, using social channels.

All the relevant information collected during the research process is explored, analysed, and presented along this work project divided into **three different sections**: **General context and applications of 3D Printing Technology**, **Supply Chain context and application of 3D Printing Technology**, and **Primary Data Results**. The **Conclusion section** sums up the main insights.

General context and applications of 3D Printing Technology

Literature Review of the technology

In the history of manufacturing, traditional manufacturing processes were subtractive. Although, AM processes were not new (Bensoussan, 2016). First 3DP attempts were developed in the 1980s by Dr Hideo Kodama who experiment the usage of a layer by layer approach, in 1980, creating an antecedent for SLA - a photosensitive resin was polymerised by a UV light. However, the first patent for SLA was filed by Charles Hull, who first invented his SLA machine in 1983 (Jackson, 2017). The process was described as a system for generating 3D objects by creating a cross-sectional pattern of the object to be formed (Freedman, 2012). Today, the technology advanced considerably - new design software, new printing methods, new materials - enabling the production of diverse products composed by multiple thin layers of material following instructions from a digital file (Dehue, 2016).

The starting point for any 3DP process is the creation of the 3D Model Digital File (Petch, 2017) using CAD software or a 3D object scanner that creates the 3D model object. Then, the CAD is converted to an STL file to tessellate the 3D Model and to slice it into cross-sectional layers. This file is transferred to the AM machine using a custom machine software, and the consumables and printing parameters are adjusted before the process begins. When the object starts printing, several layers are laid down successively to create the product. At the end of the process, the object is removed from the build platform and its support structure. To finishing the process, a cleaning, polishing, and painting might be required to be used or delivered (Redwood, 2018).

3D objects can be printed using different materials- plastics, resins, metals, textiles, biomaterials, concrete or even food - that are supplied in different states - powder, filament, pellets, granules, resin (Jackson, 2017). Because, generally, materials are developed for specific processes and machines (Petch, 2017), the material chosen specifies the 3DP methods to use (Sculpteo, 2018). **Table 1** describes the most common methods and materials.

Table 1: 3D Printing Methods and Materials

<table>
<tr><th>Technology</th><th>Materials</th><th>Description</th></tr>
<tr><td>Fused Deposition Modelling</td><td>Plastic
Aluminium</td><td>It uses melted and extruded material through a heated nozzle to form layers which move according to the features created in the CAM software package to build the desired shape.</td></tr>
<tr><td>Selective Laser Sintering</td><td>Aluminium</td><td rowspan="2">It uses a high-power laser to melt small particles of powdered material to form successive layers, and then the designed shape for the 3D object. The difference between these two methods is the material used to print the 3D object.</td></tr>
<tr><td>Direct Metal Laser Sintering</td><td>Ceramic
Plastic
Glass</td></tr>
</table>

Electron Beam Melting	Metal	It uses an electron beam as a power source which liquifies powder layer by layer within a high vacuum and can achieve full melting of the metal powder.
Stereolithography	Resin	SLA uses a vat of curable photopolymer resin, and a UV laser to build the object's layers. The laser beam traces a pattern on the surface of the liquid resin as the build plate moves in small increments and the vat is exposed to the UV laser. Then, the light cures and solidifies the pattern created on the resin and joins it to the previous layer. To finish the process, the 3D object is cleaned with a solvent solution and put inside a UV oven. This method addresses a wider range of applications.
Digital Light Processing	Resin	DLP is like SLA. The main difference is the light source. DLP uses safelight - light bulb – to cure and solidify patterns.
Continuous Liquid Interface Production	Resin	CLIP uses a digital light projector to project a constant sequence of UV images – a precise cross-section of the object – to a photosensitive curable resin. The light causes the resin to solidify with a specific shape as the fabricated object is moved up in the resin bath.
Multijet et Polyjet	Resin Multicolour	It works similarly as a traditional inkjet paper works. The material is drooped through a small nozzle guided by instructions of the design file and applied layer by layer to a build platform creating the 3D object.
Binder Jetting	Multicolour	It uses two materials powder base material and a liquid binder. An automated roller spreads a layer of powder along the build platform, and then the liquid and the colour are applied to cement the particles according to the shaped designed. In the end, the binder glues all the cross-sections of the object.
Selective Deposition Lamination	Multicolour Paper Metal	It uses sheets of different materials which are glued together via a heated roller, and the shape is created with a laser cutter layer by layer.

Source: Own Table based on https://www.sculpteo.com/en/3d-printing/3d-printing-technologies/

Applications

Healthcare Sector – 3DP Prosthetics

Formlabs company has been using professional-grade desktop 3DP to develop prosthetics. 3DP methods – SLA, SLS, and Material Jetting - enable parts to be printed with a high level of detail and in full colour using sterilizable materials, and to print durable and complex items (Redwood, 2018). Because, a prosthetic piece is unique, produced exclusively for the user, and must fit his needs, 3DP is an ideal solution. Items are customised and tailored to patient's anatomy by using a software – computerised tomography, magnetic resonance, and laser scanning - that reproduces the patient's scans into 3D digital files that incorporate information from each patient's specific anatomic or pathologic features. In addition, 3DP methods allow the production of an exact replication of the 3D digital file - for 3DP manufacturing complexity is free (Lipson & Kurman, 2013). *Formlabs* has been pushing the medicine forward and developing applications and designs which were not possible before like facial bones (**Appendix C.1**). This shift from traditional manufacturing processes to AM decreased the number of replacements and or modifications on prosthetics pieces, saving time from the Lab to the operation room. Hence, the costs decreased as the effectiveness of the production process increased (Redwood, 2018).

Education Sector – Students as Co-Creators

3DP technology has been introduced into the classrooms, allowing students to materialise their ideas or projects in a fast and innovative way (Lipson & Kurman, 2013). For Primary and High School's students, 3DP empowers students as creators. As an alternative to consuming others' creations, they can identify the problem and build a better solution that fits better their needs. It contributes to their cognitive development and enhances their creativity, as they become designers and use the technology to visualise and create their ideas. Furthermore, it engages and motivates students who would otherwise have nothing to do with their learning (McConnell, 2018). According to the feedback from Ms Robin McGinnis, a teacher at an elementary school in Ohio, *"This has been a wonderful new way to teach and motivate my students. (…) The overall enthusiasm towards school and learning has increased tremendously. Students who are typically reluctant learners have come to life*.". Also, university students have available educational courses such as CAD and 3D design, which can be applied to 3DP. 3DP knowledge means: Biology students can study cross-sections of organs; or Engineering, Design and Architecture students can print out prototypes/models of their creations, among other applications and benefits. To introduce 3DP in schools and make it available to students, there are specific programs like Create Education Project that enables the integration of AM technologies for lower costs (Haria, 2018). As a counterpart, teachers, and students share their experiences with the techniques, allowing 3D companies to illustrate how education benefits from 3DP.

Cultural Sector – Art and Patrimony Preservation

In addition to education and healthcare industry, 3DP is used for museums and archaeology in cultural preservation by providing valuable tools to capture ancient objects, artefacts, and art pieces, and allowing detailed replicas of historical items (Arrighi, 2018). AM methods are very innovative and bring three benefits to this sector. First, museums can preserve the original parts of rare or fragile objects and give more access to the public to get closer to the museums' collection without risk of loss. It improves the visitors' experience who can touch and analyse specific art pieces but, specifically, it also revolutionises the world of people with visual impairment. 3DP can be used to print physical representations of painting, allowing to touch these representations and to have a unique experience (**Appendix C.2**). Second, 3DP is used to repair damaged historical pieces. Along the last years, several art pieces have been devastated by ISIS, in the city of Palmyra. To restore those pieces, restoration specialists have been using AM methods side-by-side with 3D Scanning (Gaget, 2018). These two technologies recreate and design perfectly fitted new parts to replace the missing ones. It highlights the importance of scanning the real pieces and saving it in 3D files. If there is a tragedy, like the fire in National Museum of Brazil, in September 2018, which destroyed all the patrimony, it is possible to access to 3D models of the real object, to replicate or get detailed information about it. Finally, 3DP allow researchers to work on the 3D printed replica and to manipulate it without risk of damaging (Arrighi, 2018). The 3D model files provide a considerable advantage to researchers who can share data more efficiently and conveniently instead of shipping fragile and rare artefacts or archaeological pieces.

3D Printing Pros and Cons

3DP is a promising technology, but like any other technology, it has Pros and Cons (**Table 2**).

Table 2: 3DP Pros and Cons

Pros of 3D Printing	Cons of 3D Printing
Customisation Freedom • No additional cost to produce a different object each time. • Remove the costs associated with re-training employees or re-tooling plant machines. **Complexity Freedom** • Create 3D objects that cannot be produced using traditional manufacturing techniques.	**Material Limitations** • Need for high-quality materials to use in 3DP. • Use proprietary polymers which are not well characterised, and are weaker than the traditionally manufactured ones. **Counterfeiting** • Infringe intellectual and property rights.

Risk Mitigation • Allow a proper verification of the product prototype. **Environmental Benefits** • Reduce carbon footprint and the waste from the production process **Precise Physical Replication**	• By using an electronic schematic of the product, someone can access a 3D CAD file which replicates a third-party design and can be printed using a 3D printer. **National Security Risks** • Produce any possible sort of product including drugs, guns, knives, and other harmful objects • Enable terrorists and criminals to carry a weapon without being detected. **Lower strength & anisotropic material properties** • Physical properties that are not as good as the bulk material • Weaker and more fragile in one direction by approximately 10% to 50% since it is built layer-by-layer

Source: Own Table based on https://3dinsider.com/3d-printing-advantages/. & https://3dinsider.com/3d-printing-disadvantages/.

General Future of the technology

3DP is an unstoppable force (Reichental, 2018) which presents significant challenges – limited supply sources and lack of certified processes – to supply chain practitioners (Gartner, 2018). It presents a clear room for improvement - in speed, methods, and materials - to respond to the industries requirements. As a result of this continuous improvement along the next years, Gartner (2018) states that, by 2021, 40% of manufacturing companies will establish 3DP of excellence. The Worldwide Semiannual 3DP Spending Guide from IDC (2018) presents global spending on 3DP – including hardware, materials, software, and services – growing to $23 Billion in 2022 with five-year CAGR of 18.4%. The spending on 3D printers and materials will totalize approximately two-thirds of the worldwide spending total throughout the forecast, summing $7.8 billion and $8.0 billion respectively in 2022. Services spending will account $4.8 billion in 2022, led by on-demand parts services and systems integration services. Also, purchases of 3DP software will grow more slowly compared to the overall market with a five-year CAGR of 16.7%. Besides, IDC (2018) forecasts worldwide spending to exceed $14 Billion in 2019 (**Appendix E.1**), an increase of 23.2% over 2018. All this development combined with other technological innovations - infinite power computing in the cloud, big data and future generations robotics (Reichental, 2018) – will intensify the potential of the 3DP. At that stage, it will be possible to recognise the real impact of the so-called, Digital Revolution in fabrication – Fourth Industrial Revolution.

Supply Chain context and application of 3D Printing Technology

Literature Review of the Supply Chain Management

Supply Chain is described as a sequence of activities from the suppliers' supplier until reach the final customer to produce and distribute a commodity (**Appendix C.3**). It involves multiple people who are "linked" through a physical flow – to transport, move and store goods and materials – and information flow – to coordinate all the supply chain members' strategies and control their daily activities (SCRC, 2017). Because every product represents the cumulative effort of all organisations evolved and it is expected to be the "perfect product", it is crucial to managing all the activities along the Supply Chain as well as all the parts involved. According to CSCMP, *SCM "encompasses the planning and management of all activities involved in sourcing, 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, SMC integrates supply and demand management within and across companies*." It combines all the businesses functions and processes within and across all participants into a unified and high-performing business model. The focus of Supply Chain managers is illustrated by the Seven Principles of SCM (**Table 3**) which reflect the importance of the customer. These principles resulted from a research study on more than hundred members of the Supply Chain - manufacturers, distributors, and retailers – that revealed some commonly used supply chain strategies, and good practices (CSCMP).

Table 3: Seven Principles of Supply Chain Management

Seven Principles of Supply Chain Management	
Principle 1	*Segment customers based on the service needs of distinct groups and adapt the supply chain to serve these segments profitably.*
Principle 2	*Customise the logistics network to the service requirements and profitability of customer segments.*
Principle 3	*Listen to market signals and align demand planning accordingly across the supply chain, ensuring consistent forecasts and optimal resource allocation.*
Principle 4	*Differentiate product closer to the customer and speed conversation across the supply chain.*
Principle 5	*Manage sources of supply strategically to reduce the total cost of owning materials and services.*
Principle 6	*Develop a supply chain-wide technology strategy that supports multiple levels of decision making and gives a clear view of the flow of products, services, and information.*
Principle 7	*Adopt channel-spanning performance measures to gauge collective success in reaching the end-user effectively and efficiently.*

Source: Own Table based on https://cscmp.org/CSCMP/Develop/Starting_Your_SCM_Career/SCM_Concepts/CSCMP/Develop/Starting_Your_Career/Supply_Chain_Management_Concepts.aspx?hkey=96af0d8b-21ad-4bca-b7d1-956a25ced524

AM Supply Chain Model

At this moment not everything can be printed, but the use of 3DP to produce personalised items reduces the need for logistics. The impacts of 3DP on supply chains are immense (Mohr, 2015) and range from incremental capability and finance improvements to an innovative new customer value proposition that impacts the existing customer relationship (Gartner, 2018). Because 3DP promotes a shift from designing for ideal manufacturing design (Basiliere, 2018), it undoubtedly leads to significant value creation (Rayna & Striukova, 2016). To capture value and gain competitive advantage, new business models for 3DP (**Table 4**) should be developed to create new market opportunities to serve the customer in a customised way. Gartner (2018) defends that when a business model, is well-defined, it provides possible directions for market and organisational change, evaluating the scope and impact of the changes, and advising strategies to address and take advantage of them.

Table 4: How 3D's Printing Capabilities Transforms Business Models

Dimension	From	To
Customer	Mass Market	Individual
Finance	High FC, Low VC	Low FC, High VC
Capabilities	Supply Chain provides subassemblies	Supply Chain provides raw materials
Value Proposition	Mass Produced	On-demand customisation

Source: Own Table based on https://blogs.gartner.com/pete-basiliere/files/2018/05/Capture-3.png

Traditional models for supply chains founded on conservative features of the industry - efficiencies of mass production need for low cost, high-volume assembly workers - contrast with 3DP which explores its value in the printing of low volume customised items, complex shapes. These differences, plus the adjustments on business models, call for a new model of a supply chain (**Figure 1**) and impact seven critical aspects of supply chains (Mohr & Khan, 2015).

Mass Customization: Contrary to traditional manufacturing processes that promote mass production taking advantage of economies of scale, 3DP enables the creation of customised products tailored to each customer, involving them in design and production activities. Hence, 3DP merge design, manufacturing, and distribution – it blurs the line between purchase and creation – with clear impacts on downstream activities of the supply chain (Tien, 2012), and creating a closer relationship between these activities. It introduces a new pattern for customer relationship moving from “product push” by marketing on demand “product pull” models (Basiliere, 2018). The involvement of the customer implies a redefinition of "how, where, and who” in the supply chain’ processes (Nyman & Sarlin, 2014) as it creates on-demand solutions tailored to each customer (Basiliere, 2018). Consequently, it modifies managers priorities - cost and profit management -, and a late-stage postponement makes supply chains more agile and flexible to market changes (Petrick & Simpson, 2013). Mass Customization and Production on demand enhance Principle 4 of SCM.

Resource Efficiency: AM methods present an improved resource efficiency (Ford, 2016) compared to a subtractive process (Campbell et al., 2011). Because, the 3D objects are produced closer to customers – locally instead of globally -, transportation movements are reduced in a larger part (Petrick & Simpson, 2013). Also, it introduces a new point of view on natural resources concerning material savings along the supply chains, reducing the waste during the processes (Wigan, 2014). The late-stage postponement contributes to a significant decrease in overproduction and excess of inventory (Mohr & Khan, 2015). Thus, supply chain’ efficiency increases while the global footprint is reduced as well as the carbon emissions.

Decentralisation of Manufacturing: 3DP technology shifts production closer to the end-customer and promotes build-to-order strategies that impact the manufacturer-wholesaler-retailer relationship (Crandall, 2016). The production of goods in Asia markets could be pulled away from “manufacturing platforms” to the countries where the products are consumed (Campbell et al., 2011). This decentralisation converts the global supply chain into a globally connected, but local supply chain (Waikoloa, 2014). This change improves time-to-market responsiveness, decreases the lead time, and increases supply chains' agility for small volumes of products with technical specifications (Garret, 2014). All in all, 3DP technology transforms the way that the end-user is reached. According to Principle 7 of SCM, supply chain managers will adopt new channel-spanning measures to assess the collective success in reaching the end-user effectively and efficiently.

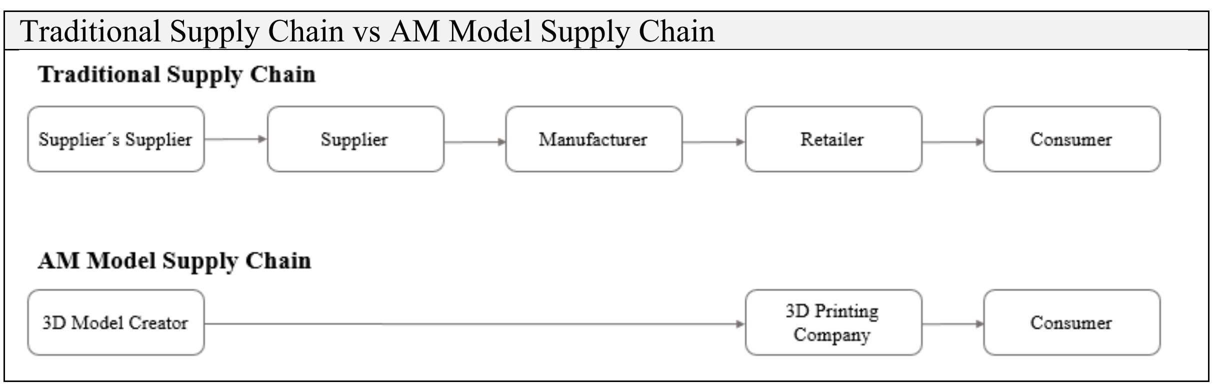
Complexity Reduction: 3DP technology reduces complexity in supply chains by replacing previously assembled parts into a single interlocked object (Gao et al., 2015). Also, the required inventory level of spare parts decreases, and a virtual inventory is created (Spare Parts 3D, 2018). Therefore, the process complexity is reduced, making the flow of material more transparent and more accessible to control (Janssen et al., 2014). Less assembly shortens supply chains, creating a high potential for savings on internal cost and time.

Rationalisation of Inventory and Logistics: The movement of physical goods across the world will be replaced by the movement of digital 3D files (Nyman & Sarlin, 2014). Also, physical inventories of finished products will be replaced by a digital inventory. By producing on demand, at the point of consumption, a new paradigm of best practices in global manufacturing and supply chain management is introduced (Goehrke, 2018). Consequently, there will be less WIP and finished goods to stock and to be transported, allowing for a rationalisation of warehousing and logistics. Although, the decentralisation of production implies a better management of an inventory for raw materials distributed in different locations. An inventory for raw materials is cheaper, safer and requires lesser skilled workers than handling the inventories mentioned above (Mohr & Khan, 2015). Because 3DP technology impacts logistics, Principle 2 of SCM will imply a reorganisation and customisation of the logistics network to new service requirements. Rationalisation of inventory and logistics will promote better management of supply sources, and hence a reduction of costs – Principle 5 of SCM.

Product Design and Prototyping: 3DP technology brings innovative tools and processes to produce and test prototypes, as well as new or updated product designs (Lee, 2013). Products can be redesigned with a focus on critical specifications like functionality and material savings without affecting any of the remaining attributes (Mohr, 2015) – reduced time to market.

Legal and Security Concerns: Scanning technology that enables to transform physical objects into 3DP files is experiencing a quick development (Nyman & Sarlin, 2014). It arises an uncertainty in areas like personal injury, intellectual property theft, and product liability because the current legal framework does not define clear laws regarding the use of 3D printers (Mohr & Khan, 2015). Some researchers defend that anything that can happen, will happen, including the printing of harmful objects or the sidestepping of legal issues built into a traditional supply chain (Schildhorn, 2014).

Figure 1: Traditional Supply Chain vs AM Model Supply Chain



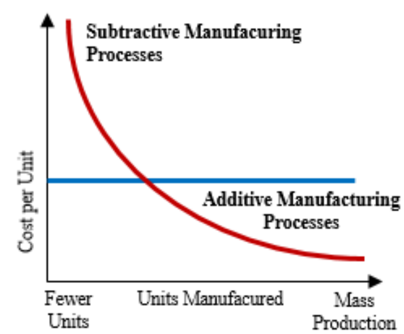
Source: Own Figure based on Kubáč, Lukáš, and Kodym, Oldřich (2017). "The Impact of 3D Printing Technology on Supply Chain". MATEC Web of Conferences, 134, p.4.

In addition to these impacts, the digitalisation of supply chains will change the supply chain-wide technology strategy focused on coordinating the different levels of decision-making – Principle 6 of SCM.

3D Printing Pros and Cons Applied to Supply Chains

Like any disruptive technology, 3DP brings several opportunities and raises some challenges and drawbacks. **Table 5** presents the pros and cons of 3DP when applied to supply chains.

Table 5: 3DP Pros and Cons Applied to Supply Chains

Pros of 3D Printing	Cons of 3D Printing
Cost Reduction • No need for large inventory, high volume production facilities, and tooling centres • Reduction of transportation movements required machining centres and needed for assembly workers • Economic mass customisation **Quick Responsiveness** • Faster design and prototype production • Reduced lead time • On-demand manufacturing • Increased supply chains flexibility **Improved Designs** • Reduce production waste and eliminates extra parts that add weight – Zero Waste • Allow customisation and incorporation of customer feedback • Lighter Strong parts **Increased Interaction with Customers**	**Lower Production Speed** • Slower compared to traditional manufacturing methods **Investment** • Represent a considerable investment: the cost of buying and setting up a 3D printer plus the cost of adjusting all the processes **Unreliable Production** **Negative Impact on Job** • A severe drop of job in manufacturing **No Economies of Scale**  • The absence of economies of scale – each object is produced individually and costs the same • For mass production, the per-unit cost is higher

Source: Own Table based on https://www.3dhubs.com/knowledge-base/advantages-3d-printing. & Kubáč, Lukáš, and Oldřich Kodym. 2017. "The Impact Of 3D Printing Technology On Supply Chain".

Applications

Sports Sector – The *Flyknit*

Sneaker companies use 3DP technology to design and produce soles of the shoes to protect the delicate the bones of the athletes' foot (Gaget, 2017). However, Nike moved forward and produced the first 3D printed textile upper part of the shoe in performance footwear (Nike, 2018). The *Flyprint* was specially designed for the world's most elite marathons and a solution for a pair of shoes which does not absorb water (**Appendix C.4**). The success factor of this project was the material used, a 3D printing plastic material. According to the company the goal was achieved in two ways: (1) TPU does not absorb the water because it is plastic, which allows the weight of the shoe to be the same during the marathon; (2) The structure of the shoe enables water from sweat to exit the shoe. Furthermore, the material used decrease the weight of the shoe when compared to the previous model, which had an upper made of *Flyknit*. The use of the 3DP technology improved the production process - capturing athlete information to test the ideal composition material and tailored the designed structure of the shoe to his anatomy - and increased the efficiency of the process. All the information collected was combined in a 3D file and used to produce the 3D part. The technology impacts on the supply chain allowed a faster design and prototype production - prototyping is 16-times quicker than in any previous manufacturing method (Nike, 2018). Also, it incorporated customer data and feedback, allowing customisation. However, the speed of production is lower compared to the traditional manufacturing processes, and only a few units of *Flyprint* were produced.

Aerospace Sector – 787 Dreamliner Aircraft

Since 2015, Boeing has been incorporating 3D printed parts in its aeroplanes (Krassentein, 2015). In 2017, it announced that would start to integrate metal 3D printed parts to build the new 787 Dreamliner aircraft instead of using only polymers and plastics (**Appendix C.5**). Before introducing 3DP technology, Boeing produced titanium parts using forging and machining methods which were complete obsolete and cost intensive. To change from traditional to 3DP methods, Boeing employed the DMLS method - commonly used in the aerospace and aerospace industries - which only requires a laser and a build platform and can be adjusted to every size of the aircraft that would be printed (Sculpteo). To get the approval from FAA, the company established a partnership with Norsk Titanium, and one year after it invested in a start-up Digital Alloys which prints exclusively 3D metal parts to Boeing (Vicent, 2017). The technology allows the company to produce functional, strength and durable metallic parts, and thanks to the investment, the company reduced the waste by-piece and the aircraft weight, while increases its resistance. (Stratasys – Direct Manufacturing). Summing up, 3DP turns the process more efficient. Specifically, regarding 787 Dreamliner construction, 3DP methods allowed the company to save up to $3 Million per aircraft (Norsk Titanium, 2017). The production of complex and customised shapes improved the system's performance. Also, it reduced Boeing's dependence on third parties, making the supply chain more agile and flexible for small volumes of parts, and reducing the lead times.

Construction Sector – 3D Printed Houses

With the development of 3DP methods and new printers as concrete 3D printers, 3DP started to have an impact in the construction sector, conveying innovation to the traditional processes. At the date, 3DP technology is applied to buildings, bridges, moulds, building components, architectural models, and interior design (Laubier & Rothballer, 2018). Along the last years, c3Dp has been challenging the traditional construction processes which present inefficiencies - (1) Low Productivity; (2) Dependent on the workforce and its skills which affect the quality and the life of the construction; (3) Production in a large scale of noise, waste, and dust – that could be overcome by c3Dp. The Winsun company is a pioneer of c3Dp and developed a continuous 3D printer for construction that is more than 1000 meters long. Using as raw materials a mix of cement, sand, and fibres – half of that is recycled demolition waste - it printed a five floors apartment block and a 1000-square-meter villa. The automated printer process resulted in hollow walls which were transported to the new location of the buildings. There, the walls are filled with reinforcing and insulating materials and then assembled. This innovation allows an exact production based on 3D models created by CAD, the creation of unique and complex designs and shapes, and an independent production with low human involvement. According to the company (2016), the automatization of the process reduces the overall construction time by 50% to 70%, labour by 50% to 80%, and materials by 30% to 60%. As a result, the overall costs of the buildings were also reduced. An autonomous construction removes the need for workforce and, hence, the skills shortage that affects the sector. It also reduces the need of the traditional construction machinery – totalizes 20% to 25% of the cost of a construction project (Laubier & Rothballer, 2018). The c3Dp gives freedom of design to architects and designers, reducing the costs associated with complex shapes, shortens the construction times, and moderates the construction sector's harmful impact on the environment.

Future of 3DP in Supply Chains

All the impacts that 3DP has on the supply chains are expected to boost conflicts between different supply chain members, imposing new challenges for supply chain managers. To avoid problematic situations, managers must predict and be aware of the possible impacts that 3DP could have on their organisations to be prepared to overcome these situations in a flexible way (Mohr & Khan, 2015), always considering the Seven Principles of SCM. However, the impact is not expected to be similar across different industries (Heutger & Kuckellhaus, 2016), neither at the same time (Campbell et al., 2011). For sectors that manufacture highly complex and customised goods, 3DP may replace traditional manufacturing methods, so the impacts will be more visible. For the remaining sectors 3DP is likely to complement the conventional manufacturing processes instead of replacing it, with minor effects (Heutger & Kuckellhaus, 2016). The decentralisation and customisation of manufacturing will force companies to rethink their manufacturing strategies to serve their customers in the best way. For this reason, it is expected companies to work together with peer companies to support the integration of the technology into their supply chains, maximising their effectiveness and to meeting customer expectations. The spare parts sector will be transformed as a consequence of the proliferation of 3DP technology (Heutger & Kuckellhaus, 2016). 3DP is not an isolated manufacturing process, it is an end-to-end process (Gatner, 2018) so spare parts will be printed on demand, and there will be no need to stock it on warehouses. To sustain the efficiency of the processes, logistic providers play a crucial role by supporting companies via a structured network of 3D printers to produce and deliver on time the spare parts. It implies “virtual” spare parts to be stored in software databases - “virtual warehouses”, and different inventories of raw materials to managed in each local of production.

To guarantee reduced lead-times for product customisation to their customers, companies will delay the final assembly to the final point of demand, giving to customers the opportunity to select features of the product's design, materials, packaging, size and shape, and item functionalities. Local distribution centres – logistics providers – will store almost-finished goods and 3D printers to customise the product before delivering it (Heutger & Kuckellhaus, 2016). In addition to local distribution centres, in the future, there will also be global networks of 3D print stores for diverse applications. All the technological development will enhance the development of Home 3D printers which will become popular and more accessible (Nichols, 2018). At home, people will be able to buy a 3D design file which can be printed at home or the 3D print store - where customers will have available a wide range of materials and different 3DP methods to print the STL file, previously purchased online (Heutger & Kuckellhaus, 2016). In the future, it is expected 3D printer stores to be as usual as printing photos or documents in stores nowadays.

Primary Data Discussion

Interview Results

To get a further understanding on the possible impact of 3DP in Supply Chains, and insights of the professionals' perception about the topic, five semi-structured interviews were conducted to Supply Chain, Transports, Logistics, and 3DP professionals. The interview guide and the interviewees' profile are presented in **Appendix A.** The professionals' perception about the topic is aligned with insights from data previously collected, reinforcing the previous research findings. The interviews outcomes can be summarised in three main topics:

- **Traditional Manufacturing Methods vs 3DP Technology**: In general, 3D printed objects are more fragile to torsion and impact than the injected objects. However, it is possible to improve the quality of the object when the printing is combined with manual finishing. Regarding advantages over traditional methods, it offers the possibility to customise objects to the needs of the end-user, in short time, promoting *"a faster evolution of the product specifications."* (Interviewee D), and a closer relationship with the customer. 3DP has a huge application-level extension. However, it is affordable to be applied to small quantities due to costs of production – *"Comparing 3DP with injection methods, we realised that printing is cheaper to produce* *until 50/100 parts."* (Interviewee E) -, printing times and workmanship of finishes. In addition to this limitation, economies of scale are not applied to 3DP.

- **Impact on Supply Chains:** With the development of technology, 3DP allows products to be produced from a digital model. It enables the products to be produced in small batches as one, anywhere. It brings flexibility to supply chains. There will be a reduction in stocks, a decrease in transport costs, a decentralisation of production – *"(...) sending a file to a printer closer to the customer."* (Interviewee C) -, less participants along the supply chain, production of customised objects and a waste reduction.
- **Impact on SCM:** Supply chains will become more digital, arising *"(...) new challenges for supply chain managers because the last mile activities will become more complex and some upstream activities will disappear."* (Interviewee A). 3/5 of the interviewees defend that the most impacted principle of SCM (**Table 3**) is the Principle 4. They consider that the most innovative topic of 3DP is the opportunity to move the production of certain products to closer to the end-customer, enabling the differentiation of each object at the same cost. The other two principles mentioned were Principle 5 and Principle 6.

Questionnaire Results

A questionnaire, based on the insights provided in the exploratory research (**Appendix B**), was conducted and presented to 41 individuals with an Academic/ Professional Background in Operations, Logistics and Supply Chain Management, with the aim of testing the insights from the exploratory research to help to answer the Research Questions previously identified (**Appendix D.1**). The Social & Demographic characterisation of the sample is presented in **Appendix B.1**, and the results of SECTION 1 and SECTION 2 are presented in **Appendix B.2** and **Appendix B.3**, respectively. **Table 6** summarises the main findings of the questionnaire.

Table 6: Quantitative Analysis Results

Impact of 3DP…	…as a disruptive technology ✚ ✙ ✙	… over traditional methods ✚ ✙ ✙	… vs the Impact of the Internet ▬ ▭ ▭	… in diverse areas ✚ ✚ ✙
Implementation of 3DP…	… implies a huge investment ✚ ✙ ✙	… arises conflicts and challenges in supply chains ✚ ✚ ✙	… improves the customer experience ✚ ✙ ✙	… brings more benefits than limitations ✚ ✙ ✙

Legend

▬ ▬ ▬	▬ ▬ ▭	▬ ▭ ▭	✚ ✙ ✙	✚ ✚ ✙	✚ ✚ ✚
Totally Disagree	**Strongly Disagree**	**Disagree**	**Agree**	**Strongly Agree**	**Totally Agree**

Source: Questionnaire Results

Conclusion

Along with this work project, the research problem was explored, and the research questions were answered. The main findings are summarised below:

<u>What is the 3DP technology and where to apply it?</u>

- 3DP turns a digital file into a physical 3D object laying down many thin layers of material in succession. The most common material is plastic but the use of some other materials, by employing different techniques, allows for the creation of complex products' shapes.
- Conventional and time-honoured manufacturing limitations are surpassed. Moreover, a new paradigm for innovation in engineering design and manufacturing processes is introduced — an exceptional tool for manufacturing custom parts.
- 3DP is the best option when one or a few pieces are required at a quick turnaround time or when the objects' shape is complex. Although, when it comes to mass production, 3DP is not an optimal solution – no economies of scale and lower speed of production.

What are the applications of the 3DP technology in Supply Chains and major pros and cons?

- 3DP has been transforming supply chains into digital supply chains. Digital files, not physical parts, would move around the globe to be printed anywhere. The production and distribution of a commodity could begin to be de-globalised as the production takes place closer to the end customer.
- 3DP shrinks the supply chain. Products can be personalised, manufactured locally and on demand, without the need to build-up inventories of finish goods. It is one-time production reducing the assembly processes, the need for labour in manufacturing and the transportation movements.
- The adoption of 3DP lead to significant value creation. In this way, organisations should develop new business models to create new market opportunities to serve the customer in a tailored way and to take advantage of the benefits offered by the technology.
- For companies that produce highly complex and customised products, the emergence of 3DP is a truly transformative technology. Companies can adapt their manufacturing strategies to take advantage of economical mass customisation and an increase in supply chain flexibility. However, they also face a reduction in production speed and higher costs when it comes to mass production.
- To support the integration of 3DP and decentralisation of manufacturing, partnerships with logistics providers are essential to serve the customers better. Even though, moving from centralisation to decentralisation of manufacturing presents clear benefits, it also raises new challenges - such as dispersion of raw material inventories, higher raw material costs, and forecast of local demand. A determination of the optimum scenario needs to be elaborated, in further research.

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Appendices

List of Appendices

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2. **Appendix B: Questionnaires**
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1. Appendix A: Expert Interviews

In total, five interviews were conducted. To ensure all the information collected is meaningful, the five interviewees are Supply Chain, Logistics, and 3DP professionals.

In the following summary, the profile of the interviewees - the Age, Gender, Academic Background, and Job Position - is presented.

Interviewee A	**Female, 50**
	BSc. in Management
	PhD in Logistics
	Supply Chain Manager at Sonae MC
Interviewee B	**Male, 23**
	BSc. in Industrial Engineering and Management
	MSc. in Industrial Engineering and Management
	Supply Chain Technician at Sonae MC

Interviewee C	**Female, 45**
	BSc. in Management
	PhD in E-Business
	Transports Coordinator at Sonae MC
Interviewee D	**Male, 35**
	BSc. Computer Engineering
	MBA
	Supply Chain Director at Sonae MC
Interviewee E	**Male, 27**
	BSc. in Industrial Management and Logistics
	Managing Partner at 3D Life

All the interviewee answered the questions presented above.

- **Part I: 3D Printing**

Question 1	Based on your knowledge about 3D Printing Technology, do you consider that 3D printed products as good - regarding quality - like the ones which are "traditionally" manufactured? Why?
Question 2	In general, what are the main benefits of 3D Printing?
Question 3	In general, what are the main limitations of 3D Printing?
Question 4	In your opinion, how broad is the application of 3D Printing?

- **Part II: The Impact of 3D Printing in Supply Chains**

Question 5	What are the main features of the technology that will cause an impact in Supply Chain?
Question 6	What will be the positive impacts in Supply Chains?
Question 7	What are the main drawbacks that 3D Printing present compared to traditional manufacturing processes?
Question 8	What the skillsets will Supply Chain managers require in the future?
Question 9	Considering the Seven Principles of Supply Chain Management which of those principles will be the most impacted by 3D Printing?

2. Appendix B: Questionnaires

The survey was conducted online, during five days – from November 27th until December 1st.

The structure of the survey is presented above:

PRE-RECRUITING QUESTIONNAIRE → **SECTION 1** 3D Printing → **SECTION 2** The impact of 3D Printing in Supply Chain → **SOCIAL & DEMOGRAPHICS**

- **PRE-RECRUITING QUESTIONNAIRE**

Question A Do you have an Academic/ Professional Background related to Operations, Logistics or Supply Chain Management?

- ☐ Yes → move to next question
- ☐ No → end the questionnaire

Question B Have you ever heard about 3D Printing technology?

- ☐ Yes → move to **SECTION 1: The Impact of 3D Printing**
- ☐ No → end the questionnaire

- **SECTION 1: The Impact of 3D Printing**

Question 1 To which extent do you agree with the following statements?

	Totally Disagree	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Totally Agree**
3D Printing is a disruptive technology							

3D Printing will replace the traditional manufacturing methods							
"Manufacturing Industries need to embrace 3D Printing, which will have an even bigger impact than the internet (…)" Sammartino, 2015							
3D Printing has several benefits compared to the traditional manufacturing methods							
3D Printing has several limitations compared to the traditional manufacturing methods							
3D Printing has a broad range of application							
3D printed objects are as good as the ones produced using traditional manufacturing methods - regarding quality							

Question 2 To which extent do you agree with the following statements?

3D Printing can be applied to…	**Totally Disagree**	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Totally Agree**
… Industrial Goods							
… Aeronautic & Aerospace							

… Healthcare							
… High-tech							
… Services							
… Consumer Goods							
… Education							
… Automotive							
… Mechanic							
… Electronic & Electric							

- **SECTION 2: The Implementation of 3D Printing**

Question 3 To which extent do you agree with the following statements related to the implementation of 3D Printing as a manufacturing process?

	Totally Disagree	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Totally Agree**
The implementation of 3DP as a manufacturing process implies a considerable investment							
The implementation of 3DP as a manufacturing process arises some conflicts among the Supply Chain participants.							

The implementation of 3DP as a manufacturing process imposes new challenges for Supply Chain Managers.							
The implementation of 3DP as a manufacturing process improves the customer experience.							
The implementation of 3DP as a manufacturing process offers more benefits than limitations.							

Question 4 How do you evaluate the potential impacts of 3D Printing in Supply Chains?

	Not at all important	**Slightly important**	**Somewhat important**	**Important**	**Fairly important**	**Very important**	**Extremely important**
Production of Mass Customization objects							
Introduction of a co-creation model with customer							
Reduction of Inventories							
Reduction of Waste							
Production closer to the end-customer							
No Economies of Scale							

Production of objects with complex shapes							
Shrink of the Supply Chain							
Limited range of materials							
Lower speed of production							
Reduction of the labour force							
Proper verification of the product prototype							

- **SOCIAL & DEMOGRAPHICS**

Question 5 Age

☐ 18-24

☐ 25-34

☐ 35-44

☐ 45-54

☐ 55-64

☐ >65

Question 6 Gender

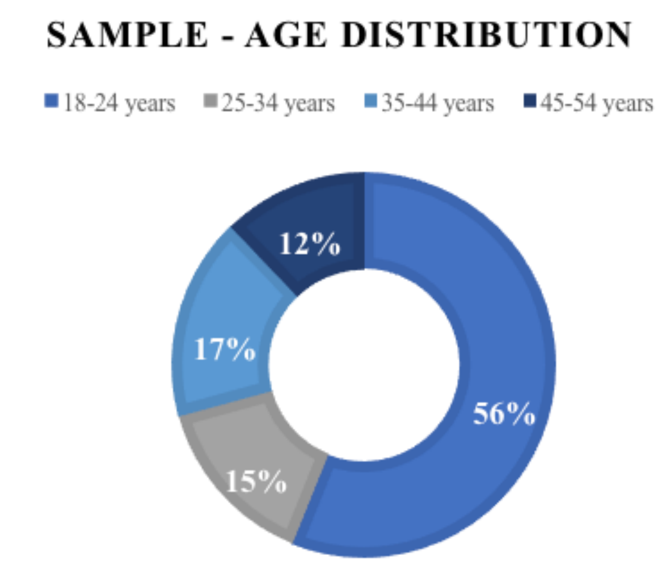
☐ Male

☐ Female

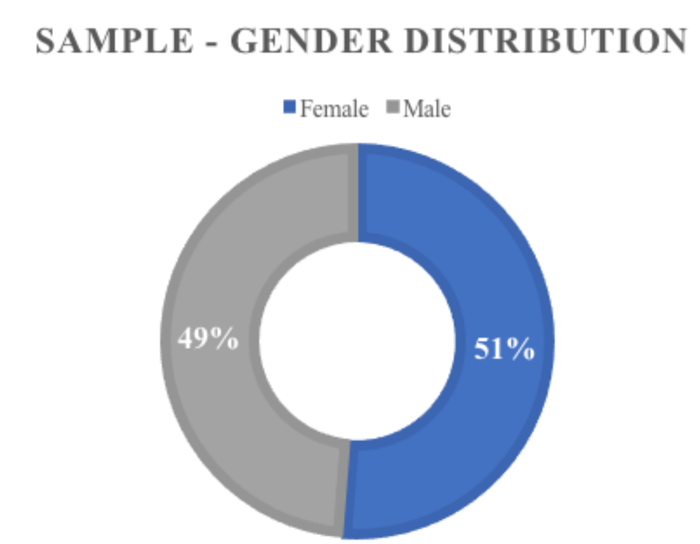
- **RESULTS – Quantitative Analysis (n=41)**

- **SOCIAL & DEMOGRAPHICS RESULTS - Appendix B.1**

Age



Gender



- **SECTION 1: 3D PRINTING – Appendix B.2**

QUESTION 1							
3D Printing is a disruptive technology							
Results	Totally Disagree 0,00%	Strongly Disagree 2,33%	Disagree 4,65%	Neutral 4,65%	Agree 37,21%	Strongly Agree 32,56%	Totally Agree 18,60%
3D Printing will replace the traditional manufacturing methods							
Results	Totally Disagree 2,33%	Strongly Disagree 6,98%	Disagree 23,26%	Neutral 6,98%	Agree 34,88%	Strongly Agree 20,93%	Totally Agree 4,65%
"Manufacturing Industries need to embrace 3D Printing, which will have an even bigger impact than the internet (…)" Sammartino, 2015							
Results	Totally Disagree 4,65%	Strongly Disagree 11,63%	Disagree 39,53%	Neutral 27,91%	Agree 9,30%	Strongly Agree 4,95%	Totally Agree 2,33%
3D Printing has several benefits compared to the traditional manufacturing methods							
Results	Totally Disagree 0,00%	Strongly Disagree 2,33%	Disagree 9,30%	Neutral 18,60%	Agree 34,88%	Strongly Agree 32,56%	Totally Agree 2,33%
3D Printing has several limitations compared to the traditional manufacturing methods							
Results	Totally Disagree 2,33%	Strongly Disagree 4,65%	Disagree 16,28%	Neutral 48,84%	Agree 23,26%	Strongly Agree 4,65%	Totally Agree 0,00%
3D Printing has a broad range of application							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 11,63%	Neutral 2,33%	Agree 20,93%	Strongly Agree 39,53%	Totally Agree 25,58%

3D printed objects are as good as the ones produced using traditional manufacturing methods - regarding quality							
Results	Totally Disagree 0,00%	Strongly Disagree 4,65%	Disagree 27,91%	Neutral 37,21%	Agree 16,28%	Strongly Agree 9,30%	Totally Agree 4,65%

QUESTION 2							
3D Printing can be applied to…							
… Industrial Goods							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 9,30%	Neutral 6,48%	Agree 41,86%	Strongly Agree 32,56%	Totally Agree 9,30%
… Aeronautic & Aerospace							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 0,00%	Neutral 13,95%	Agree 27,91%	Strongly Agree 27,91%	Totally Agree 30,23%
… Healthcare							
Results	Totally Disagree 0,00%	Strongly Disagree 2,33%	Disagree 4,65%	Neutral 13,95%	Agree 25,58%	Strongly Agree 34,88%	Totally Agree 18,60%
… Retail							
Results	Totally Disagree 2,33%	Strongly Disagree 6,98%	Disagree 11,63%	Neutral 27,91%	Agree 30,23%	Strongly Agree 16,28%	Totally Agree 4,65%
… High-tech							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 4,65%	Neutral 18,60%	Agree 41,86%	Strongly Agree 23,26%	Totally Agree 11,63%
… Services							

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	2,33%	13,65%	20,93%	30,23%	11,63%	16,28%	4,65%

… Consumer Goods

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	2,33%	6,98%	20,93%	18,60%	25,58%	18,60%	6,98%

… Education

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	0,00%	4,65%	25,58%	13,95%	37,21%	16,28%	2,33%

… Automotive

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	0,00%	0,00%	0,00%	4,65%	39,53%	27,91%	27,91%

… Mechanic

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	0,00%	2,33%	4,65%	13,95%	30,23%	30,23%	18,60%

… Electronic & Electric

Results	Totally Disagree	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Totally Agree
	0,00%	0,00%	0,00%	11,63%	27,91%	32,56%	27,91%

- **SECTION 2: THE IMPACT OF 3D PRINTING – Appendix B.3**

QUESTION 3							
The implementation of 3DP as a manufacturing process implies a considerable investment							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 7,32%	Neutral 12,20%	Agree 34,15%	Strongly Agree 14,63%	Totally Agree 31,71%
The implementation of 3DP as a manufacturing process arises some conflicts among the Supply Chain participants							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 17,02%	Neutral 19,51%	Agree 29,27%	Strongly Agree 29,27%	Totally Agree 4,88%
The implementation of 3DP as a manufacturing process imposes new challenges for Supply Chain Managers							
Results	Totally Disagree 0,00%	Strongly Disagree 0,00%	Disagree 9,76%	Neutral 7,32%	Agree 39,02%	Strongly Agree 34,15%	Totally Agree 9,76%
The implementation of 3DP as a manufacturing process improves the customer experience							
Results	Totally Disagree 0,00%	Strongly Disagree 2,44%	Disagree 4,88%	Neutral 26,83%	Agree 31,71%	Strongly Agree 21,95%	Totally Agree 12,20%
The implementation of 3DP as a manufacturing process offers more benefits than limitations.							
Results	Totally Disagree 0,00%	Strongly Disagree 2,44%	Disagree 17,07%	Neutral 24,39%	Agree 31,71%	Strongly Agree 14,63%	Totally Agree 9,76%

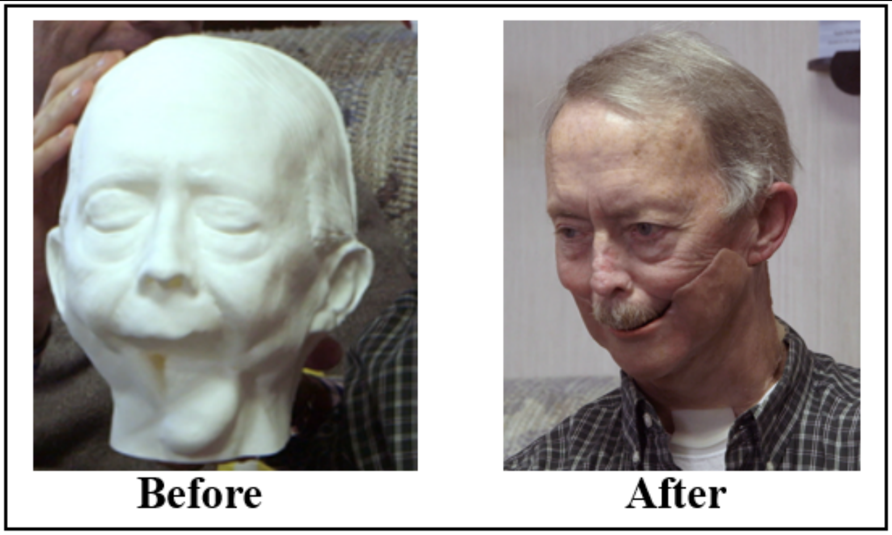
QUESTION 4							
Production of Mass Customization objects							
Results	Not at all Important 4,88%	Slightly Important 2,44%	Somewhat Important 2,44%	Important 7,32%	Fairly Important 17,07%	Very Important 36,59%	Extremely Important 29,27%
Introduction of a co-creation model with customer							
Results	Not at all Important 0,00%	Slightly Important 4,88%	Somewhat Important 9,76%	Important 9,76%	Fairly Important 17,07%	Very Important 51,22%	Extremely Important 7,32%
Reduction of Inventories							
Results	Not at all Important 0,00%	Slightly Important 2,44%	Somewhat Important 9,76%	Important 19,51%	Fairly Important 14,63%	Very Important 39,02%	Extremely Important 14,63%
Reduction of Waste							
Results	Not at all Important 0,00%	Slightly Important 0,00%	Somewhat Important 2,44%	Important 12,20%	Fairly Important 21,95%	Very Important 29,27%	Extremely Important 34,15%
Production closer to the end-customer							
Results	Not at all Important 0,00%	Slightly Important 2,44%	Somewhat Important 7,32%	Important 14,63%	Fairly Important 24,39%	Very Important 26,83%	Extremely Important 24,39%
No Economies of Scale							
Results	Not at all Important 0,00%	Slightly Important 0,00%	Somewhat Important 7,32%	Important 26,83%	Fairly Important 36,59%	Very Important 24,39%	Extremely Important 4,88%
Production of objects with complex shapes							
Results	Not at all Important 0,00%	Slightly Important 4,88%	Somewhat Important 12,20%	Important 7,32%	Fairly Important 12,20%	Very Important 31,71%	Extremely Important 31,71%

Shrink of the Supply Chain							
Results	Not at all Important 0,00%	Slightly Important 2,44%	Somewhat Important 9,76%	Important 14,63%	Fairly Important 14,63%	Very Important 34,15%	Extremely Important 24,39%
Limited range of materials							
Results	Not at all Important 0,00%	Slightly Important 17,07%	Somewhat Important 14,63%	Important 19,51%	Fairly Important 9,76%	Very Important 29,27%	Extremely Important 9,76%
Lower speed of production							
Results	Not at all Important 0,00%	Slightly Important 12,20%	Somewhat Important 9,76%	Important 17,07%	Fairly Important 19,51%	Very Important 29,27%	Extremely Important 12,20%
Reduction of the labour force							
Results	Not at all Important 0,00%	Slightly Important 9,76%	Somewhat Important 12,20%	Important 14,63%	Fairly Important 24,39%	Very Important 26,83%	Extremely Important 12,20%
Proper verification of the product prototype							
Results	Not at all Important 0,00%	Slightly Important 0,00%	Somewhat Important 7,32%	Important 7,32%	Fairly Important 9,76%	Very Important 48,78%	Extremely Important 26,83%

3. Appendix C: Figures

Appendix C.1: Real Example: Production of a Facial Bone – Before and After

Real Example: Production of a Facial Prosthesis – Before and After



Source: https://formlabs.com/blog/shirley-technique-facial-prosthesis/

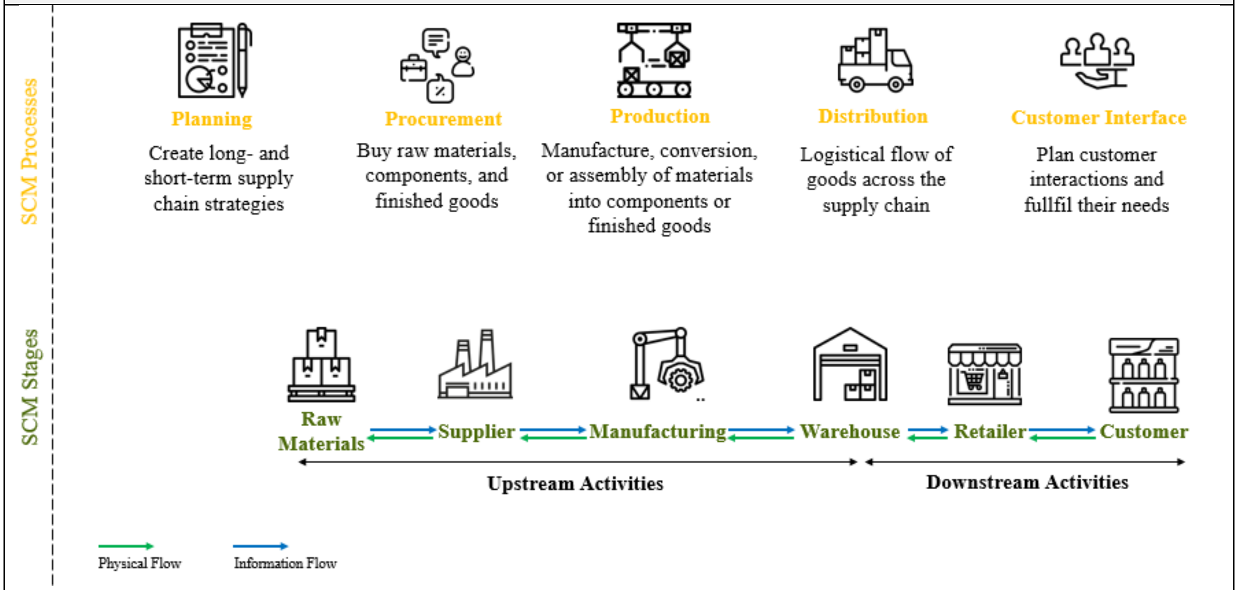
Appendix C.2: Real Example: 3D Replication of a painting

Real Example: 3D printed painting displayed at the Prado Museum in Madrid

Source: https://www.aniwaa.com/3d-printing-for-archeology-and-museology/

Appendix C.3: Traditional Supply Chain Model

Traditional Supply Chain Model



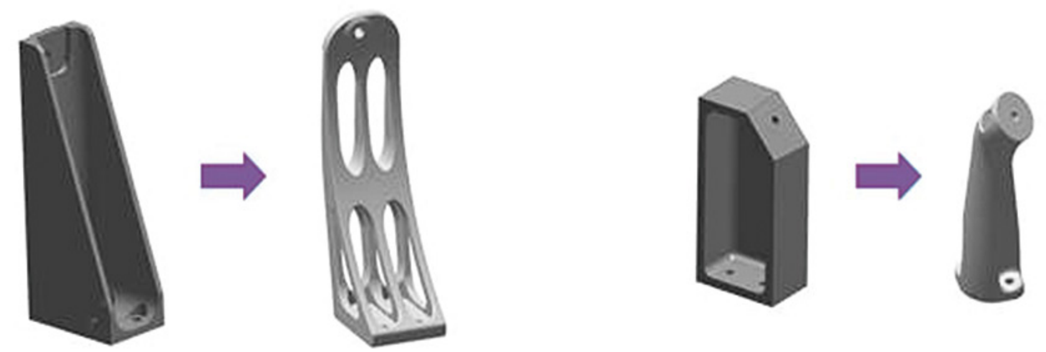
Source: Own Illustration

Appendix C.4: Prototypes for Flyprint

Prototypes for Flyprint

Source: https://www.popsci.com/nike-3d-printed-sneakers#page-4

Appendix C.5: 3D printed parts for 787 Dreamliner - Boeing

Real Example: 3D printed parts opens the possibility to create more efficient mechanical designs for Boeing Airplanes


Source: https://www.boeing.com/features/innovation-quarterly/nov2017/feature-thought-leadership-3d-printing.page

4. Appendix D: Tables

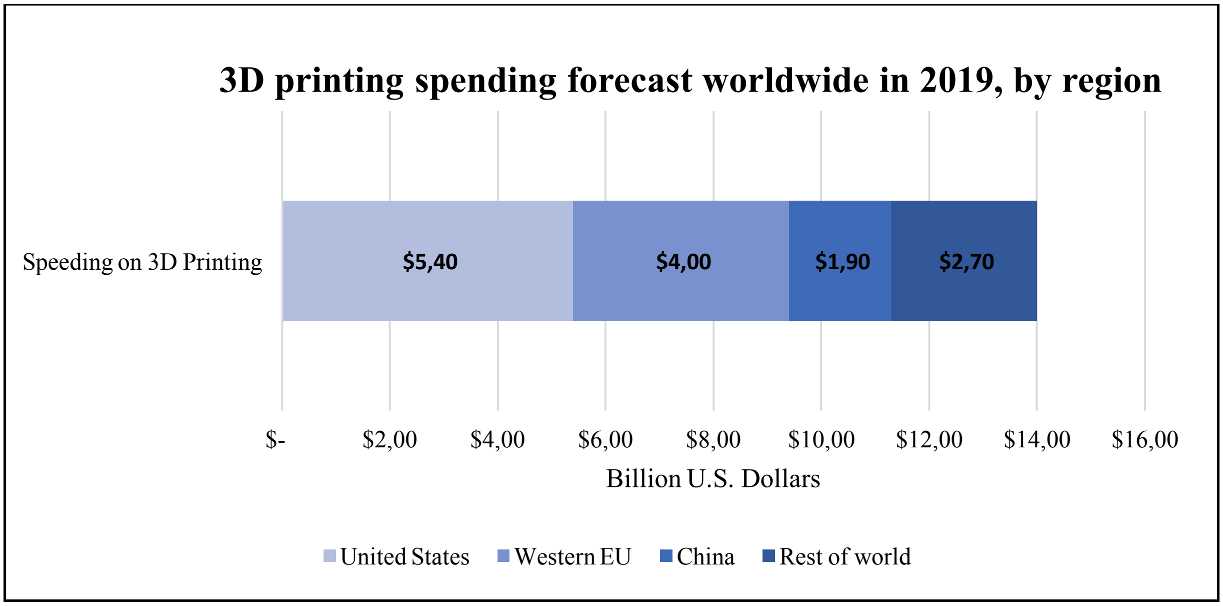
Appendix D.1: Research Questions & Sub-questions

Research Questions & Sub-questions	**What is the 3D Printing technology and where to apply it?** Are 3D printed products as good as those manufactured "traditionally"? What are the limitations of 3D Printing? What are the main benefits of 3D Printing? How has been 3D Printing evolution? How broad is the application of 3D Printing? Will 3D Printing change the world?
	What are the applications of the 3D Printing technology in Supply Chains and major pros and cons? What are the main features of the technology that will allow impacting the Supply Chains? Will 3D Printing disrupt traditional manufacturing process? Will assembly lines be reduced? Will be inventories needed in the future? Is 3D Printing process greener than the traditional manufacturing process? What skill sets will Supply Chain managers require in the future?

Source: Own table

5. Appendix E: Charts

Appendix E.1: 3D Printing spending forecast worldwide in 2019, by region



Source: Own chart based on data available on https://www.statista.com/statistics/891767/worldwide-3d-printing-spending/.