Louvain School of Management

Industry 4.0: Redesigning supply chain management by implementing additive manufacturing: is it really more sustainable?

Comparison of the conventional and digitalized medical supply chains according to the 3 pillars of sustainability.

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List of acronyms

3D: Three-Dimensional

AM: Additive Manufacturing

CAD: Computer Aid Design

CIM: Computer Integrated Manufacturing

DLP: Digital Light Processing

IaaS: Infrastructure as a Service

IoT: Internet of Things

IIoT: Industrial Internet of Things

IT: Industry and Technology

KPI: Key Performance Indicators

MDR: Medical Regulation Devices

PaaS: Platform as a Service

RP: Rapid Prototyping

SaaS: Software as a Service

SC: Supply Chain

SCM: Supply Chain Management

SLA: StereoLithography Apparatus

SSCM: Sustainable Supply Chain Management

SPI: Sustainable Performance Indicators

TBL: Triple Bottom Line

UNDESA: United Nations Department of Economic and Social Affairs

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Introduction

The objective of this thesis is to compare the conventional medical supply chain and the digitalized medical supply chain with the implementation of the technological advances of Industry 4.0, more specifically the additive manufacturing, in order to know which supply chain is the most sustainable.

First, a literature review explains the main terms and sectors useful for this research in order to have knowledge strong enough to understand the study itself and its' direction. The different chapters mention the Industry 4.0 and its components, the 3 pillars of sustainability, the supply chain management and the sustainable supply chain management with the notion of metrics and indicators. The literature review is based on secondary data, existing documents and research.

The methodological approach is then described, stating the different steps followed during this study, the choice of the qualitative study as the working method, the way qualitative data is gathered and analyzed as well as the choice for the interview's sample.

The data and qualitative information are then analyzed, allowing the setting of the main sustainable performance indicators needed in this research for the proper comparison of both supply chains. The mapping of the conventional and digitalized supply chain in the medical sector is also done, stating the advantages and disadvantages of implementing such a technology within the supply chain and the company itself.

Following this, the different interviews with experts are discussed, explaining the corporate's context and providing the main advantages and disadvantages associated with additive manufacturing implementation, in terms of sustainable indicators. To conclude this section, an analysis matrix gathers the different interviewees explanations according to the sustainable indicators set before.

Finally, part V resumes the in-depth analysis of both supply chains, comparing the conventional and digitalized medical supply chain under the different sustainable performance indicators, according to a horizontal and vertical analysis.

To conclude I will be establishing an opinion as to whether implementation of new technologies thanks to Industry 4.0 within the medical supply chain is really more sustainable than the conventional supply chain or not. Recommendations, limits and future extensions of this research are also stated in the conclusion.

Part I. Problem

Supply chain managers are currently facing a significant increase in various factors, such as globalization, the increase of customer requirements, needs and mass customization, competition in the business market, the growing demand for sustainable products and practices, and the ever-increasing use of scarce resources (Cetinkaya, Cuthbertson, Ewer, & al, 2011). This constant evolution forces supply chain managers to always bounce back, to understand the market and their businesses in order to adapt their strategies and supply chains according to these different factors, and more particularly to identify sustainability issues (Cetinkaya & al, 2011). According to Pagell and Wu (2009), to improve supply chain sustainability, supply chain managers have to think about innovation. Today, sustainable supply chains have to fit with innovation and new technologies, usually called Industry 4.0.

At the same time, technology is constantly improving, and today's companies are entering a phase of Industry 4.0, where the different technological processes allow a real inter-connection between industry, production, digitalization and customers (Cetinkaya, Demirel, Ozceylan & Sabirlioglu, 2017). Among these new technologies, additive manufacturing, also known as 3D printing, is becoming more popular in the manufacturing market and in many different sectors (aeronautics, automotive, healthcare, food). 3D printing has many advantages, such as manufacturing on demand, no tooling required, the ability to produce more customized devices based on customer requests, faster manufacturing while reducing inventory requirements, waste reduction by more than 90% compared to traditional manufacturing process and many more (Cetinkaya, Demirel & al, 2017).

The supply chain of companies using 3D printing technology is therefore different from companies producing in the traditional way (Cetinkaya & al, 2017). Indeed, additive manufacturing allows the adoption of a much shorter supply chain, because instead of shipping a product across the world, companies are sending data across the internet.

Thanks to its many advantages, the medical sector is becoming increasingly interested in this new technology, while remaining somewhat skeptical. Whether for the production of spare parts, customized prosthetics, orthotics and implants, anatomical models for surgical planning and education, personalized medical equipment and products and more, 3D printing technology is more and more used (Voets, 2020).

However, the implementation of this technology also includes many barriers, such as the cost of 3D printers, the lack of knowledge about additive manufacturing and the fear of the “unknown technology” (Giglio, 2020).

Despite its’ many advantages such as the implementation of additive manufacturing within a medical supply chain to satisfy customer’s needs (sustainable and customized products requirements), turning the conventional medical supply chain into a digitalized medical supply chain, does it really meet customer expectations and is it a really more sustainable manufacturing process?

Part II. Literature Review

CHAPTER 1. The Industry 4.0

1. History and context

For many years, the production and automation processes within companies have been undergoing changes as a result of various technological advances (Aquilani, Gatti & Piccarozzi, 2018). The first technological transformation started around the 1780s, due to the introduction of steam power and water, called the first industrial revolution, commonly known as Industry 1.0. The second industrial revolution (Industry 2.0) was brought in with electrification, the production line, and the huge production of steel, developed around 1870. Next, the third industrial revolution is represented by the development and implementation of digital computers in the industry (in 1970s) to finally come to the fourth industrial changes (Industry 4.0), reflecting the digitalization over the whole value chain of the life cycle of the product (Aquilani, Gatti & Piccarozzi, 2018), booming at the moment.

The industry is turning to mass customization rather than mass production thanks to industry 4.0, but for the moment the implementation of digitalization as a core process in industries is still rather a vision than a completed revolution (Reuter, 2020).

There is not a single and established definition for Industry 4.0. This is a broad term, which includes different elements playing a key role in the implementation of the fourth industrial changes. The 2 definitions hereafter resume the main ideas and goal of the Industry 4.0:

> "Industry 4.0 is the digitization of the manufacturing sector, with embedded sensors in virtually all product components and manufacturing equipment, ubiquitous cyberphysical systems, and analysis of all relevant data"
> (Mc Kinsey & Company, 2015).

> "Industry 4.0 encourages manufacturing efficiency by collecting data smartly, making correct decisions and executing decisions without

any doubts. By using the most advanced technologies, the procedures of collecting and interpreting data will be easier. The interoperability operating ability acts as a ‘connecting bridge’ to provide a reliable manufacturing environment in Industry 4.0. This overall consciousness gives Industry 4.0 the most important aspect of artificial intelligent functions”
(Qin, Liu & Grosvenor, 2016).

However, there is a difference between digitization, digitalization and digital transformation (Dobrica, 2019). The term digitization is the first step of the process transformation, by transforming physical data into digital ones. In that way, the digital format can be introduced in computer systems and different digital devices (Dobrica, 2019). The digitalization is the continuum of digitization, when different businesses exploit the digital data obtained by digitization, in order to enhance business processes while putting a new digital culture in place in the company. The third step is reached by setting up digitalization as the core of the business and is known as the digital transformation. The aim of the digital transformation is to change corporate culture and the way of working in order to improve the management, efficiency, productivity and profitability of the company (Dobrica, 2019). According to these explanations, the word digitalization instead of digitization is more suitable within the definition given by Mc Kinsey & Company (2015).

Certain recurrent elements emerge from the 2 definitions of Industry 4.0. Firstly, the digitalization of the manufacturing sector through the concept of data collection to reach a digital transformation of the business itself. Then, the notions of cyber-physical and connected processes are put forward, defining the basis of Industry 4.0.

Industry 4.0 has been implemented to improve and extend the gap between the machines, people and objects, thanks to the business digital transformation and engineering processes. It enables the manufacturing businesses to work from mass production to mass customization (Alcacer & Cruz-Machado, 2019). By being horizontally and vertically internet-based connected (Kiel, Müller & Voigt, 2018), the management of businesses and engineering processes becomes way easier.

The goal of the implementation of the industry digitalization, due to the emergence of new technologies, is to improve the company management broadly: improving the efficiency, the flexibility, the productivity of the production processes as well as reducing the waste consumption and the costs, controlling the energy consumption and the overproduction (Ambad, Bhosle & Vaidya, 2018). It also improves the interaction between the suppliers, the customers and the producers as well as the relationship among the human workers and the machine systems (Ambad & al, 2018).

The current broad challenges that companies have to face with the implementation of industry 4.0 technologies are, among others, the increase of global competition between firms, the volatility of the supply and demand in the markets, enhancing the life cycle of products, satisfying customer's requests, data management and value adding (Kiel & al, 2018). However, these specific challenges are closely related to the kind of new technology implemented within companies.

2. Components of Industry 4.0

The idea of Industry 4.0 implementation comes from the improvement and the emergence of new digital technologies, built around 9 main pillars (Lydon, 2020).

There is a concrete difference between the terms industry 4.0 and Computer Integrated Manufacturing (CIM), to understand the human being role within the industry 4.0 and the 9 main technologies of this new industry. In Industry 4.0, the human worker has a primary role and is completely integrated in the manufacturing process, while in the CIM, computers play a key role in the automation of control systems and manufacturing processes. The entire value chain of products is under the total control of computers, only (Ambad & al, 2018).

A brief explanation of 8 components is described below, while point 1.3 provides a more concrete explanation of the 9th component, the Additive Manufacturing (AM), which is the main technology studied during this research paper.

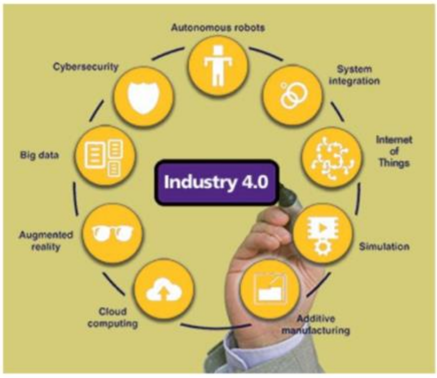

Figure 1: 9 components technologies of Industry 4.0
(Lydon, 2020)

Autonomous robots: Robots are able to do the work that humans are not especially capable of (Alcacer & al, 2019). Customer requirements are more and more specific and customized, so the manufacturing industries have to be more flexible to any demand, made possible through autonomous robots (Alcacer & al, 2019). The autonomous robots work by themselves, in a short period of time, intelligently and cleanly, while being flexible to any situation. Thanks to industry 4.0, robots can interact not only with each other but also with humans, demonstrating the full integration and the inter-connected link with workers in the manufacturing process (Ambad & al, 2018) and the difference with CIM (Ambad & al, 2018).

Simulation: this technology is a powerful tool to see virtually what a project, a process, a design or even a product will look like after its creation or implementation. It helps companies to have a better understanding of the complexity and the functioning of the system, by simulating a prototype of the finished product (Alcacer & al, 2019). This technological breakthrough is mainly used in 3D printing manufacturing businesses, in order to have a concrete idea of the resulting product. This new technology is also widely used to define the cycle time of a product or an installation, as well as the energy consumption, the ergonomic aspects, the materials requirements, etc. of production facilities. Simulation decreases the production lead time and the production costs, but also avoids inconvenience during the launch of a project, having already analyzed the potential barriers of the business processes (Ambad & al, 2018).

Software integration: There are 3 different dimensions of integration in the Industry 4.0, in order that inter- and intra-company communication can flow more easily and quickly (Omron, 2020).

Firstly, vertical integration gathers and shares manufacturing process information between the different departments, within a same organization. It creates bi-directional connections among business processes, IT systems and communication channels between the hierarchy of the company (Omron, 2020). Vertical integration is used to detect defects in the system or to communicate the correct progress of production, so that the controller can closely follow this progress and change the sequence of operations in the system if needed (Omron, 2020).

Secondly, the horizontal integration enables companies to communicate specific and concrete information in value creation networks and production processes (Rathfelder, 2015). The different processes are inter- and intra-linked and connected, while communicating information throughout the process between different entities and companies (Omron, 2020).

Thirdly, the end-to-end engineering integration takes place over the entire life cycle of a product, linking and connecting all the phases and different actors present in the product life cycle, from raw material to storage, transport and manufacturing, to the finished product and beyond. Customers, suppliers, equipment and products are all connected on powerful software to interact with each other and exchange information across the product life cycle (Seliger & Stock, 2016).

Internet of things: this new technology regroups 2 words: Internet and Things. The Internet is a network, a worldwide system provided to users all around the world thanks to interconnected computer grids. The Things can be an object, a device, a person, an infrastructure, anything “physical” (Alcacer & al, 2019).

According to Atzori, Iera and Morabito (2017), the Internet of Things (IoT) is defined as

> “A conceptual framework that leverages on the availability of heterogeneous devices and interconnection solutions, as well as augmented physical objects providing a shared information base on global scale, to support the design of applications involving at the same virtual level both people and representations of objects”.
>
> (Atzori & al, 2017)

In other words, the Internet of Things is the direct connection between the physical production and the virtual cloud of a network, both linked directly thanks to sensors and communicating actuators (software, telephone, network, alarm, etc.) There is a difference between the IoT and the Industrial Internet of Things (IIoT), more accurately for this paper. This difference is represented by the fact that the IoT can be used in any common system, especially for consumer usage, while the IIoT is particularly used in the industrial sector, useful for manufacturing, supply chain and management system processes (Gunawan, 2016). So, IIoT uses IoT in for an industrial purpose. Each specific sensor is connected to a virtual network to communicate all the recovered data and information about the object (the "things"), within an industrial environment (Boyes, Cunningham, Hallaq & Watson, 2018).

Cyber security and cyber physical systems (CPS): The cross-linking between physical world and cyber world is mainly due to exchange and communication of data, most of the time confidentially. All these data, collected by sensors, computing and networks, have to be stored and shared in security, in a cyber-physical system (Alguliyev, Imamverdiyev & Sukhostat, 2018). The trend and rapid expansion of CPS is one of the key challenges of Industry 4.0. Indeed, the security of such systems has to deal with more cyber-attacks due to the vulnerability of the new systems leading by the increase of new wireless devices and the advanced technologies attacks (Alguliyev & al, 2018).

Cloud computing: the cloud is an Internet-based platform gathering all the data and resources provided by different IoT applications and other cyber-physical devices present in the Industry 4.0. According to Microsoft (2020), the cloud computing is

> "The provision of IT services (including servers, storage, databases, network management, software, analytical tools, artificial intelligence) via the Internet (the cloud) in order to deliver faster innovation, flexible resources and economies of scale".
> (Microsoft, 2020)

Their implementation reduces costs (there is no more need to manage and configure different software of which costs are very high), increases the speed of work (information is available directly and allows greater flexibility for companies), raises the accessibility (the clouds are available anywhere and at any time) and increases productivity (employees do not lose time to manually update programs, handling different software so that they can be more productive) (Microsoft, 2020). Companies using cloud computing services achieve economies of scale, i.e. reducing the cost of use while increasing their production capacity, thanks to resource sharing, data storage and accessibility in the cloud (Le big data, 2017).

Different forms of cloud services exist, as summarized by the figure below. It shows the differences between the 3 types of services that cloud computing can provide (Infrastructure as a Service (Iaas), Platform as a Service (Paas) and Software as e Service (Saas)), the different tasks that the service provider manages (in red) and those that the customer using the service manages (in blue).

Figure 2: Different types of Software

(Raza & Watts, 2019)

<u>Augmented reality</u>: Augmented reality is the right balance between the virtual and the reality. It allows the human being to connect with the digital world thanks to new technologies, while remaining in the real world. The real world is augmented but not replaced, by adding to the real-world virtual information (Egger & Masood, 2019). Augmented reality is not to be confused with virtual reality, where the human being is immersed in a virtual world, giving the impression that they are somewhere else from where they truly are. In other words, virtual reality completely replaces one's real vision in order to put humans in another place and environment, which are virtual (Greenwald, 2018). The different ways of using augmented

reality are digitalized glasses, mobile applications using the surroundings area of humans, projectors, etc.

Big data and analytics: The use of big data in enterprises is becoming more and more common and is even inevitable in the era of Industry 4.0, if industries want to stay in the competitive market (Le big data, 2020). According to Le Big Data (2020), big data

> "Refers to a very large set of data that no conventional database or information management tool can really work with. (…) It's information from everywhere: messages we send each other, videos we publish, weather information, GPS signals, transactional records of online purchases, and much more."
>
> (Le Big Data, 2020)

Big data represents all the different data that can be collected from all digitized devices and structures while the data analytics is the management and the review of all these data collected, in order to draw solutions, conclusions and ways forward (Le big data, 2020). Using big data allows companies to have a clear view of their business by measuring and monitoring their systems, see where the gaps are and where to focus on, rework their strategies and decisions to ultimately improve their organization, performance and revenue (Ittmann, 2015).

Additive manufacturing: Additive manufacturing is an advanced technological process in Industry 4.0 that enables a collected data model (digital) to become physical, such as objects, spare parts but also complete infrastructures (Alcacer & al, 2019). This technological edge allows companies to create new products at any time, to have a new business model but also to have a new digitized supply chain (Alcacer & al, 2019). 3D printing enables to manufacture devices of any size up to whole buildings, thanks to different materials possible to the elaboration of this object (liquid droplets, metal, wire, powder, etc.) The manufacturing of the object by 3D printing is done layer by layer under the control of a digital system, which takes all the data necessary for its design (Bandyopadhyay & al, 2018).

3. Additive Manufacturing

<u>Context</u>

Additive Manufacturing, also known as Direct Digital Manufacturing (DDM) or 3D printing, plays a key role in Industry 4.0, especially in the manufacturing processes. CECIMO (2019), the European Association of the Machine Tool Industries and related Manufacturing Technologies, defines the Additive Manufacturing as

> "The technology that applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material".
>
> (CECIMO, 2019)

Another deeper explanation, given by the ASTM Standard F2792, the standard terminology for additive manufacturing technologies is defined as

> "A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies, such as traditional machining.[…] It is a disruptive technology, and a technological shift that can lead companies into a new area of manufacturing characterized by phenomenal changes to industries and the development of new business models."
>
> (ASTM Standard F2792, 2015)

This method is a manufacturing process is the act of creating a physical and end-usable object, using a "layer-by-layer" or "drop-to-drop" method to product new industrial structure or product, on the contrary of conventional manufacturing process that needs machinery to build, forge or cut out a product coming from a big material (Bandyopadhyay, Bose, Charitidis & al, 2018). The first 3D printing machine was built at the end of the 1980s, by the company 3D Systems Corporation (American firm), after that the first patent was issued in 1986 (Bandyopadhyay & al, 2018). While Additive Manufacturing is the act of creating a physical and end-usable object, a final product, layer by layer, using various 3D printing technologies, without molding, machining or casting. Otherwise, the way the parts are obtained is the same, using the layer-based technique as 3D printing technologies (Lehmhus, 2014).

Whether in the aeronautic sector, the automotive replacement parts industry, the medical sector, the aviation industry or in construction, this new type of technology is used more and more during the manufacturing process (Bandyopadhyay & al, 2018). The evolution of AM technology and machines is constantly growing, making it possible for any company to purchase 3D printing machines at a lower cost (Bandyopadhyay & al, 2018).

The 3D printing technology allows the production of specific spare parts in a broad variety of different materials, such as metal, ceramic, polymers, nanomaterials but also materials of pharmaceutical and biological origin (Bandyopadhyay & al, 2018).

Different processes of 3D printing

7 main functional processes for additive manufacturing exist, using a different and specific 3D printing technique (Bandyopadhyay & al, 2018). Each of these 7 processes includes other even more specific manufacturing processes depending on the material used, but the way to print the finished product in 3D remains the same, depending on the functional manufacturing process (Bandyopadhyay & al, 2018):

- Vat photopolymerization (VP): This type of 3D printing is done using a liquid photopolymer (a resin), placed in a tank (called a container), which is cured layer after layer by means of a heat source (a laser or a light beam such as a UV ray). This light beam scans the surface of the resin very precisely, drawing the exact shape of the expected object. These layers, hardened by the interaction of the heat source with the polymer, will form the expected product in 3 dimensions, layer after layer. The VP process is very precise but only works with polymer and ceramic material and the 3D printing machines used are quite expensive. This process is used in the medical 3D printing method, known as StereoLithography Apparatus (SLA) and Digital Light Processing (DLP)

- Material jetting (MJ): This process assembles, layer by layer, a liquid photopolymer resin heated between 30 and 60 degrees. This heated resin is projected onto a support in the form of micro droplets, thanks to a very thin print head, and then comes directly to harden. The MJ system allows to manufacture objects of different materials but also of different colors, thanks to the existence of different “print heads”, each one corresponding to a specific type of material. However, the volume of 3D printed objects is still very limited, and the quality of the objects can be limited over time due to the degradation of the materials when they come into contact with light (3D natives, 2020).

- Binder jetting (BJ): It is a 3D printing method also known as "binder spraying", which uses a binder material deposited on a thin layer of powder. The printing is done following the basic model, layer by layer, in order to achieve the complete printing of the object by gluing the different layers together. The binder can be different materials, such as metal, polymers, ceramics but also sand. This production system allows companies to create very precise devices of any size and customized in a short period of time. It is the cheapest 3D printing method of all, due to the low cost of the basic material required. However, the finished objects are often more fragile, and the material is not perfectly smooth.

- Material extrusion (ME): This type of technology uses (mainly) a thermoplastic material as the basic printing material, which is heated to obtain a liquid compound and is deposited in the form of a continuous filament. Using a print head, called a nozzle, the molten thermoplastic material is deposited on a base to print the first layer of the desired object. The process repeats and proceeds layer by layer to obtain the finished object. This type of 3D printing, also called continuous filament deposition, is possible with different materials such as concrete, thermoplastics, ceramics and also chocolate (3D experience, 2018). This process is used in the medical 3D printing method, known as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM)

- Powder bed fusion (PBF): This 3D printing method fuses powder particles together using a thermal heat source (laser or electron beam) to build layer by layer the expected object with high precision. This technique makes it possible to obtain objects whose shape is difficult to print but also offers a wide range of choices in the design of objects in 3D printing. This process is used in the medical 3D printing method, known as Selective Laser Sintering (SLS) or Selective Laser Melting (SLM).

- Sheet lamination (SL): This 3D printing technology allows the manufacturer to print objects by superimposing different layers of foil or sheets. Also known as "Laminated Object Manufacturing" (LOM), this technique uses standard sheets of paper most of the time. They are all gathered together in the 3D printer, which will pick them up one by one and cut them out precisely (with a knife or a laser), before being glued to the sheets that have already been cut out. By superimposing the different layers of paper, each cut into the right shape, the final object is obtained.

- Directed energy deposition (DED): This technological process allows different materials to be split together, melting the materials as different layers are produced. The materials are melted using concentrated energy beams, such as a laser or electron beam. The materials injected onto the substrate are mainly powder or metal wires but can also be polymers. This manufacturing process again allows for fast and high-quality production, allowing the repair of damaged parts and the addition of new functionalities to existing objects.

These 7 different 3D printing techniques can all be used to obtain an object, but some methods are more efficient than others depending on the desired object. For example, the polymer material or polymers-based products cannot be exposed to too high temperatures (object melting risk), so methods using metal or ceramic material are then preferred. Indeed, in the Additive Manufacturing processes, each machine is more conformal to certain states of matter in order to build a certain type of device/structure in a specific material (Bandyopadhyay & al, 2018). Here after, the figure resumes the different methods of 3D printing and the suitability of different materials depending on the method. As we can see, the polymer-based materials are the most suitable, followed by ceramics and then the metal materials.

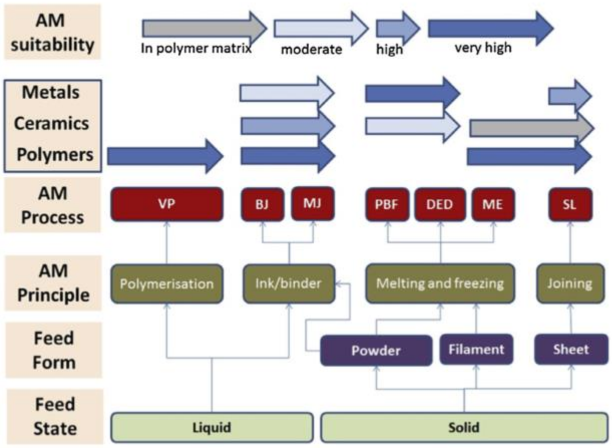

Figure 3: 7 mains 3D printing processes and the material suitability
(Bandyopadhyay & al, 2018)

AM in the healthcare sector

Unlike conventional manufacturing processes, AM allows a customized manufacture, layer-by-layer, on demand. This is a direct manufacture process from the design of a low volume of device to the high-quality finished product (Bandyopadhyay & al, 2018).

At the beginning, 3D printing was mainly used for prototyping and research development, but since then, medical sector can produce customized and on-demand products. When it comes to orthotics and prosthetics, 3D printing is commonly more and more used. The fact that you can produce any shape after a 3D scan of a patient make it super valuable for patients (3D natives, 2020).

The production phase has complete freedom as to how the devices are manufactured, while at the same time being precise and having constant control during production. It is for these reasons that the medical sector and technology experts have been looking into this new way of production. What if additive manufacturing revolutionized the medical world?
Thanks to this new technology of manufacturing, medical sector can never be out of pieces (Gradl, T., 2020). According to the European Commission (2017), medical devices are divided in 5 main categories:

- Models for preoperative planning
- Tools, instruments and parts for medical devices
- Inert implants
- Medical aids, supportive guides, splints and prostheses

- Bio manufacturing

And defines medical devices as

"any instrument, apparatus, appliance, software, material or other article, whether used alone or in combination, including the software intended by its manufacturer to be used specifically for diagnostic and/or therapeutic purposes and necessary for its proper application."

(European Commission, 2017)

Each supply chain is different depending on the category, and this is the fourth one that will be discussed and analyzed deeper during this research, and more precisely the manufacture of medical devices such as orthotics, prosthetics and bandages in the orthopedics sector.

3D printing of medical devices such as these have many advantages, making it possible to produce a device made specifically for the patient's injury, minimizing production time while producing a quality product. These are medical devices that are placed outside the body, allowing a part of the body to be restored, relieved, maintained or supported. Orthotics correct a part of the body, while prosthetics replace entirely a part of the body (SPF, 2019).

CHAPTER 2. Sustainability and Triple Bottom Line

In recent years, Sustainable development and Sustainability have been one of the main discussions in the industry world. According to the United Nations World Commission Environment and Development, Sustainable development was defined in 1987 by the Brundtland Commission as

> "A development that meets the needs of the present without compromising the ability of future generations to meet their own needs".
>
> (Brundtland Commission, 1987)

In 2015, the United Nations Members States adopted 17 Sustainable Development Goals, with the goal for them to be implemented before 2030, in order to have a better economy, environment and society for our planet and our living conditions. The aim of the UN World Commission Environment and Development is to sensitize, support and evaluate companies, government and stakeholders in relation to the different goals set up, concerning water, energy, climate, environment, urbanization, science, technology and oceans (Sustainable Government Goals, 2020). By stakeholders, this is including children and youth, local authorities, farmers, non-governmental organizations, women, workers, the science and technology sector, volunteers, the education sector and more. In 1984, Freedman defined stakeholders as

> "All persons or groups with legitimate interests participating in an enterprise do so to obtain benefits and that there is no prima facie priority of one set of interests and benefits over another".
>
> (Freedman, 1984)

The 17 sustainable development goals bring together the essential elements to improve the global economy, taking into account poor countries, while respecting the environment and the planet. In addition to this, respect for working conditions, human beings and health must also be included (Sustainable Government Goals, 2020).

Figure 4: Sustainable Development Goals (2020)

These 17 sustainable development goals can be grouped under 3 major categories: the human-being side, the economic side and the environment side. These 3 categories are closely linked with the 3 pillars of Sustainability, better known as the Triple-Bottom-Line (TBL), which are the People, Profit and Planet.

Before, in the business sector, companies were used to follow one bottom line, which was the profit or the loss (Fischbach & Ksiezak, 2017). Today, and for the past 50 years, corporate strategies are changing as people become more aware of thinking about human and environmental issues. That's why, since 1994, 2 new bottom lines have been added to Profit to form the Triple-Bottom-Line: The People aspect and the Planet aspect (Fischbach & al, 2017). The Triple Bottom Line is a kind of marker, which informs and measures the rate of performance within a company by analyzing the profitability of the 3 pillars, separately and all together. The firm performance gathers the positive and negative impacts of environmental, social and economic dimensions over the long run but also the competitiveness of the firm among the market. However, companies are still struggling to measure their social, environmental and economic impacts. This is why it is essential, at the present time, each company have to find adequate indicators to measure their impacts, such as defining their Key Performance Indicators (KPIs). Finding good performance indicators for the 3 pillars of sustainability is one of the main researches of this paper, carried out in chapter 4.

1. People

The Social bottom-line is measured within a company as human capital. It can be measured or analyzed under different characteristics, such as the respect of human rights, fair work (adequate wages and adequate working hours), the place of the employee in the enterprise, the well-being of the employee at work, the interdiction of child labor, the safety of the employee, equality of genders at works, … (Fischbach & al, 2017). The social pillar measures the relationship between a community, customers and employees linked to the company (directly or indirectly) and the company itself, which should be as fair and as close as possible. The company must feel concerned and invested by the social link with its close community. This social interdependence is essential, because without direct or indirect actors, an enterprise cannot function (Fischbach & al, 2017). The most a company will care about its customers, employees and community, the most those will feel concerned and attached to this company, and the most the company will be reliable and trustworthy about the social bottom line. Competitiveness and the place in the market of a company depend of all these social and ethical responsibilities.

2. Profit

The economic dimension of sustainability is not, as one might think, all about profit. It is a measurement indicator to see how a company manages its business and uses its assets and resources efficiently, appropriately and responsibly in order to generate profit over the long term (Fischbach & al, 2017). Although many companies want to rely solely on the profit pillar, a company cannot be sustainable without the contribution of social and environmental dimensions. This is why the economic dimension must be put on an equal footing with the other two pillars. Different characteristics are covered under this pillar, such as risk-taking by companies, good business management and the inclusion of different shareholders in the business, as employees, customers, suppliers and communities linked to the company (Fischbach & al, 2017). It is for these reasons that this pillar is also referred to as the good governance pillar, because it considers the vertical integration of all people directly and indirectly impacting the business. This economic dimension can therefore be summarized as an indicator for evaluating the sustainability, by measuring the company's profit and growth thanks to different characteristics over the long term, without hampering the social and environmental pillars. It is indeed by respecting these two pillars that profit can be generated over the long run (Fischbach & al, 2017).

3. Planet

The environmental pillar includes the different impacts that can be done "environmentally speaking" on the planet but also on the humans. This third dimension, which is the last one of the triple bottom line, can be also measured through different indicators, such as the pollution generated by the company in water, air and soil, the raw materials used to manufacture the finished products, the energy consumed by the company throughout the supply chain, etc. Different ways to analyze the eco-friendly responsibility of a company exist (Fischbach & al, 2017). A first possibility to assess the effect of a business on the environment, is by analyzing the ecological footprint of the various resources that a company generates over an entire year and comparing them to the resources still available on the planet. Thanks to this comparison, the company know exactly what kind of resources were being used and the equivalent amount and analyze the different emissions when these resources are used, which are potentially bad for the planet (Fischbach & al, 2017).

Another indicator often used to measure whether a company is environmentally friendly or not, is the Life Cycle Assessment. This kind of assessment is used by many businesses to see the environmental impact (positive and negative) of their activities. It covers all the steps necessary to make a product, from raw material to finished product or recycled product, often called "from cradle to grave", and analyses the effects and impact of each step on the environment (Peterson, 2019).

All the applications that a company will implement in order to fight against environmental degradation will improve its reputation, satisfy more customers and therefore have a better place in the market (Fischbach & al, 2017).

The figure below shows how the interaction between the three pillars :

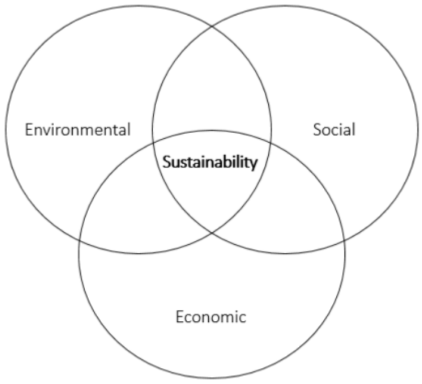

Figure 5: Triple Bottom line representation
(Wilson, 2015)

CHAPTER 3. The Supply Chain

1. Supply Chain Management

Definition

According Chopra and Meidl (2007), a supply chain is defined as

> "All stages involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves".
> (Chopra & Meindl, 2007).

Also known as a Supply network, the supply chain includes the movements of products in all stages but it also "includes the movement of information, funds, and products in both directions" (Chopra & Meindl, 2007).

The objective of a supply chain is to deliver a product to a customer, while fulfilling its specific requests, to maximize the overall value created all along the supply chain as well as matching the supply and the demand sides. To match the supply with the demand, Supply Chain Managers have to study both sides, evaluate each step and actors playing a key role, and trying to minimize the costs of the whole Supply Chain.

Keeping in mind that the customers are the only revenue generators, the different costs are the flow of information, products and funds between stages of the supply chain (Chopra & Meindl, 2007).

Objectives

It is all about the proper management of the supply chain in order to have good performance of the company. Supply Chain Management (SCM) consists of

> "The management and control of the flows of material, information, and finances between and among supply chain stages to maximize total supply chain profitability."
> (Chopra & Meindl, 2007)

To reduce the costs and increase performance, the supply chain manager must handle the waste all along the supply chain (Chopra & Meindl, 2007). Waste can be the use of a wrong material, a defective machine, an unnecessary quantity of raw material, an inefficient inventory management in the warehouse, delays to transport products from the warehouse to the wholesale, ineffective promotion, and marketing campaign, etc. If all this waste is managed properly and the supply chain manager has correctly optimized the company's performance, the "7Rights" of logistics are respected. The Charted institute of Logistics and Transport UK (2019) defines the 7 rights as the right time, right product, right quantity, right price, right condition, right place and right customers.

Principles

Each supply chain has its own strategy, in order to know when a product has to be manufactured, transported, sent to the retailers to finally be available for customers.

Depending on the customers demand and the time required to respond to customers demand, 2 different strategies of logistics processes exist: the push strategy and the pull strategy (Maritz, 2017).

Push supply chain strategy is implemented when companies anticipate customer demand by manufacturing the product in advance of the customer's request. The order comes from the manufacturers, to the suppliers and to the downstream steps of the supply chain. This enables companies to plan their raw material stocks properly, to correctly plan the production steps and to manage the warehouse of the products (Maritz, 2017). For this, we talk about speculative strategy.

Pull supply chain strategy is implemented in order to directly respond to consumer requirements. The order comes from the customers and goes in the upstream supply chain processes, passes by the retails, the distributor and the manufacturers to finish to the suppliers. Also known as "just-in-time" strategy or "reactive" strategy, the companies begin to manufacture a product only when there is a customer demand for it. It allows companies to improve the inventory management (less stock in the warehouses) and reduce their costs due to overstock.

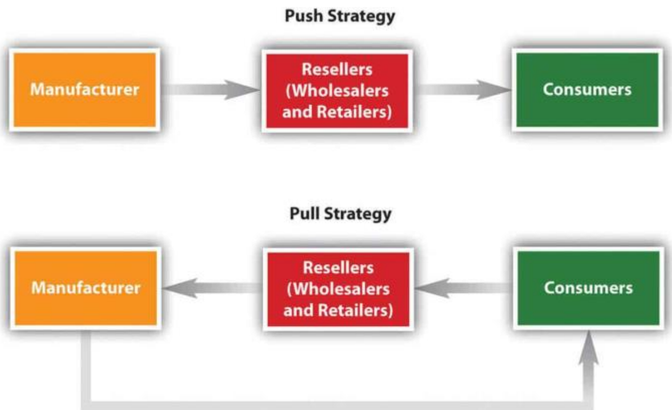

Figure 6: Push and Pull strategy

(Maritz, 2017)

Challenges

Any supply chain management faces 3 main challenges: the uncertainty, the transparency and the complexity (Chopra & Meindl, 2007).

Supply and demand are uncertain in nature. Uncertainty of demand, for example, can lead for example to shortages of raw materials and then disrupt the whole process and smooth running of the supply chain. There are different factors impacting the demand uncertainty (Chopra & Meindl, 2007).

Each customer has different needs, requirements and expectations, so companies need to understand the specific needs of their customers and fitted their strategies in order to respond to customer requests as best as possible: whether it is the average quantity requested, the price, the maximum time a customer will tolerate for its product delivery, the service quality, but also the specificity of the product (customers are increasingly attracted by innovative products), all these factors affect demand uncertainty.

Supply capacity can be limited but also inflexible, yields are not sufficient to continue production, product quality is too poor, suppliers encounter social and environmental problems, hindering the smooth running and evolution of the manufacturing process, etc. Uncertainty must be controlled and reduced through the collection and analysis of relevant data (market studies, past sales, customer consumption habits, etc.) as well as knowing product characteristics in order to be able to properly manage the whole supply chain and never fall into shortage, disruption or delay. This uncertainty can be very costly for companies if they do not manage it correctly and efficiently (Begen, Pun & Yan, 2017).

The transparency of the supply chain is a big challenge for companies, because the word “transparency” is not defined just how transparent this should be. According to Bateman & Bonnani (2019), supply chain transparency requires “the companies to know what is happening upstream in the supply chain and to communicate this knowledge both internally and externally”. However, the question of which pieces of information in the supply chain suppliers must communicate, how far the information should be revealed and to who is still unclear. Consumers, but also other stakeholders such as NGOs and the government, increasingly want to know where the products they buy come from, how they have been produced, how they have been transported to the point of sale, what exactly the product is made of, etc. (Bateman & al, 2019). This constant demand pressure to transparency is a problem for companies, because by updating and making all the information needed to make a product available to everyone, companies can lose out on competitiveness. On the other hand, if companies do not comply with this demand, customers will turn to other companies that meet their expectations (Bateman & al, 2019). A study conducted by the MIT Sloan School of Management also showed that customers are aware of the importance of human well-being in the workplace and take care that the products they buy are not made by children and that employees are treated well throughout the supply chain. Indeed, they are willing to pay 2 to 10% more for a product from an enterprise that ensures more transparency in its supply chain (Bateman & al, 2019).

Finally, the complexity of the supply chain remains one of the main challenges today, because it requires many independent players. Julien Mosquera (2016), a professional in

Supply Chains and Operations, regroups the whole complexity of supply chain into 7 dimensions of complexity:

- the customers: companies have to satisfy services customer requirements;
- the network: a whole supply chain requires sometimes stakeholders and suppliers from all over the world, which is difficult to manage properly;
- the organizational: the internal and external organization of the supply chain includes different business activities and organizational structures, which must be adapted and managed for the smooth running of the activity;
- the process: the degree of complexity of a supply chain also depends on the number of processes that the manufacturing of a product requires. The more different steps to manage, the more complex the supply chain will be;
- the product: the complexity of sourcing the right raw material, of delivering a quality product to customers by assembling parts from different companies requires complex continuous control;
- the range: this involves properly managing the product life cycle and its different variations, which are constantly improving. Precise monitoring of each product and the diversification of the range must be managed properly to decrease the complexity of a product range;
- the supplier dimension: suppliers of a manufacturing industry can come from all over the world, increasing the complexity of the network and the management of the entire supply chain (Mosquera, 2016).

Figure 7: Example of the complexity of a Conventional Supply Chain
(Mosquera, J., 2016)

2. Sustainable Supply Chain Management (SSCM)

As for supply chain 4.0, this part will define broadly the concept of the sustainable supply chain management, the objectives to reach being sustainable and the challenges this kind of supply chain has to deal with. A more in-depth analysis is carried out in the research section, integrating the different dimensions of the supply chain 4.0 and the sustainable supply chain in the case of the medical sector, thanks to 3D printing.

<u>Definition</u>

Over the past two decades, the topic of sustainability has become an important part of the business world. Supply chain managers and researchers are trying to introduce this notion and the associate's values within their supply chains, in order to become a real challenge and a research sector of business activity today (Pagell & Shevchenko, 2014). This is why the terms "green supply chain", "corporate social responsibility", "ethical supply chain", etc. are incorporated more and more by businesses. By combining the sustainability and the supply chain processes, supply chain managers measure sustainable supply chain performance thanks to the profit or the loss, but also thanks to the environmental and social impacts of such a supply chain. But what does a sustainable supply chain really mean? According to Pagell and Wu (2009), to be truly sustainable, a supply chain would

> "At worst do no net harm to natural or social systems while still producing a profit over an extended period of time; a truly sustainable supply chain could, customers willing, continue to do business forever"
> (Pagell & Wu, 2009).

Taking into account that a sustainable supply chain has to be managed, a Sustainable Supply Chain Management (SSCM) is defined as

> "The designing, organizing, coordinating, and controlling of supply chains to become truly sustainable with the minimum expectation of

a truly sustainable supply chain being to maintain economic viability,
while doing no harm to social or environmental systems."
(Pagell &Shevchenko, 2014).

In both definitions, the Triple Bottom Line are taken into account to measure the social, economic and environmental components of performance and evaluate these impacts in the whole life cycle of a product.

According to Carter & Roger (2008), the implementation of sustainable practices within the supply chain offers many advantages, for example cost reductions (thanks to the decreasing of packaging waste as well as the reduction of the inventory management), improve the working conditions of employees, an improved corporate image, etc. But the implementation of such activities also presents some barriers such as the strenghtening of regulations, the lack of knowledges about this culture, and so on.

Objectives

The first thing to understand in the sustainable supply chain, is that sustainability is first about changes. According to Kersten and Saeed (2017), the goals of a SSCM are "to provide a maximum value to all stakeholders and to fulfill customer requirements by achieving sustainable flows of products, services, information and capital as well as enabling the cooperation among SC participants" (Kersten & Saeed, 2017).

Never mind the objectives, challenges, strategies, the sustainable supply chain manager has to rethink all these business processes because they are going to be changed, or at least modified (Pagell & Shevchenko, 2014).

The primary objective of sustainable supply chain management is that companies become aware of the issue of sustainability within a business, that they become familiar with this topic and that they fully adopt it.

Once adopted, the second objective is to improve the business performance by implementing the environmental and social pillar in the core of the business and that these two dimensions have to be treated on an equal footing with the traditional economic pillar (Pagell & Shevchenko, 2014). Implementing a sustainable supply chain must bring real change within the company, by measuring positive impacts on economic, environmental and social aspects.

To reach these objectives, sustainable supply chain managers have to change the culture and the behaviors of the enterprise as well as the way of taking managerial decisions and thinking about performance (Pagell & Wu, 2009).

Challenges

In addition to the challenges faced by the conventional supply chain, Sustainable Supply Chain Managers have to understand, address and deal with even more specific challenges, more focus on the sustainable side.

After rethinking the way to switch from conventional supply chain to sustainable supply chain, and how to deliver value to consumers and for what purposes (Pagell & Shevchenko, 2014), one of the big challenges of Sustainable Supply Chain Management is to convince employees, managers and all stakeholders of the company, of changing the firm **culture**. That is to say, the way of working as well as the way of thinking. They first need to understand the real potential and challenges of setting such a supply chain, but also what sustainability means exactly. Implementing SSCM requires a real change in how managing the Supply Chain, and that this new strategy be fully integrated into the corporate strategy and culture, no longer as an isolated strategy and management (Pagell & Shevchenko, 2014).

Another challenge of a SSCM is obviously to **manage the risk over the supply chain** as well as **fixing problems that are interorganizational.** According to Carter and Rogers (2008), sustainable supply chain risk management is defined as

“The ability of a firm to understand and manage its economic,
environmental, and social risks in the supply chain”.
(Carter & Rogers, 2008)

Risk management is essential to set priorities in the supply chain. By analyzing those risks, supply chain managers know where to focus on, in order to observe a difference, a reduction of the negative impacts of the 3 pillars on the supply chain management and directly on the performance. Supply chain managers and businesses have to understand that they will never see a total elimination of the environmental, social and economic negative impacts and harms applying sustainable facets, but a potential decrease of negative impacts of each. They must therefore set themselves targets for the expected and optimal rate of decline they have to reach **over the long run** (Pagell & Shevchenko, 2014).

One not going without the other, to understand and control the challenge just below, the difficulty not only for a sustainable supply chain manager but also for governments and other stakeholders, is to answer to the questions: "How do we know we are a (more) sustainable supply chain than before? What are the realistic and feasible targets to reach?". According to Pagell and Shevchenko (2014), supply chain managers have to find a way to **measure sustainable impacts** (in a positive or negative way) in order to know if changes improve the firm's performance or not. Companies have to take into account direct as well as indirect measurements of economic, social and environmental impact during the whole supply chain process (Pagell and Shevchenko, 2014).

As an integral part of the challenges of the conventional supply chain, **transparency** in the sustainable supply chain is of course a major challenge for companies implementing sustainability dimensions. As mentioned in the supply chain challenges, customers and stakeholders are increasingly demanding visibility in the supply chain, credible and detailed information, in order to know where the products they buy really come from and "how sustainable" the supply chain of the firm is. According to Chopra and Meindl (2007), nowadays, too many misconducts that do not comply with the 3 pillars of sustainability are still taking place in the upper supply chain (child labor, poor working conditions, etc.). Customers are becoming more and more sensitive to the respect and implementation of sustainable dimensions in businesses culture and stakeholders need visibility on the environmental and human aspects as well, so transparency in the sustainable supply chain is paramount. The image and reputation of companies can be severely damaged by different stakeholders if the firms have unsustainable behaviors. A company with a bad reputation will see direct repercussions on its profits (Kersten & Saeed, 2018). Here again, companies are struggling to find out how far this transparency should go, what information stakeholders really want to know, while remaining competitive in the market. The fact that we are currently living in an innovative and highly technological society puts even more pressure on companies with regard to the transparency system, because if a company hides something or does not tell the truth, it will find out very quickly (Carter & Rogers, 2008). Indeed, there are more and more strict regulations and controls on the social and environmental dimensions of sustainability in companies, such as The UK Bribery Act, UN Guiding Principles for Business & Human Rights, Dodd-Frank-Act, UN Global Compact and many more (Kersten & Saeed, 2018).

Sustainable supply chain actors

The typical sustainable supply chain is composed of 5 different functional categories (Chopra & Meindl, 2007), such as a conventional supply chain. However, the way the different processes are managed (internally and externally) and for what purposes are different, by implementing the sustainability culture in the product's life cycle. Whatever the stage of the supply chain, the sustainable supply chain manager takes care to adopt an ethical guideline and to reduce negative environmental impacts for the environment as much as possible (in terms of energy consumption, water, polluting emissions, etc.). The sustainability of a supply chain can be measured thank to different indicators, that companies have must settle down.

Hereafter is a description of the 5 main functional categories of the sustainable supply chain and some examples of things put in place by a firm to be as sustainable as possible (Chopra & Meindl, 2007):

- The first actor of a supply chain is the **raw material supplier**. Sustainable companies must procure from certified sustainable companies, which pay attention to the types of raw materials extracted as well as the types of machinery used.
- Another actor playing a role in the upper supply chain is the **component supplier**. As for the raw material supplier, firms have to make contracts with suppliers as sustainable as possible, in order to have all the parts necessary for the manufacturing of a product.
- Then, there is all the manufacturing process, thanks to **producer.** The production phase consists of different steps, beginning with the purchasing of raw material and component material, the product design, all the internal processes and manufacturing processes and all the logistics to maintain a good management of this functional category. All these phases require particular attention and efforts on the sustainable dimensions, such as optimizing the product's life time by using suitable materials, not

using machines whose emissions are too damaging for the environment but also not consuming too much electricity or water, that the employees working in these different phases also work under respectable and safe working conditions. Finally, the finished products, ready to be sent for consumption, have to be manufactured in an environmentally conscious way, paying attention to the type of packaging used and how the product can be reused or recycled.

- To ensure the link between the place of production and consumers, **distributors** and **retailers** are paramount. They too must minimize CO2 emissions during transport and minimize energy consumption at the warehouse sites.
- Finally**,** the **end consumers** have an essential stake in the supply chain, in terms of how he will use the product but also what he will do with it at the end of its life (reusing, recycling, etc.).

3. Sustainable supply chain measures: metrics and indicators

Sustainable Supply Chain Management aims to manage social, environmental and economic impacts throughout the supply chain of companies (Pagell and Shevchenko, 2014). To manage the sustainable supply chain properly, it is therefore necessary to measure these impacts in order to know if the objectives set are achieved or not. These impacts are analyzed under the term of performance through different metrics and indicators, better known as Key performance indicators (KPI) or more precisely Sustainable Performance Indicators (SPI) in this context (Kersten & Saeed, 2017). Measuring the performance allows companies to improve and raise the level of awareness, to improve the good cooperation between the supply chain managers and all the stakeholders included in the supply chain as well as facilitate the proper integration of these sustainable indicators within the supply chain (Kersten & Saeed, 2017).

Sustainable Performance Indicators is defined as

> "Indicators that help to measure the performance of an organization at least in one of the three dimensions of sustainability"
>
> (Kersten & Saeed, 2017)

There are plenty of sustainable performance indicators such as international standards or guidelines to assess sustainable impacts regarding the environmental, economic and social indicators within a supply chain (Kersten & Saeed, 2017).

The lack of transparency throughout the supply chain is partly due to the fact that there is no single standard or methodology for setting corporate sustainability performance. There are different Environmental Social and Governmental (ESGs) standards and disclosure framework revolution (GreenBiz, 2020).

One guideline is not better than the other, some standards focus more on environmental aspects, others on social aspects and others on all 3 aspects at the same time. Many studies shown, however, that sustainable performance indicators in relation to the social pillar are still less developed than the environmental and economic pillar (Kersten & Saeed, 2017).

For example, some of the existing guidelines about environmental performances are ISO 14001 and Carbon Disclosure Project (CDP). As for the social dimension, standards known as SA 800 and ILO already exist. Finally, guidelines gathering two or the three dimensions of sustainability in one report are the Sustainable Development Goals (SDGs), Global Reporting Initiatives (GRIs), UN Global Compact (UNGCs), Ceres roadmap, Dow Jones Sustainability Indexes, Sustainability Accounting Standards Board (SASB), Task force on Climate-related Financial Disclosures (TCFD) and many more (Kersten & Saeed, 2018; Reuter, 2018).

These standards are all driving and accelerating the transformation to a more sustainable business world. As Joel Makower said, “Without standards, there is no hope. You can’t measure what matters without standards. What can’t be measured doesn’t count” (GreenBiz, 2020). Dealing with these standards allows companies to manage and mitigate the risks, drive efficiency and costs, build brand values as well as enabling a future increase (GreenBiz, 2020).

Some companies create their own framework and SPI to sort their data and know how to calculate their sustainable performance, based on qualitative or quantitative indicators. According to GreenBiz (2020), each company has to define and chose its own guideline, depending on the type of business, objectives to reach and feasibility to set them, which is a real challenging task (Kersten & Saeed, 2017). Moreover, each corporate culture depends on the localization over the world, meaning that the culture, the politics and environmental settings can be different (Kersten & Saeed, 2017).

PART III. Methodological Approach

1. First approach

The aim of this paper is to compare the conventional supply chain and the digitalized supply chain with the implementation of a new technological advance of Industry 4.0, the additive manufacturing.

The in-depth analysis of these 2 forms of supply chain is made under the 3 pillars of sustainability: People (the positive /negative impacts on humans), Profit (the impacts on the economy of companies) and Planet (the impacts of such an implementation on the environment).

The analysis of 3D printing technology is done in the healthcare industry, more specifically in the orthopedics field (3D printing of orthotics, prosthetics and bandages). The advantages and disadvantages of implementing such a technology within a supply chain process and the company itself is also analyzed.

The goal is finally to understand if Industry 4.0 and the change to a more digitalized supply chain, commonly known under the term supply chain 4.0 is really more sustainable than the conventional supply chain.

We decided to focus on the orthopedics medical devices for several reasons. Firstly, orthotics and prosthetics are types of medical devices similar in regard to their manufacturing process. They also use the same types of raw materials (plastics, rubber, etc.). Finally, both types of medical devices are classified as "class 1 medical devices" (Broze, 2020), i.e. they are devices used outside the body. Medical products belonging to class 1 are those with a lower risk, that is to say the least dangerous for health. Although medical regulations are strict for any type of product, medical products placed outside the body face fewer regulations and are less risky (Broze, 2020)

2. Choice of the working method

2.1. A qualitative survey

The choice of working method, for the realization of this thesis, is based on a qualitative method, within the framework of an exploratory study. According to Adi Bhat (2020), an exploratory research is defined as “A research used to investigate a problem which is not clearly defined. It is conducted to have a better understanding of the existing problem but will not provide conclusive results". A qualitative study is therefore necessary in order to understand the sector according to experts, the environment and the context.

The first argument for this choice is that there are few literatures on this specific research question. Industry 4.0, sustainability, supply chain 4.0 and 3D printing in the medical sector are new resources that are in the process of being implemented but are not yet a complete revolution (Reuter, 2020). As a result, few analysis and research papers exist on these 4 sectors at the same time.

The second argument is that the objective of this thesis is to understand the implementation of a digitalized supply chain in the medical sector, and to draw the main advantages or disadvantages in terms of corporate sustainability. The digitalization of the supply chain through additive manufacturing depends on the culture of the company, on the perception of the users but also on the important changes that medical companies are ready to do or not. With all these arguments, qualitative research seemed to us the most appropriate.

2.2. A case study

This exploratory study also included a case study, looking at 4 different companies. According to Yin (2009), a case study is used to answer questions such as "How" and "Why". It is conformed with the different research questions of this thesis, namely

- How to compare both supply chain in terms of sustainability?
- Why implementing additive manufacturing within a company, is it really more sustainable?

A case study's goal is to understand a real-world case, where "contextual conditions are pertinent to our case" (Yin, 2009). That is why interviews with additive manufacturing as well as medical experts were done, to gather pertinent and real-world information depending on their company.

3. Data gathering

An initial collection of informative data is possible through the research we did during the literature review. Data available through previous and scientific research, more commonly referred to as secondary data, are found thanks searches on specific terminology.

Then, it is also possible to collect data "in the field", by meeting the different supply chain managers, medical experts and research & development experts in order to understand more easily the concept and the business process.

In spite of the COVID19 situation, it is impossible to collect information and significant data “in the field” for the proper advancement of this thesis. However, a lot of online conferences and webinars have been organized about additive manufacturing in the healthcare sectors, sustainable supply chain and many more. So, lots of useful information are available online thanks to these online videos.

In addition, four individual interviews were conducted, to collect the necessary and essential.

Individual interviews are preferred to a group interviews in this research. Individual interview allows us to deepen our knowledge of a situation, understand complex behaviors and talk to professionals, while the group interviews encourage the generation of new ideas through the interaction of respondents (Dessart & Steils, 2016). The interviews were then conducted in a semi-directive way. A semi-directive guide allows interviewees some freedom with open-ended questions. It influences the answers less than a directive guide, but allows the interview to remain precise, keeping a certain structure in the process. All the important topics will be addressed, but in no particular order. The interview is therefore flexible and easy to conduct.

Interviews are conducted by video conferencing, with the aim of obtaining qualitative data that captures experience, personal opinions and actual working conditions, which can therefore be used as relevant data.

4. Choice of sample of the interviewees

The interviewees are selected as sample of medical experts, additive manufacturing experts and supply chain managers. This sample was chosen based on previous research, knowing what kind of information were wanted from.

Interviewee 1: Louis-Philippe Broze, CEO of Spentys. Spentys is a company providing a software to orthopaedists and medical experts so that they can introduce a 3D printing solution in their manufacturing processes. It helps medical firms and hospitals to produce 3D printed medical devices but also provide a platform and software for 3D printing.

Spentys represents research and development expertise, end-user software as well as manufacturing of orthopaedists medical devices.

Interviewee 2: Rémi Giglio, technician and orthotics specialist at Giglio orthopédie. Giglio orthopédie produces orthotics and prostheses in the traditional way and begins to use by 3D printing technology in its manufacturing process.

Rémi Giglio represents an end-user of Spentys software in the downstream supply chain and also represents 2 opinions for a good comparison of the digitalized supply chain and the traditional supply chain.

Interviewee 3: Chief Operation Officer at Alpha Company. Alpha Company is one of the biggest mass-producing company in Belgium, running technical orthopedic and providing technical solution for clients. The company owns 120 different sites in Belgium. This firm uses 3D modeling for 10 years now and develops 3D devices as well, getting more and more adopted in the production process.

Alpha Company produces medical devices in the traditional way and begins to use 3D printing technology more and more, while being still skeptical by this new technology.

Interviewee 4: Laurent Voets, teamleader of additive manufacturing at Sirris. Sirris is a collective center of the technology industry, helping companies to implement new technologies in the core process of their business.

Laurent Voets brings an external perspective and expertise of the implementation of additive manufacturing within a company.

5. Data Analysis

The data analysis was divided into several stages.

Firstly, each interview was transcript and read several times in order to understand the content.

Next, an analysis of the meaningful sustainable performance indicators, directly linked to the medical supply chain and this particular sector, is done. The literature review already stated the purpose of setting KPI in a business strategy, and experts mentioned that these KPI depend on the industry and the sector. Based on the literature review as well as primary data collected thanks to different interview, a clear guideline of meaningful SPI is done in order to compare both supply chains at the end.

Having already analyzed the main steps of the conventional supply chain (regardless of the sector) during the literature review, the second step of the qualitative survey is to adapt the information according to the healthcare sector. Thanks to different interviews, online webinars and discussions with experts, a mapping of the conventional medical supply chain as well as the digitalized medical supply chain is done. The advantages and disadvantages of the additive manufacturing implementation are also analyzed in this part.

Then, an analysis of the interviews gathering the information collected and the sustainable performance indicators statements is done.

At the end, and analysis matrix, synthesizing the information collected, is developed. This analysis grid lists the individuals in columns and the different SPI in rows, synthesizing the SPI relationship according to the various companies.

Finally, a general complete analysis of the different SPIs in the medical sector implementing the additive manufacturing is carried out, to finish this part with a comparative table of the traditional supply chain and the digitized supply chain according to the SPI.

6. Ethical aspects

The following ethical aspects have been put in place to ensure the rights of respondents (Dessart & Steils, 2016):

- Anonymity is preserved when requested.
- Recording of data is only permitted with the consent of the participants.
- Respondents have been informed about the use of the data.
- Participants are not obliged to answer when they do not want to.
- The recording of respondents is made available to them, if they so wish.

PART IV. Data gathering and qualitative survey analysis

CHAPTER 1. Sustainable supply chain measures in the healthcare sector

1. *Sustainable Performance Indicators in SSCM*

This section analyzes the most relevant sustainable indicators needed to compare the conventional and the digitalized supply chains during the manufacturing of orthopedic medical devices. As mentioned during the literature review, all indicators and metrics depend on the company, the type of sector and the type of sustainable goals the firm wants to reach (GreenBiz, 2020). To do so, companies have to create their own frameworks to sort their data and know how to calculate their sustainable performances, based on qualitative or quantitative indicators.

The setting of the relevant SPI for this research is done according to primary and secondary data, so existing documents, different sustainable guidelines and standards, webinars and thanks to the different interviews with experts. The most important information used in this part are adapted from Kersten and Saaed research (2017), that have already analyzed the main important supply chain sustainability performance indicators. However, an adaptation of the specific SPI for the medical sector, more precisely the orthopedics sector, has been made.

Hereafter is a representation of their methodology to discover and create a framework of the best supply chain sustainability performance indicators possible, to prove the expertise of their statements.

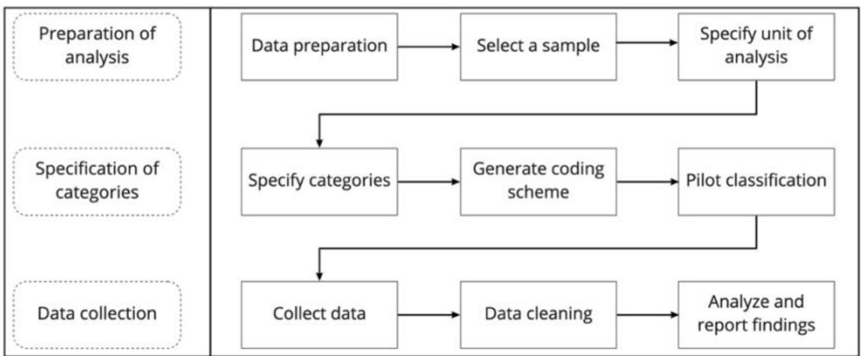

Figure 8: Content analysis methodology, adapted from Kersten and Saaed (2017)

Sustainable performance indicators are grouped in 3 different categories, the assumed 3 pillars of sustainability: environmental, social and economic dimensions. Each sustainable pillar includes different attribute categories as explained below.

2. Environmental performance indicators

The environmental dimension takes into account all resources and emissions that can impact the planet and the ecosystem in terms of inputs (energy, water, raw material, …) and output (gas emissions, product waste, …) (Kersten & Saaed, 2017). These indicators can be measured quantitatively through metrics and data collections or qualitatively through reports. This study only focuses on qualitative data and information. In the medical sector, the meaningful environmental performance indicators can be analyzed under 6 main attribute categories.

Attribute categories	Definitions
Energy consumption	This category gathers the total energy used all along the supply chain, within a company. The energy consumption analysis is done from the extraction of raw material to end-product, taking into account the machineries, renewable and non-renewable resources, etc.
Material	This category represents all the material used and needed during the manufacturing process and all along the supply chain. Material gathers raw material, already-used material and recycled material.
Waste management	This category represents the proper control of all kind of waste during the manufacturing process, such as total waste produced, and total waste reused or recycled.
Air emissions	This category includes all indicators related to the emissions released along the supply chain and the manufacturing process of the medical devices, during transports for example or because of different machineries.

Land use	This category involves all the areas used by a company, for the proper manufacturing of a product and the proper management of the company operations (warehouse, buildings, …).
Environmental regulations	This category is essential to understand if the company follows the right environmental regulations assessed by governments or other entities. That can be indicators related to the right compliance to mandatory environmental standards, regulations, certificates and labels.

Table 1: Environmental Performance Indicators
(Adapted from Kersten & Saaed, 2017)

3. Social Performance indicators

The social dimension is the one with the least existing research and papers. This sustainable dimension takes into account the employees and broad-human responsibilities within a company. However, considering that this paper is about the medical industry and the manufacturing of medical devices to fix patient's injuries, "human" and "patients" are paramount in this sector. The categories and indicators stated below are all qualitative, because we can't count and measure those indicators. To properly assess these indicators, different methods are used such as employee and patients survey, monitoring and codes of conduct. Social performance indicators, in the medical field, can be analyzed under six main categories.

Attribute category	Definition
Human resource	This category involves lots of indicators related to human resources such as employee's satisfaction, employee well-being at work, number of available jobs and gender equality at work.
Training and education	This category gathers indicators such as the trainings provided to employees to improve their work and being familiar with their daily work.

Consumer issues	This category deals with all the “after-sale service” such as complaints, returns and manufacture’s defects.
Patient’s care	This category involves all the benefits that patients (consumers) derive from a product (medical device).
Social regulations	This category relates indicators about the compliance with specific social laws such as social certificates, standards or guidelines
Time	This category involves timesaving according to human dimension such as product delivery time to consumers, timesaving for employee during the manufacturing process, ….
Table 2: Social Performance indicators (Adapted from Kersten & Saaed, 2017)	

4. *Economic Performance indicators*

The economic sustainability performance gathers all the costs and revenue resources that an organization has to manage in order to move on to sustainability. The aim is to control costs and revenues while minimizing negative impacts on the planet and society. To qualify and quantify these indicators, in the orthopedic sector, economic sustainability can be divided into four main attribute categories.

Attribute category	Definition
Sustainability expenditures	This category gathers indicators about all costs and spending for sustainability purpose such as more local procurement, implementation of new sustainable corporate culture and labeling to improve its sustainable performance.
Profit and stability	This category evaluates the sustainable financial health of the company. It also includes helps from the government, investors and other entities thanks to the implementation of sustainable practices.
Costs and income distribution	This category includes all costs and expenditures a company has to pay such as wages, taxes and payment to the government

Time	This category gathers all timesaving process that leads to a better time management and then save money.

Table 3: Economic Performance Indicators
(Adapted from Kersten & Saaed, 2017)

CHAPTER 2. Traditional Supply chain in the medical sector

1. Context

Today, the conventional supply chain is being severely disrupted by the advent and development of new technologies. However, the medical sector is still quite skeptic about technological advances, especially orthotist/prosthetists (Broze, 2020). The manufacturing process of orthotics/prosthetics has always been a manual job, where the manufacturer needs to see and feel the patient's limb to be corrected. Rémy Giglio, an orthotist/prosthetist for 20 years, explains that the way of touching the patient and feeling the injury is essential for medical experts, and that this ancestral way of working and technique is difficult to change. During this research, we wanted to find companies that operated and manufactured these medical devices only in conventional ways, that is to say that the production of orthoses/orthotics is only done manually and with machineries, without the use of 3D printers. There are still some small companies that only work in that way. However, more and more have turned to printing medical devices in 3D, alternating and combining manual work and technology (Alpha Company, 2020). Most orthopedic procedures are very time-consuming and labor-intensive having experienced very few changes in last decades (Broze, 2020).

2. Principles

The supply chain process begins with the procurement of raw materials and at the same time, the meeting between the patient and the orthopedic specialist. The specialist does a prototype of the medical device needed by measuring (manually) the body segment and adapting it according to the patient’s body. The orthotics specialist manufactures a positive and a negative plaster mold to understand the patient’s injury (Giglio, 2020).

Once the prototype is ready, the manufacturing stage begins. After modifying the positive model with the patient’s body structure, the orthopedist has to shape the medical device, using big machineries and materials to get the right fitting as the prototype. Once the medical device is ready, it has to be transported to the orthopedic site before the patient comes to pick it up. At that moment, the patient tries on the medical device and potential adjustments can still be made.

The mapping of the conventional supply chain of orthopedics medical devices can be found under APPENDIX 1

CHAPTER 3. Digitalized Supply chain in the medical sector

1. *Context*

Due to new technological advances to improve performance and competitiveness among industries, companies need to rethink the way they operate and change their corporate culture, especially within the supply chain (Bienhaus & Haddud, 2018). This is why, inevitably, companies are introducing technological advances in their supply chain to turn into a more digitalized supply chain, commonly known as Supply Chain 4.0.
ET edge (2019) defines Supply Chain 4.0 as

> "A concept delves into 3 main aspects: increasing demand for a responsive or connected end-to- end Supply Chain, a better collaboration in the ecosystem – right from suppliers to customers, and enhanced need for customer centricity".

As a comparison with the literature review, the digitalized supply chain is supposed to include suppliers, manufacturers, transporters, warehouses, retailers, distributors and customers (Chopra & Meindl, 2007). However, it would be a bit minimalistic to reduce the sustainable analysis of this research only to these different steps of the supply chain from raw material to finished product, without including the so-called "support activities", part of the value chain. Indeed, all the research and product development part (of software in particular) is an essential step for the implementation of additive manufacturing in the medical supply chain, and this activity is not directly included in the supply chain itself, but as a support activity among the value chain of the firm.

Although the two terms may be quite similar, there is a clear distinction between the two chains: On one hand, the supply chain represents the different steps needed to the manufacturing of a product and the operation management of these steps, in order to satisfy consumer's requests. The value chain on the other hand, represents all the interrelated activities necessary for the firm to create, design, manufacture and deliver a product by adding value to this product (through the different stages of production, sales,...), in order to create a competitive advantage (Reuter, 2018).

According to Porter (1985), the product value chain consists of two different but complementary areas of activity: the core (or primary) activities and the support activities.
The core activities correspond to five complementary ones (MindTools, 2020):

- The internal logistics (inbound logistics): it regroups all the intern activities taking place in the upstream supply chain, before the production phase but after the reception of raw materials, such as the transportation of raw materials as well as its storage, the communication system inside the firm and the information system technology.
- The production / operation: it consists of the transformation of raw materials into a subset of finished products. It's all the manufacturing step, inside the company.
- The external logistics (outbound logistics): it includes the transport from the manufacturing plant to the warehouse for the storage of the products and all the management of this distribution phase.
- The marketing and sales activity: everything that revolves around the promotion and marketing of the product.
- The service activity: it includes all the services related to the sale of the product itself but also the after-sales service.

Support activities, for its part, consists of 4 significant activities:

- The procurement: any activity involving the purchasing of raw materials, machines needed for production, etc.
- The technological development: all the research and development activities, uses and implementation of software
- The human resources management: activities that take over the social side of the company, such as job interviews, remuneration, training and employee relations.

- The infrastructure of the firm: necessary for the proper functioning of the company such as accounting, legal aspects and management.

The picture here after is a representation of the Porter value chain

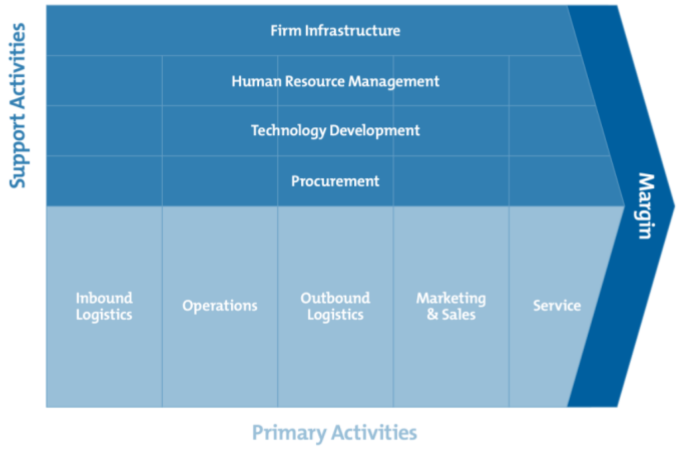

Figure 9: Value chain activities
(MindTools, 2020)

As the digitalized supply chain is, by definition, the complete integration of new technologies within the supply chain, we will therefore consider the creation and use of software, the technological development, the data transfer, 3D scans and all that refers to additive technology as part of the supply chain. Indeed, the value added thanks to the additive manufacturing technology is principally in the production step (thanks to the performance of the software and 3D printers) and in the use of the finished product.

2. *Principles*

After researching existing information on the supply chain of additive manufacturing in the medical sector, and after organizing information gathered during the different interviews with experts of this specific digitalized supply chain, the different activities of the supply chain 4.0, including the additive manufacturing, in the medical sector are as follows:

In the upstream supply chain, 3 different activities occur at the same time.

- Procurement of the raw materials and 3D printers. The medical devices can be produced with carbon, propylene, thermoplastic polyurethane (TPU) and many more (Broze, 2020).

- Data collection of the patient’s 3D body scan: the patient’s 3D body scan and related data are needed to send it as a virtual file to the software.
- Product and research development: it gathers the end-to-end software, 3D scanner and 3D printer development. Also known as Computer Aid Design (CAD), the software is needed to stock and transform the 3D body scan into different layers, so that the software sends the patient’s data information to the 3D printer. It exists different software used in the medical sector, such as Spentys, All 3DP, Fusion, etc. (Broze, 2020).

Then, the second step and the one that makes the real difference between the conventional and digitalized supply chains, is the medical devices manufacturing phase. Once the raw materials as well as the 3D body scan are ready, the 3D body scan file is sent virtually to the CAD software. The software analyzes the 3D body scan and separates the scan into different layers, in order to obtain a digital file. The file is sent to the 3D printer and transmits the precise information for the correct design of the medical device (Broze, 2020). The 3D printer will then create the part, layer-by-layer. The sentence “Instead of shipping a product across different industries, we are sending data across the internet” makes perfect sense.

Finally, the last phase occurs in the downstream supply chain, which includes the distribution to the orthopedic specialists, surgeons or hospitals to deliver the medical device to the end consumers, the patients.

APPENDIX 2 represents the mapping of the digitalized supply chain, in the medical sector. The red arrows represent "virtual" transfers, such as data transfers from computer to computer, while the black arrows represent "physical" transfers of materials and products. The dark blue boxes represent the activities carried out in the upstream supply chain, the blue diamond represents the main production activity and finally the light blue boxes represent the activities that occur in the downstream supply chain.

The digitalized supply chain is a real evolution of the traditional supply chain. Indeed, a conventional supply chain has a lot of different lines: supplier lines, assembly lines, production lines (cf. figure 8). In these different lines, lots of parts are involved: the production of the mold in the milling machine, the different parts of the bridle to be assembled, the components made of different raw materials, etc. Sometimes, some of these parts may break down and so manufacturers need new parts, orthotist - prosthetists ordering these parts, designing these new parts to manufacturers and that takes time (Giglio, 2020). However, if orthotists/prosthetists/manufacturers put a 3D printer next to their line when they need a new part, it's lot faster than ordering a new part elsewhere. Indeed, manufacturers and medical experts can skip all the time wasted in ordering, purchasing and shipping.

For example, Spentys, one of the interviewed companies, provides healthcare industries with all of the services needed for the 3D printing of medical devices (Broze, 2020):

- The implementation and maintenance of the software (combining the 3D body scan of the patient, the data processing on the platform in order to print the medical device physically)
- The 3D printers
- The research and development expertise
- Training to change the medical company's way of working.

With this service, there is no distribution and no long transportation needed, because everything is done in the same place. Therefore, production step of medical devices can be done locally and quickly. The medical device can be 3D printed between 2 and 10 hours (depending on the patient's trauma) and directly provided to patients (Giglio, 2020). This is a kind of "all-in-one suppliers", significantly reducing the required number of steps within the supply chain to produce a medical device (Karevska, 2019). The digitalized supply chain using additive manufacturing in the healthcare sector is represented in APPENDIX 3.

So, the way the supply chain is coordinated is completely different (Alpha Company, 2020). Indeed, if each manufacturer produces medical devices on their own buildings, the production process becomes a so called "distributed manufacturing". Additive manufacturing allows digitalized supply chain to be closest to the patient by providing distributed manufacturing processes way more locally. The digitalized manufacturing accelerates the world transition to digital distribution and local manufacturing (Ultimaker, 2020). An example of distributed manufacturing in the medical sector is represented in APPENDIX 4.

3. Challenges

As a comparison to the challenges quoted during the supply chain and sustainable supply chain literature review, interviews with additive manufacturing experts reinforced in one hand some challenges, adding further explanations; whilst also stating new challenges. Additionally, the digitalization of the supply chain in the medical sector reduced, if not, eliminated some challenges that the conventional supply chain has to deal with.

Changing a company's culture is the biggest challenge companies have to face to implement additive manufacturing within their supply chain. The four interviewed experts said that this is the main barrier to the implementation of additive manufacturing. Primarily, new technologies frighten employees, medical experts and patients (Broze, 2020). Knowledge is a key driver, but there is a big question mark over how fast AM knowledge and skills will spread. Due to the innovation of this technology in the medical field, medical experts and practitioners are skeptical and have to be technically trained. Rémy Giglio mentioned "there is a fear of loss a know-how". This fear comes from the lack of training availability and the technological limitations, that companies need to work on. This is essential for the proper implementation of 3D printing technology, such as dealing with data and software, understanding and learning how to virtually work on patient's injuries. The learning curve of additive manufacturing is long, it takes time but it's all surmountable (Giglio, 2020). If companies turn more and more to this new technology, it's because there is a real potential, already proved and improving everyday (Alpha Company, 2020).

Measuring sustainable impacts is also one of the biggest challenges for companies today. Because there is not one single guideline of sustainable performance indicators, companies have to take the time to create their own standards and sustainable objectives to reach. This is actually one of the biggest challenges of this paper; setting the right sustainable performance indicators in order to compare both supply chains. In addition, some indicators are measured qualitatively (through consumer's surveys, reports, ...) and others are measured quantitatively. As this technology is new, measuring quantitative indicators such as total greenhouse emissions, costs, profit, … of the AM implementation within the supply chain is currently impossible due to complexity, novelty and lack of accurate data.

Regarding the transparency, whether in terms of sustainability within the company but also in terms of raw materials procurement, machineries, and the way the medical devices are manufactured, 3D printing allows a greater transparency. Indeed, medical experts have to explain to their patients the way the medical device is manufactured (Giglio, 2020). Furthermore, lots of information is present on the company's website, as Louis-Philippe Broze mentioned during the interview "We are 100% transparent on the origin of our products but also on all stages of our supply chain. The brand of our 3D printing machines is available on our website, this is a key value for Spentys" (Broze, 2020). However, in order to keep a certain competitiveness in the market, the number of 3D printed medical devices per month for example is quite confidential, as Rémi Giglio stated during the interview.

The complexity of the digitalized supply chain has been adapted and improved with the implementation of additive manufacturing in the medical industry. Even though the 3D printing supply chain could seem more complex due to the multiple actors from different sectors (software developers, 3D printer developers, raw material suppliers, medical experts), they all can be brought together in the same manufacturing place, as proposed by Spentys.

Compared to the 7 complex points of the traditional supply chain, here are the changes in the digitalized medical supply chain:

- the customers: companies have to satisfy customer requirements. The 3D printing technology allows companies mass customization, even more in the medical sector because medical devices are manufactured depending on patient's injuries (Alpha Company, 2020). The orthotics and prosthetics devices are manufactured on demand, customized and meet the needs of patients.
- the network: the network becomes less complex due to the distributed manufacturing process. The relocation makes the manufacturing process more flexible (Voets, 2020). However, the distributed manufacturing requires a company's complete reorganization due the whole line of the supply chain and the network change (cf. APPENDIX 4).
- the organizational: the internal and external organizations of the digitalized supply chain include different business activities and organizational structures, but the distributed manufacturing process facilitate the smooth running of these activities because everything is done at the same place (Voets, 2020).
- the process: once the software, the raw materials, the trainings and the right implementation of the AM technology is done within the medical company, the degree

of complexity of the supply chain is better because the number of required processes is shorter (Broze, 2020).

- the product: the complexity of delivering a qualitative product to patients is improved thanks to AM technology, because the 3D body scan is precise, and the rate of the 3D printing machine error is low (a gust of wind that would move a drop of layer for example). However, once the product is finished, orthopedists can’t work on the material anymore. Medical experts have to learn to do it virtually, thanks to software. Ultimately, there is a fear but also an assurance of having the right measures and a finished medical device (Giglio, 2020).
- the range: orthopedic sector gathers a whole spectrum of insoles, prosthetics and orthosis devices, podiatry, wheelchairs, compression for lymphoedema patients and many more (Giglio, 2020). So, it's a whole range of very different products, requiring different manufacturing processes. However, once the 3D data files are entered into the software and modified according to the patient's dimensions, the 3D manufacturing becomes easier.
- the supplier dimension: depending on the suppliers, the complexity of the supply chain changes. Subsequently, it depends on each company and their own suppliers. Among the interviewees, suppliers come from Belgium, Germany, Italy or Spain. They try to procure inside of EU for a sustainability point of view as well as for a better after-sale service (Giglio, 2020).

As the manufacturing of medical devices reflects a pull supply chain strategy, the uncertainty is greatly reduced in the medical sector. Pull supply chain directly responds to consumer’s requests. In the healthcare domain, more precisely the orthopedic one, medical experts manufacture medical devices especially for patients, depending on patient’s injury. So, the order comes from the customers (due to injury) and goes in the upstream supply chain processes (3D printing machine) after the 3D body scan. Even in the conventional medical supply chain, the uncertainty is reduced for the same reasons stated above. However, the digitalized supply chain allows even more on-demand production of medical devices, on site, which bypasses the time-consuming process of transportation and warehousing (Broze, 2020).

4. Advantages

The advantages of implementing 3D printing within the medical supply chain are numerous:

- Medical devices are manufactured directly from the 3D body scan, creating custom-made and patient-specific medical devices and decreasing the error rate. The rate of unsuitable products is very low (Broze, 2020).
- Medical devices manufactured in the traditional way are very often returned to the producer to modify its rigidity, efficiency or flexibility. 3D printing allows the direct modification on patient’s body at the same place (Giglio, 2020).
- On-demand manufacturing and distributed manufacturing is key for patients and the healthcare sector. It is a very flexible process and allows the 3D printing whenever and wherever patients need it.
- 3D printing enhances the patient care pathway at every stage: planning, patient consent, procedure, recovery, outcomes (3D natives, 2020).
- AM avoids risks (optimized planning to decrease risks), save time and ensure better outcomes (less invasive, quicker recovery and shorter procedure) (3D natives, 2020).
- Reduces raw material usage, which is a key contribution to environmental sustainability (Voets, 2020). 3D printing produces only what is needed: material is added layer by layer, we don’t cut out big material, so the material waste is really decreased.
- Opportunity to produce complex structures not possible in the traditional manufacturing way and ability to customize medical devices.
- No physical warehouse needed in the digitalized medical supply chain. It is a digital warehouse with all data files required for the 3D printing of medical devices. Manufacturers do not send parts anymore, but virtual files directly to the software, accessible from all over the world. Digital warehouse allows medical experts to share their knowledge, experience, and data files. Medical experts just have to download the file, press start on a printer on their location and the medical device appears. Digital warehouse cancels parts transportation directly linked to the reduction of footprint emissions.

CHAPTER 4. Interview results and analysis matrix

This chapter explains the information stated during the semi-directive interviews. The information is structured by explaining the context of the company first and the place of additive manufacturing within the company. Then, an analysis of the potential sustainable performance indicators that are directly or indirectly linked to the company is done. Finally, the potential disadvantages of the AM implementation quoted by the experts are explained. At the end of this chapter, an analysis matrix gathers the main information of the interviews according to the different sustainable performance indicators.

1. *Interview 1: Louis-Philippe Broze: Spentys*

The interview guideline with Spentys is stated in APPENDIX 6.

Context

Spentys is a Belgian company, introducing an end-to-end complete and simplified cloud platform solution for the workflow of orthotics. Spentys wants to find a solution enabling orthopedists to easily introduce 3D technology within medical firms. Spentys facilitates the research and development work and helps customers on the integration of the 3D technologies in their daily work, allowing both cost and time efficiency. The platform aims to bridge the gap and simplify communication between medical expertise (the expertise of orthopedists and medical experts), technological experts, and the added value of 3D technologies. The software is complete, efficient and clinically validated by scan (Broze, 2020).

Spentys allows customers to obtain a 3D body image (the 3D patient's scan), a 3D model (the custom medical device 3D image) and the high quality and low-cost 3D printing of the medical device (Broze, 2020). This is an open system, so any 3D printer is compatible with the platform, where more than 70 orthotic files are available with unlimited design possibilities.

The 3D printed medical device has many advantages:

- Custom-made: adapted to the patient's needs and limbs
- Waterproof: water-resistant and non-porous raw materials

- Lightweight: the medical device weighs about 50 grams
- Recyclable raw materials
- Ventilated: the medical device has holes in a way that allows patients to feel more comfortable in the orthosis – prosthesis device.
- Adaptable: the medical devices can be thermoformed, i.e. modified after manufacturing process, using very flexible, light and rigid materials. These products can be printed in carbon, propylene and TPU, which means that medical experts have a very interesting range of materials (Broze, 2020).
- No knowledge of CAD (Computer Aid Design) required.

Due to another observation made from the plaster room, Spentys expanded its range of products, adding trauma type orthotics (plaster for traumatic pathologies) to chronic type orthotics. During the manufacturing of the cast, lots of raw materials as well as other components are discarded and wasted. This leads to both poor stock management (as not all processes are digitalized yet), and a considerable delay in creating a cast for the patient. In this instance, Spentys offers a solution. For example, scanning the arm of a patient in the emergency room directly in 3D (time taken: 2 minutes), to model the brace directly in the plate room (time taken: less than 5 minutes), and finally to print up to 3 braces in less than 60 minutes. As with chronic orthotics, trauma type orthotics are much lighter, waterproof and recyclable.

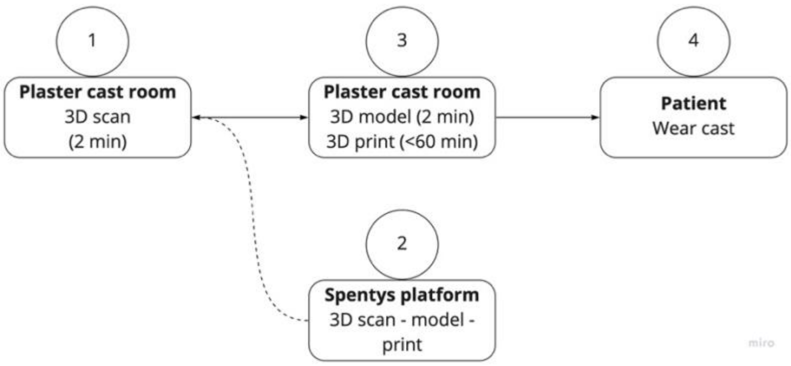

Figure 10: Spentys's base model

Louis-Philippe Broze insists on the "complementarity" of 3D printing technology in the medical field, because there is always a need for medical intervention and expertise during the manufacturing process. 3D printing technology is not intended to replace traditional medical practices. It is very important to give practitioners the opportunity to adapt the medical device if needed or to work on the material. Additive manufacturing brings an extra dimension to the conventional process.

Spentys's aim is to provide software, printers, services, and all the support during the AM technology implementation within the supply chain. Customers (hospitals and medical experts) are then equipped with the 3D printing machine and an appropriate software, combining the 3D body scan of the patient, the data processing on the platform and the 3D printing of the medical device at the same place (Broze, 2020).

As for the regulation in Europe, all medical devices sold and used on the healthcare market must comply with the regulations known as "Medical Device Regulation" (MDR). The MDR, adopted in March 2017, had to be implemented by companies from 26 May 2020. However, due to the COVID-19 crisis, the compliance with this regulation was postponed in May 2021 (Broze, 2020). The MDR applies to any medical device, as defined in the literature review, all 3D printing machines for medical devices, but also medical software "used as an accessory to a medical device" (Bouscaud, 2019). The new MDR regulations replace those that were previously implemented (highlighted applications with commercial interests) and are more patient-oriented, for example valuing product quality management and risk reduction.

Spentys MDR compliant but also ISO 13 485 certified. According to the European Commission (2016), the ISO 13485 standards specifies "requirements for a quality management system where an organization needs to demonstrate its ability to provide medical devices and related services that consistently meet customer requirements and regulatory requirements applicable to medical devices and related services" (European Commission, 2016). This standard is used by "organizations involved in the design, production, installation and servicing of medical devices and related services" (ISO, 2020).

Sustainable Performance Indicators

Spentys does not refer to special sustainable guidelines or standards, but the company tries to be as sustainable as possible. Using the Sustainable Development Goals as an example and setting such large goals while they are still a young company would be too optimistic, according to the CEO.

However, lots of indirect sustainable actions can be taken into account among the sustainable performance indicators used in this research.

- The 3D printing of medical devices allows for mass customization. This technology meets customer's needs for several reasons: medical devices are manufactured on demand, with an airy shape, lightweight and adaptable.
- Currently, Spentys is developing an idea to manufacture all the medical products with recyclable materials. Raw materials come from Spain, Italy or Belgium. Spentys' goal is to recover orthotics and prosthetics that are no longer needed (ie. once the patient has healed), melt the orthotics and prosthetics made of plastic raw material, recover the plastic and be able to create a new medical device with this raw material. The aim is to have a "closed-loop" life cycle.
- Spentys' employees try to decrease their carbon footprint emissions by using public transport when they meet with their customers.
- The 3D printers come from China, however this is the only product coming from outside of Europe. Otherwise, as far as raw materials are concerned, materials come from Spain (Smart 3D), Italy (Treed materials) and Belgium.
- Spentys wants to be 100% transparent with customers, patients and companies about the raw material procurement and all stages of its supply chain. Everything is explained on the Spentys website, from raw material origin to the implementation of the software. The customer's trust is paramount.
- Additive manufacturing is an adaptable technology. For example, during the COVID-19 crisis, Spentys was able to modify its offer and provided to hospitals essential spare parts to the proper functioning of respiratory machines. These parts were previously out of stock and had to be ordered in from China, however the waiting time was far too long for the sick patient. Additive manufacturing technology allowed Spentys to 3D print these parts directly in Brussels and help hospitals in need.
- Even though 3D printers are quite expensive (a minimum of 5000€), the fact that the 3D printer produces layer by layer only what is needed, means that there is no material waste. Also, orthotics and prosthetics are lighter, reinforcing the use of few raw materials. The reduction of transport is also included in the costs saving.

Negatives points

The first negative point to the AM implementation within a medical supply chain is the cost in general. At a first glance, 3D printers can appear to be quite expensive. However, as previously explained above, these costs must be balanced with the profit created by 3D printing technology (less material waste, lighter medical device, etc.)

Then, employees, patients and medical experts are still skeptical about new technologies and additive manufacturing. This fear comes from a lack of technological knowledge. It is for this reason that Spentys offers to their customers support from start to finish when implementing the software or using the products, in order to feel comfortable with this innovative manufacturing process. It is important to realize that complemented traditional manufacturing with 3D printing technology is a real change within the manufacturing process itself and in corporate culture.

Finally, the error rate can be a barrier. Some manufacturing errors may occur during the 3D printing of medical devices. For example, if a gust of wind disrupts the machine, the laser may miss a layer and therefore the finished product will not be 100% perfect. However, it can be clearly controlled by producing the medical device in packaged parts and avoiding disturbing elements

2. *Interview 2: Rémi Giglio, Giglio Orthopédie*

The interview guideline with Giglio Orthopédie is stated in APPENDIX 7.

Context

Giglio Orthopédie is based in Geneva and cover the entire spectrum of orthopedic technology (wheelchair, prosthesis and orthosis devices, compression for lymphoedema patients). Rémi Giglio's areas of interest are research and development, podiatry, morphology and sales.

Innovation is an integral aspect of corporate culture within the company, and since 2013 the firm has been looking into the implementation of 3D printing technologies. Rémy Giglio directly understood the real potential of additive manufacturing for the orthopedist sector.

Giglio Orthopédie still works in a more conventional way, while 3D printing some medical devices. The company is turning more and more to additive manufacturing, although they are still skeptical compared to the traditional manufacturing process.

Rémi Giglio sees additive manufacturing as a technology that complements their medical expertise and know-how. Orthopedic surgeons like to be able to touch the patient, the injury, and the medical device in order to modify it as they wish; this is not possible in the digitalized manufacturing process. However, orthopedists are also able to appreciate the precision of AM due to its layer-by-layer wire deposition. It allows the thickness of the deposit to be adjusted more easily, create a lighter medical device, and have the right fitting.

The reason the company has not yet fully adopted 3D printing is that it has little knowledge of the software. According to Rémi Giglio, the software is useful for engineers, but orthopedists are medical experts. So, there is a need to bridge the gap between the orthopedic technician and the cartesian side of engineers.

He also insists on the fact that additive manufacturing is something extra and should be considered as an additional asset. Additive manufacturing cannot replace a leather sandal, a knee brace that must be rigid and made of carbon. It is just an alternative manufacturing method. So, this new technology does not entirely replace jobs.

Sustainable Performance Indicators

First, additive manufacturing improves waste management. In the interest of being completely transparent, Rémi Giglio explained that in the traditional way, the mold needed to manufacture the orthosis is milled out of a block of foam, and all the waste of this foam is then burned. This wasteful approach is environmentally detrimental. With 3D printing, the process creates zero waste as 3D printers print only what is necessary.

Then, orthopedics experts do their job to heal or at least relieve patient’s injuries. It is a job that requires a high level of listening skills in order to care for patients. As Giglio Orthopédie begins to implement AM, it is influenced by the common goal of caring for the patient and because orthopedists are convinced that this technology is positive for patients. Additive manufacturing allows the firm to produce medical devices that are closest to the patient, both in terms of fit and the production process.

Finally, 3D printing technology decreases the overall cost. As stated by Rémi Giglio: “50 years ago, wire deposition machines were about half a million euros. Today, they are much more affordable, and we can find a good 3D printer from 5000 euros”. The prices of this technology will become increasingly affordable, and this will only get better.

Negative points

Rémi Giglio has highlighted some disadvantages of the implementation of additive manufacturing in an orthopedic company, with the caveat that they are all surmountable over time.

The biggest negative point according to the interviewee is about investment. First, investment in terms of money. The acquisition of software (and licenses) as well as 3D printers are relatively expensive. Then, investment in terms of time. As Rémi Giglio said “the learning curve of additive manufacturing is long”. It takes time to understand the new technology, to change the corporate culture, to carry out training, to change the habits of the team, to understand the new materials and how it works. The learning curve is long, but the results can be incredibly satisfying if the process is done well. Time also includes the manufacturing time. Rémi Gilgio insists on the fact that the AM process is not faster than the traditional manufacturing method. Giglio Orthopédie utilize their 3D printing machines during the night so as not to lose time during the day. A prosthesis or orthosis takes approximately 13 hours to be 3D printed, while traditional manufacturing takes on average 2 hours.

Fear of this new technology is also another negative aspect of AM implementation. This fear comes from the new technology in general, but also the fear of loss of know-how. Implementing 3D printing technology requires a real change in corporate culture.

Orthopedists must learn to work differently because they cannot physically work on the material anymore. All the orthopedist work is done virtually and directly on the software. However, if medical experts take time to understand and feel comfortable with this technology, this fear will vanish. It is a question of being ready to change.

This fear also comes from the lack of existing training. Employees are not trained to use new technologies, because they work at the same place and in the same way for years. There is a strong need of knowledge sharing if companies want to get into additive manufacturing.

Finally, another negative point is the raw material used, with lots of unknown characteristics. For example, plastic wires are extremely sensitive to humidity. Additive manufacturers have to be aware of this before 3D print, otherwise the finished product may be degraded due to bubbles. All manufacturing conditions have to be known and analyzed to launch the 3D printing of medical devices. Also, some material cannot be used with 3D printing technology (for the moment) and orthopedists cannot get equivalent characteristics, such as carbon fiber.

3. Interview 3: Alpha Company

The interview guideline with Alpha Company is stated in APPENDIX 8.

Context

For various reasons, this company decided to remain anonymous. However, all the information stated during the interview are meaningful and are of real benefit for the analysis of this research.

Alpha Company is a business-to-consumer Belgian company, providing technical appliances for people to aid them in terms of physical capability. It ranges from insoles to prosthetics, dealing with severely disabled people. Its mother company, Beta Company, is the creator of one of the biggest high-quality and technologically outstanding products in the sector of medical technology in the world.

Alpha Company’s goal is to improve the physical capability of a client by at least 1%, and always care for their patients. The firm has 120 sites where patients are seen throughout Belgium.

According to the firm, orthopedics is very traditional work because, for the most part, parts are handmade. However, Alpha Company has been using 3D modeling to 3D scan a patient’s injury for 10 years now, and it has been 3 years since the firm has also been developing some 3D medical devices as well. Additive manufacturing is becoming increasingly adopted in the production process, while the company remains slightly skeptical for different reasons.

Sustainable Performance Indicators

Alpha Company cares about sustainability, and its main strategy is to always scan the market, distributors and suppliers to see if they can be more sustainable compared to the rest of the market. The firm also learns a lot from its mother company, Beta Company, which is known to undertake many environmentally conscious initiatives. Alpha Company only has one real SPI, which is transport kilometers, but they do not have special sustainable guidelines or standards.

- Its most important challenge is currently lower the carbon footprint during the transportation process. The headquarter and production facilities are located in Wetteren (Belgium) and the company has to serve their 120 sites daily. The company's strategy is to do it every night with 2 big lorries driving around Belgium, outside rush hour, directly reducing transportation time and carbon emissions. As a result, the 120 sites do not have to deal with any transport to the production facilities; everything is transported close to them, optimizing the kilometers driven. In the same way, the company tracks employees' kilometers thanks to company cars. The firm also wants to reduce kilometers travelled by employees and make them aware of this indicator.
- The raw material comes from Benelux or Germany. Only 10% procurement is from outside of Europe.
- The firm also wants to manage its waste by using reusable packaging, laver bags or reusable bags in order to avoid plastics when delivering medical devices to the 120 sites in Belgium. There are other small ecological investments also, such as reducing water consumption and reducing usage of air conditioning.
- Medical devices are more and more affordable for everyone. 90% of the patient's invoice is reimbursed by the healthcare institution, so the assets remain in Belgium.
- The firm has to comply with social regulations such as MDR. The company is imposed to strict rules because it is in the medical devices business, so patient care is paramount.
- Even if the company only produces 2 or 3 different 3D printed medical devices, Alpha Company admits that additive manufacturing allows mass customization rather than mass production because they can print whatever they want depending on the 3D

body scan. Also, additive manufacturing allows companies to bring production much closer to patients. Medical experts see a patient, 3D scan the body and can directly and immediately print the medical device.

Negative points

The first element that Alpha Company is currently struggling with is the investment in order to implement additive manufacturing. According to this firm, the 3D printing process is expensive to implement, and this technology cannot consistently deliver the same level of quality.

Another negative aspect highlighted by Alpha Company is that they do not have the time to properly implement 3D printing technology. This company is a mass production company (they have approximately 35% of the Belgian market in their core business), so they must work fast. Orthopedists cannot wait 10 hours for a 3D printer to manufacture the proper medical device when it can be done in 1 hour using the conventional method.

Also, the employees, the company and even the patients are not ready to change. Implementing AM as a core process within a company requires a change in corporate culture, and it has to be adopted by patients too. They have to understand how their medical devices are made and if it can be trusted or not. Employees are afraid of new technologies because they see it as a replacement of their manual jobs.

4. *Interview 4: Laurent Voets, SIRRIS*

The interview guideline with Sirris is stated in APPENDIX 9.

Context

Laurent Voets is a team leader expert in additive manufacturing, having worked in the additive manufacturing field for 17 years now. He currently works at SIRRIS. SIRRIS is a Belgian industry-oriented company with the goal to transfer and help companies to implement new technologies within their core business.

In Belgium, the main sectors implementing 3D printing technologies are the aeronautic and aerospace sector as well as the medical sector. The medical sector is sometimes discreet about new technologies but uses more and more the additive manufacturing process.

The company organizes campaigns, specific to each company that wants to implement additive manufacturing in their core business.

Laurent Voets noted multiple advantages to the implementation of such technology. First, the design and functionality of parts. 3D printing allows companies to produce devices or parts with lots of functionalities, such as lightness and perforations specifically for the medical sector, which is impossible to produce using the conventional method.

Then, AM allows the medical device's customization according to customer's needs. This is an integral aspect, as in the medical field, medical experts must produce medical devices specific to the patient.

Also, additive manufacturing technology reduces lead times in general and in terms of delivery. It also reduces (or even eliminates) the need for stock. The software provides lots of files and experts can print on demand, depending on a patient's body scan. The relocation and distributed manufacturing make the manufacturing process much more flexible because experts send files around the world and can produce locally.

Finally, 3D printing is a technology that requires manpower, so this new technology will not replace jobs for the moment, as some people might have thought. AM allows the relocation of production, so it still needs lots of employees to manage the different sites.

Sustainable Performance Indicators

Laurent Voets stipulated meaningful sustainable performance indicators that would make sense when implementing 3D technology in the medical sector, according to him.

- Reduction of transports (and CO_2 emissions) and augmentation of local production: additive manufacturing allows the production on demand of medical devices by just sending files across the world to the right manufacturing center.
- Reducing time in general: in transport, inventories, production, etc.
- Reducing costs: avoid excessive tooling and producing lighter parts, so less raw material is used and directly reduces costs.
- Reducing or even eliminating stock: products are 3D printed on demand, therefore there is no need to stock all medical devices in a warehouse because it is directly given to patients.

- The technological sector and medical sector are quite open between men and women, and there is no discrimination between genders.

Negative points

Laurent Voets is aware of the negative side of additive manufacturing. According to him, each negative point can be overcome by adapting it to a company's profile.

The first negative point stated by the additive manufacturing expert is investment. According to him, there is no clear business model (depreciation, profit, etc.) with the implementation of additive manufacturing, so investment and costs are unclear for companies.

Another negative point is the lack of training, knowledge and information about this new technology. People and companies are frightened by new technologies, and even more so due to the misinformation that companies have about this technology. Lots of advertising about AM has existed for a few years now, for example sending mini 3D printers to the public, which portrays a more trivial image of this technology. SIRRIS tries to maintain a positive image of additive manufacturing within companies, and to prove to them that this technology is not only reserved to large aeronautics companies, but also to SME's according to their needs. Indeed, the expert stated there must be a big shift in the mentality of global companies, to understand the benefits of such a technology and the advantages companies can get from it.

Laurent Voets also mentioned that additive manufacturing is still a relatively young technology. He sees huge potential in additive manufacturing for the next few years but, for now, it must be improved and better implemented. The raw materials will improve in terms of quality, and 3D printing applications will increase as it will be more accessible to companies.

5. *Analysis Matrix*

The analysis matrix gathers information about the 4 different companies and the proper sustainable performance indicators interpretation collected during the interviews. These results come from a qualitative study and are therefore specific to our case.

This matrix is available in APPENDIX 5, table 4.

PART V. Discussion of the results

The research subject of this paper is the comparison of traditional and digitalized supply chains using 3D printing in the medical sector, in order to find out which one is the most sustainable. In order to conclude on our research subject, this chapter aims to discuss the results presented in the previous chapter.

1. Horizontal analysis

Horizontal analysis is done under the 3 categories of Sustainable performance indicators and their attribute categories, stated in chapter 1 - Part IV, according to the interviews with experts.

Environmental dimension

Regarding environmental dimension, the following explanations start with the fact that AM technology allows the production of the right medical device, in the right quantity, at the right time, at the right place, for the right person.

The first environmental attribute category is **energy consumption**. Undoubtedly, AM technology consumes a lot of energy because of the 3D printing machines. Also, as everything is done via the internet and data collection software, software and data utilization also consume energy, which the traditional method does not require. The experts interviewed do not have actual data to provide on the total energy consumed during the entire manufacturing process, as this technology is still too new, and they have not yet investigated this.

Regarding **material**, 3D printing technology uses plastic (in most cases) for the manufacturing of orthopedic medical devices. The use of this kind of raw material allows companies to consider a “closed-loop” strategy and recycling the old medical device by melting it to obtain new, raw material. In comparison, in the traditional manufacturing process lots of prototypes are required so that devices ultimately fit patients properly.

For **waste management** as an environmental performance indicator, additive manufacturing, by definition, adds material layer by layer, compared to conventional manufacturing that extracts material from a large piece of material. Consequently, only the necessary material is used. This makes AM technology part of a waste reduction and material use reduction approach. In addition, work is currently being done on the recycling of raw materials and finished products. Various initiatives show that it is indeed possible to reuse used plastic in order to melt it, and to reuse it as a raw wire material, most notably as a 3D printing filament. Plus, AM technology allows the manufacturer to produce lighter and airier parts and therefore reduce the quantity of raw material needed.

Today, additive manufacturing tends towards local production: less transport is required and therefore environmental impacts such as **air emissions** are significantly reduced. Transportation includes the transportation of finished product and the shipping requirements, but also spare parts that need to be collected to create the final medical device. Thanks to additive manufacturing, medical experts send data files over the internet rather than miles and miles across the world. So, the total air emissions emitted with the digitalized supply chain are smaller than those of the conventional supply chain. In terms of quantitative data, along with energy consumption, the experts interviewed do not have actual data to provide as this technology is still too new.

Finally, additive manufacturing technology does not need a physical warehouse, because medical devices can be produced on demand, at the desired location. So, the total **land use** is smaller (or even non-existent) in the digitalized supply chain, thanks to the virtual warehouse.

Social dimension

The social dimension of sustainable performance indicator gathers all qualitative data. Although this dimension, in most cases, is the one that is often overlooked and on which there is little in-depth existing research, it nevertheless has an important place in this paper. On one hand because the medical sector places the human being and the patient at the center of the business, and on the other because the interviewees give great importance to this dimension in their companies.

The **human resources** attribute category is related to employee’s satisfaction, employees’ well-being at work, the amount of available jobs, etc. Knowing that the additive manufacturing sector is a sector in full expansion, there will be more and more supply in this area. However, experts' opinions diverge on this attribute category. On the one hand, some say that additive manufacturing will replace "physical" jobs, knowing that medical devices will be manufactured using 3D printers. On the other hand, some nuance this opinion by noting that 3D printing is not self-sufficient, and there is always a need of supervision of a medical expert throughout the process (whether it is at the level of retouching once the product is finished, retouching during printing, etc.).

As for the **training and education** attribute category, this is the one that needs to be the most improved in the social dimension, at the level of the digitalized supply chain. All the experts noted a real lack of training, both from a technological point of view and in terms of 3D printing itself. Employees as well as manufacturers do not know enough about this new technology, which makes them quite reluctant and afraid to switch to this type of manufacturing. It is for this reason that Spentys, aware of this fear and lack of knowledge, offer a product that bridges the gap between medical and technological expertise thanks to the ease of use of its software. Rémy Giglio also specified that by as early as 2021, orthopedic companies would provide training to their employees to assimilate this manufacturing method and feel comfortable with the technology.

Whether in the digital or traditional sector, **consumer issues** are followed from the beginning of the treatment by the medical expert until their recovery. 3D printing technology allows a follow-up throughout the printing of the medical device which allows a modification at any time if the medical device does not fit perfectly with the needs of the patient. On the one hand, modifications of the 3D printed medical device are possible (changing the thickness, the rigidity, etc. during the printing process), a level of precision that is not possible during the traditional manufacturing method. On the other hand, some modifications are only feasible during traditional manufacturing process as well.

So, as for the consumer issues attribute category, **patient's care** is above all important in both traditional and digitalized sectors. The orthopedics sector is focused on patients to improve their motor skills and is close to patients. However, the digitalized sector allows for a very accurate 3D scan of the body closer to the patient, rarely requiring modification on the finished product. The accuracy of the software currently available (and it will continue to improve) allows a complete visualization of the patient's injury, which allows the medical expert to quickly understand the problem and heal it as well as possible by 3D printing a medical device specially adapted for the patient. Also, additive manufacturing allows a mass customization strategy for medical companies, so that each medical device can be 3D printed according to patient’s injury and personally customized.

Additive manufacturing and expertise are made available to a large audience and customers thanks to healthcare regulation and **social regulation**. As stated by Alpha Company, the healthcare regulation requires 90% of the patient's invoice to be reimbursed by the Belgian healthcare system. Also, because additive manufacturing can produce medical devices at a lower cost, they can make it available to more people; this is not necessarily the case for the traditional medical devices.

In terms of managing the manufacturing process and the **time** required throughout the supply chain, additive manufacturing is beneficial for companies manufacturing medical devices. Moreover, everything is done mechanically due to 3D printers (everything is supervised and retouched if necessary, by medical experts), so this technology saves time. Also, because of distributed manufacturing, medical products can be produced on demand at the requested location. This saves time for patients who then are able to receive their medical devices close to home, and also for the manufacturer who can produce these medical devices at their workplace.

Economic dimension

The economic dimension is the most difficult one to estimate, according to this qualitative survey. Moreover, Laurent Voets, an expert in Additive Manufacturing, made it clear during the interviews that there is not yet a concrete business model for 3D printing technology. Too many factors are still unknown to make a quantitative study on the profit and costs of implementing this technology in companies.

Investing in **sustainability expenditures** has a price, and it all depends on the ability and willingness of companies to move towards a more sustainable enterprise. Thinking ahead, as sustainability is a current concern in the business world, considering sustainable standards and sustainable reports are key for companies, because more and more investors pay attention to this new vision, too. The more you invest in sustainability practices, the more investors will agree to invest in a company. Investors ask questions about these issues and prioritize companies that put effort into being sustainable, which is a substantial opportunity for the companies.

Additive manufacturing **costs, profit and stability** are difficult to estimate, and this technology is still too new to have a proper business model. However, experts all mentioned that the costs of additive manufacturing implementation are the main barriers to this new technology. This is a real investment that can pay off only in the long run. The various investments encompassed are made in raw materials needed to 3D print (raw wire material), 3D printing machines, post-processing costs, the necessary licenses for the implementation of the software, training for employees, the proper adaptation to this new technology, etc. All of these investments have a cost that depends on the company, and profit can only be seen in the long run.

The **time** attribute category also depends on different factors. According to the total lead time needed during the whole manufacturing process, from raw material to the finished product, the digitalized supply chain allows there to be a huge time saving. The fact that the medical device can be manufactured on demand at the right place saves a lot of time on transportation, and the waiting time between the different stages of manufacture. However, the 2 experts who manufacture medical products (Alpha Company and Giglio Orthopédie) both mentioned that the manufacturing process itself was not at all faster than the traditional method. A medical product can be manufactured in 1 or 2 hours in the traditional way, whereas 3D printing requires between 10 and 13 hours of printing per medical device.

2. Vertical analysis

Vertical analysis is done according to the conventional supply chain and the digitalized supply chain. As a reminder, Alpha Company as well as Giglio Orthopédie still operate in the traditional way, while trying to implement additive manufacturing step by step. These 2 experts therefore represent 2 different points of view, representing the traditional supply chain on the one hand and the digitalized supply chain on the other.

The experts' opinion is that additive manufacturing will never 100% replace the traditional manufacturing process, but rather it will complement it. Some medical devices can be produced using 3D printing but not in the traditional way, and vice versa. Moreover, the 3D printing method requires a medical follow-up throughout the manufacturing process if there is a need for adjustments, but also during recovery.

According to this paper and as SPI stated, the digitalized supply chain is more sustainable from the point of view of 2 pillars: the ecological dimension and the social dimension. Thanks to distributed manufacturing, medical devices can be produced closer to the patient. This avoids the various transport present in the conventional supply chain, but also allows a huge reduction of raw material waste during the manufacturing process.

From a social dimension point of view, 3D printing allows the manufacturing of specific products for each patient, answering a patient's requests and offering a better-quality product (lighter, more flexible, airier, etc.). This technology is closest to the patient, in terms of distribution, medical device and customization. Moreover, the technology is more and more affordable and allows patients to obtain medical devices at lower prices.

From the economic dimension point of view, the implementation of additive manufacturing in a company still has too many negative points. The economic aspect is the main barrier mentioned in the different interviews with experts. Turning to 3D printing requires a complete reorganization of the company and a change in corporate culture. Not only employees, but also patients must be ready to change, in order to see the benefits of this new technology and be trained to use it. These changes require a lot of investment, both financially and personally. However, the costs associated with the implementation of 3D printing should be viewed positively, with the idea of moving towards a more sustainable business which then improves competitiveness in the market. Also, the costs related to the implementation of additive manufacturing must be viewed in more depth. For instance, understanding the fact that distributed manufacturing allows devices to be produced closer to the patients significantly reduces transport costs.

However, it is important to mention an essential aspect of 3D printing in the medical sector today, only possible thanks to the digitalization of the medical industry, entering into the social dimension. Although this research is focused on the orthopedic sector, 3D printing has allowed companies to adapt their manufacturing process and help hospitals in need during the current COVID-19 crisis. 3D printing provided an effective solution to overcome a supply-demand gap that occurred at the beginning of the pandemic. Indeed, in April 2020, the supply of masks was about 4.5 billion units, while demand was about 7.5 billion units in that moment (Gradl, 2020). As for face shields, demand increased by approximately 800% in 2020 compared to 2019. It shows how doctors, nurses, patients, and all those working in the medical sector were not adequately protected and risked their own lives to save those of patients, due to a huge supply-demand gap.

Different factors contribute to the supply-demand gap, such as the centralization of production, dependence on manual labor leading to closure of facilities, the just-in-time manufacturing model (consistently manufacturing the exact quantity), the insufficient production capacity, lack of production efficiency and the intellectual property issues (Gradl, 2020). But this supply-demand gap has been reduced thanks to the adaptability of 3D printing technology.

For example, Spentys has been able to modify its manufacturing process by adapting the data files in software, allowing 3D printers to print spare parts that are out of stock, which was essential for breathing machines. Indeed, hospitals were in need of very specific, spare parts for the proper functioning of breathing machines. These spare parts are usually procured from China. However, borders were closed and the waiting time for these spare parts was much too long to save patients in need. That is why Spentys was able to adapt its offer and print these spare parts in 3D for the hospitals in Brussels. Without this technological adaptation, many breathing machines would still be waiting for these spare parts. It is also thanks to distributed manufacturing, because Spentys could print specific spare parts in its own Brussels premises, that the company has been able to meet the demand of the hospitals. The waiting time of transportation was then minimized thanks to this local production. Spentys is just one example, however Giglio Orthopédie also provided masks for their entire canton in Switzerland by adapting its manufacturing process.

Additive manufacturing technology and open software allow the exchanges of important data files, adaptable to any kind of 3D printer. If hospitals are equipped with their own 3D printing machines, software can give access to open files in order to print directly in their centers, finally allowing them to create the components parts required.

3. Implications

To refer back to our basic research question, i.e. "Does the implementation of a digitalized supply chain, thanks to 3D printing, really increase sustainability compared to a conventional supply chain?", this paper states that the digitalized supply chain is more sustainable according to the environmental dimensions. This is mainly thanks to transport reductions due to distributed manufacturing, better waste management and the recycling of finished products. In terms of the social dimension, AM allows mass customization so medical devices are specifically made for patients, lighter and best suited.

From an economic point of view, the conventional supply chain is nowadays more sustainable, because adding additive manufacturing to the conventional manufacturing requires a large financial investment (3D printer, licenses, software, trainings, long learning curve, etc.).

However, as mentioned several times during this paper, all statements depend on the Sustainable Performance Indicators that medical companies choose according to their goals and vision of sustainability. Each supply chain has its advantages and disadvantages and are ultimately complementary. It will depend on the company's willingness to change its corporate culture, but also the price to be paid for moving towards a more sustainable business

The perception of the benefits related to the implementation of additive manufacturing within a company depends on each firm. Other factors are also linked to this perception, such as the sector of the company, the available resources, the time to be given to this technological change.

At the end of this thesis, we therefore respond to our research problem by concluding that the medical sector is turning to the implementation of additive manufacturing according to a set of indicators, called Sustainable Performance Indicators, depending on each company according to the goals to be achieved and their perception of sustainability. The digitalized supply chain is more sustainable than the conventional supply chain, according to our SPI and interviewee. Also, recognizing that the economic dimension is the most challenging one for the medical sector at the moment for the implementation of 3D printing, perhaps also requires the realization that becoming a more sustainable business requires a core investment. This is both necessary and profitable in the long term. Medical experts therefore need to look beyond the price of 3D printers and software licenses, change their perception of sustainability, get out of their comfort zones, and move forward with this growing wave of sustainability.

The table 5 below concludes this research, gathering the main information of the traditional supply chain and the digitized supply chain with the implementation of additive manufacturing, in the medical sector, according to the stated sustainable performance indicators.

	Conventional Supply Chain	Digitalized Supply chain
Environmental Performance Indicators		
Energy consumption		-- Software and 3D printers
Material	+/- Can use whatever material needed	+/- Recyclable raw material goal Limited 3D print material
Waste management	--- Huge waste of raw material	+++ Print only what is needed: no waste Lighter parts: less raw material used
Air emissions	-- Lots of transportations	+++ Distributed manufacturing
Land use	-- Spare parts warehouse	+++ Digital warehouse
Environmental regulations	+++ ISO 13 485	+++ ISO 13485
Social Performance Indicators		
Human resource	++ Complementary manufacturing processes	
Training and education	+ Traditional and handmade Ancestral method	--- Lack of technological training Fear of new technologies
Consumer issues	+	++ Mass customization
Patient's care	+	+++ Technology close to the patients Adaptable
Social regulations	+ 90% of the invoice paid by Belgian healthcare	+++ 90% of the patient's invoice payed by Belgian healthcare More affordable medical devices
Time	++	-- Learning curve of AM implementation is long

Economic Performance Indicators		
Sustainability expenditures	--	+
Profit and stability	+ Ancestral manufacturing method	++ In the LR Investors invest more and more in sustainable companies
Costs and income distribution	+	-- Huge investments in the sort run
Time	+	-- Need to change corporate culture
<u>Table's key</u> --- really insignificant +++ really significant		
Table 5: Comparison of both medical supply chains		

Conclusion

The motivation for this research paper was to understand the digitalization of the medical supply chain, in order to know if turning to the additive manufacturing technology is more sustainable than the conventional manufacturing within a supply chain.

First, based on a literature review, we addressed the concepts of Industry 4.0, sustainability, and the conventional and digitalized supply chain.

Then, a guideline of the most appropriate sustainable performance indicators for this study was drawn up. In the same section, an analysis of the medical supply chain and the medical digitalized supply chain was carried out, in order to understand the main steps and the advantages and disadvantages of each, based on interviews.

Subsequently, a horizontal analysis of the expert interviews allowed us to identify the main SPIs involved in the medical supply chain, the conventional and digitalized ones.

A vertical analysis was also conducted to compare the main steps of the two supply chains and the appropriation of these different SPIs according to the manufacturing method throughout the supply chain.

Finally, we conclude this research paper stating that the digitalized supply chain is more sustainable according to the social and environmental dimensions (mainly thanks to transport reductions due to distributed manufacturing, and also thanks to mass customization so that medical devices are specifically made for patients, lighter and best suited with 3D printing). From an economic point of view, the conventional supply chain is nowadays more sustainable, because switching to additive manufacturing requires a large financial investment (3D printer, licenses, software, trainings, long learning curve, etc.) but with the caveat that every change requires an investment.

Keeping in mind that digitalized supply chain is complementary and will not, for the time being, replace the traditional supply chain, this conclusion is nuanced by the fact that it is the responsibility of companies to stipulate their own sustainable performance indicators to see if they are ready to implement this new technology and, above all, change corporate culture.

1. *Recommendations*

Based on the findings during this research, some corporate recommendations can be done.

First of all, each company has to set itself sustainable guidelines or standards to follow, either existing or by creating its own sustainable guidelines according to the goals the company wants to achieve, in terms of sustainability.

Next, the supply chain managers must take the time to learn the real potential and benefits of implementing additive manufacturing in their manufacturing process, and the changes it will bring to their supply chain. Understand what the stakes are and associate them with the sustainable guidelines that companies must follow to move towards a more sustainable business.

Also, a better understanding of the word "sustainability" has to be improved. An observation made during the interviews was that the first thing that comes to mind when we speak about sustainability is "preserving the environment". People are not always aware that this term encompasses 3 pillars, and that we need to look beyond environmental impacts.

There is also a real need for training and education about the technology and 3D printing in the medical sector, so that employees feel comfortable with this new manufacturing process. Training also includes education of how to use the software, as one cannot work without the other, so that orthopedic experts can make this new working method their own. It takes a lot of time, but it is necessary so that employees are no longer afraid of this new technology and can see the real benefits of 3D printing. Moreover, this technology does not replace the traditional manufacturing method, but complements it and sublimates it, by allowing the manufacture of certain medical devices that cannot be manufactured in the traditional way.

2. *Limits of this research*

The limitations of this research are mainly related to the qualitative aspect of this study. The Sustainable Performance Indicators that we chose to compare the conventional and digitalized medical supply chains are based on interviews, secondary research papers and our point of view. Also, all explanations are based on qualitative information, for the 3 pillars of sustainability. It was impossible to do a quantitative study (as the footprint emissions, energy used, the real costs and profit made thanks to 3D printing, etc.) due to the lack of data and the novelty of the additive manufacturing technology in the medical sector. Even the experts interviewed did not have their own business model for the implementation of additive manufacturing in their companies. Too many points are still unknown and further research needs to be carried out in this area, such as a life-cycle assessment.

Also, the results are specific to our case and the companies interviewed. Because this qualitative method includes a case study of 4 different companies in the medical sector, the conclusions might have been different with other companies interviewed.

Moreover, the results are specific to our case and cannot be generalized without further research. This study focuses in the orthopedics medical sector, while the medical sector is much broader than this sector and therefore the implementations and use of 3D printing can be different.

Another limitation is the size of the sample used for the qualitative interviews, which is too small to legitimize the results. Because of the COVID crisis, it was impossible for me to meet the experts at their workplace, which could be beneficial to better assimilate the different implementations and manufacturing processes in the medical sector. In addition, many experts were not available for any interviews, as their concern was mainly about this pandemic and therefore did not have much time to spare me.

3. *Future and extension*

The above-mentioned limitations can be used as a basis for an extension of our search. Indeed, it would be highly relevant to conduct a quantitative study to measure and statistically support the environmental and economic impact through a life-cycle assessment.

As a first step, it would be interesting to interview more medical experts as well as supply chain experts, and this study could also be extended to other healthcare sector.

Then a further quantitative study through the collection of quantitative data could be carried out, in order to have the environmental and economic impacts in a quantitative way, such as a life cycle assessment graph. Since this technology is still new, few quantitative data researches are available, and it would then be interesting to look at a complete and quantitative life cycle assessment of the additive manufacturing implementation within a medical supply chain.

Additive manufacturing technology is in the early stages of growth. As stated by the different experts interviewed, the use of 3D printing in medical companies will grow over the next 10 years. The potential of this technology is enormous, but it is still too unknown. Advanced technology scares medical experts, who like to work in an ancestral way without changing their habits. With more training on additive manufacturing, the willingness to change by medical companies and knowing the many benefits of this technology, the implementation of 3D printing will grow more and more in the coming years.

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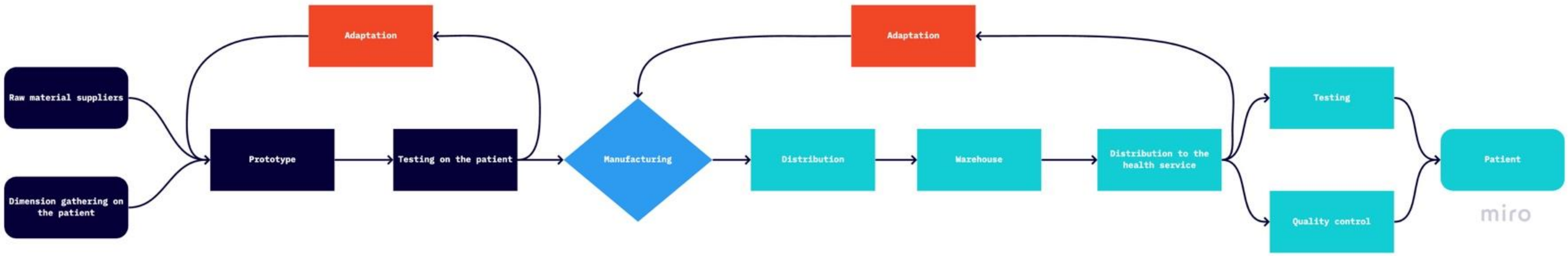
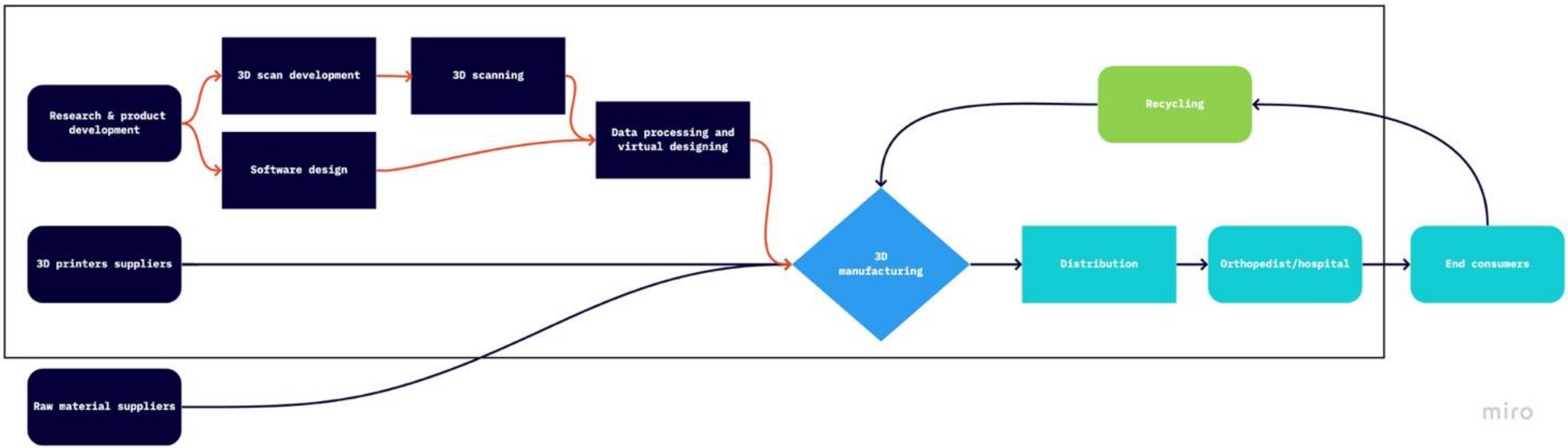
Appendix

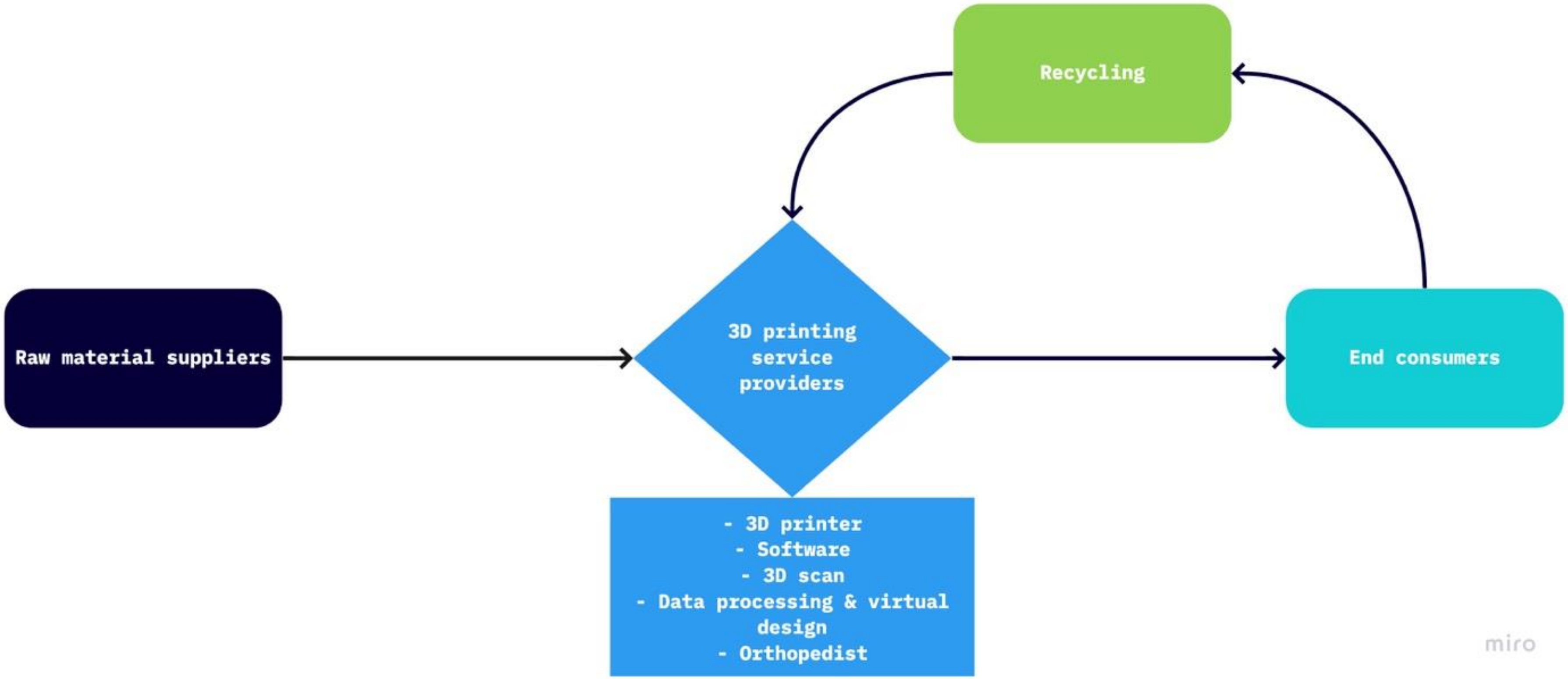
APPENDIX 1. Conventional supply chain of orthopedics medical devices



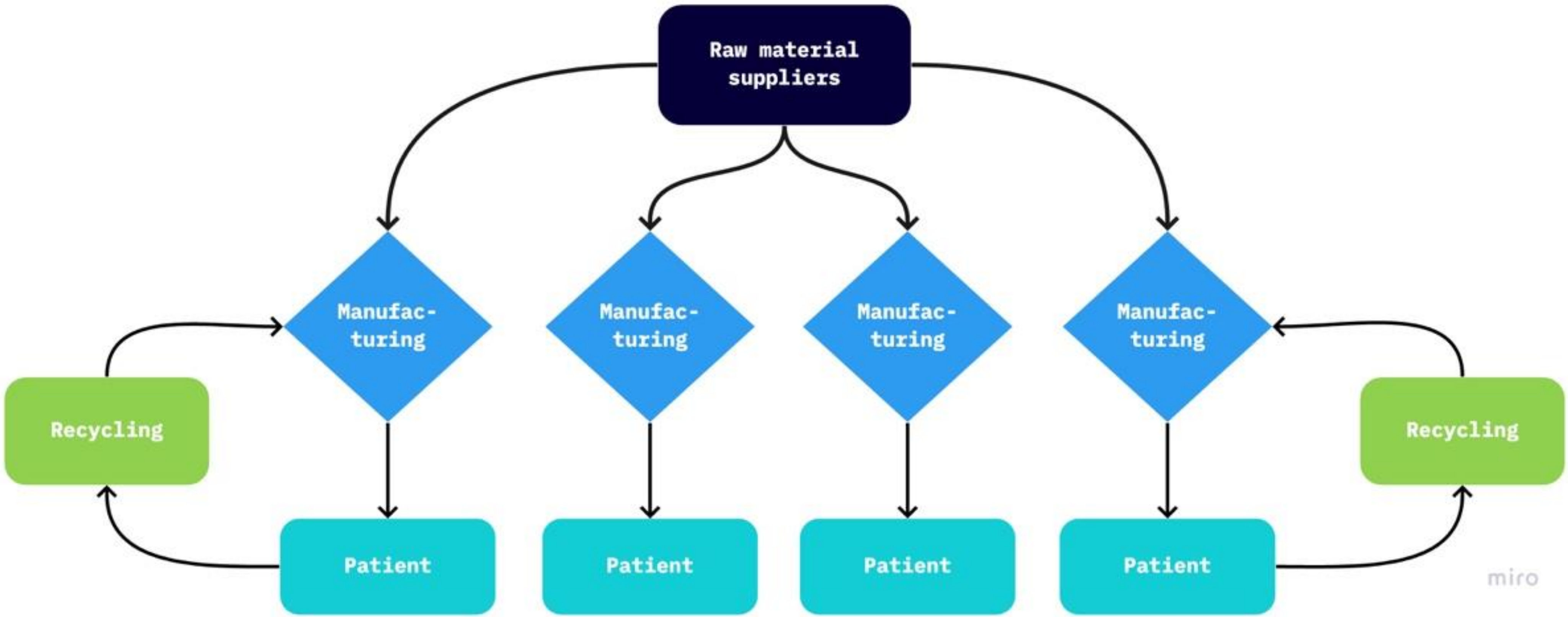
APPENDIX 2. Broad digitalized supply chain of orthopedics medical devices



APPENDIX 3. Digitalized supply chain using Additive Manufacturing



APPENDIX 4. Example of distributed manufacturing in the medical sector



APPENDIX 5. Analysis Matrix

	Spentys	Alpha Company	Giglio Orthopédie	SIRRIS	Horizontal Analysis
	Upstream SC Research & development software	Middle SC Mass production company	Downstream SC Manufacturer and experts	Additive Manufacturing expert Research & development	
Environmental Performance Indicators					
Energy consumption		Reduce air conditioning use	Use 3D printing during the night	Software and 3D printers require energy	AM requires more energy consumption
Material	Procurement in Spain, Italy or Belgium. 3D printers from China	Procurement in Benelux and Europe. Only 10% comes from outside Europe	Procurement in Europe. Improvement has to be made on the raw material characteristics	AM needs qualitative raw material	Source mainly in Europe. Raw material has to improve to be recycled
Waste management	No waste: produce only what is needed. Recyclable raw material	Reusable bags packaging	Disaster when handmade because burns the waste	Avoid lots of waste materials (lightness, produce only what we need, etc.)	AM is the solution for a better waste management. Traditional manufacturing is a disaster for the waste
Air emissions	AM allows distributed manufacturing so footprint reduction	Reducing transport kilometers	Traditional method burns unused material	Reduction of transport	AM allows reduction of transportats so air emissions
Land use	No warehouse needed. Virtual warehouse with data files	120 sites around Belgium	All manufacturing process in their own buildings	No warehouse needed with AM	AM do not need physical warehouse (digital warehouse)
Environmental regulations	ISO 13 485	ISO 13 485			ISO 13 485 regulations
Social Performance Indicators					

Human resource	AM does not replace jobs; it is a complementary manufacturing process	Lots of sites in Belgium and lots of jobs. AM will replace physical jobs	AM does not replace job, complementary manufacturing process. More and more affordable to everyone	Does not replace jobs. Gender equality	AM is complimentary to traditional manufacturing.
Training and education	Provide trainings to customers to implement AM technology	Lack of technological trainings and knowledge	Lack of technological training sand knowledge. Fear of loss a know-how	Lack of technological trainings and knowledge	Lack of trainings about new technologies. Fear of new technologies. Medical firms are not ready to change yet.
Consumer issues	Patient-based strategy	Patient-based strategy After sale service	Patient-based strategy		Patient-based strategy. Medical expert's follow-up during convalescence period
Patient's care	Customization Lightness medical device	90% of patient's invoice is reimbursed	Patients are their priority	Customization On demand manufacturing process	AM allows mass customization. Sector where the patient is in the spotlight
Social regulations	Medical Device Regulation (MDR)	MDR Specific regulation for each device	MDR and patents	MDR	All medical devices manufacturers have to respect MDR
Time	AM is way easier for manufacturer and medical experts, because they can work directly from their workplace	Reducing transportation time. Mass production company	AM takes more time than the traditional way, but can launch machineries during the night	Reducing transportation time	AM learning curve is long. Need to take the time to learn. AM is not faster than producing in the conventional way
Economic Performance Indicators					
Sustainability expenditures	Sustainable goals for 2021, based on SDG	Not ready yet	Not ready yet	Have to invest a lot.	AM requires lots of investments

				Investors are increasingly sensitive to corporate sustainability	(machineries, raw material, software, …)
Profit and stability	Mass customization	90% of the invoice is reimbursed	The AM learning curve is long, profit only in the long run	Profit in the long run	Profit in the long run.
Costs and income distribution	86 healthcare institutions using Spentys	Machineries are too expensive.	Machineries are expensive but more and more affordable	Lack of a clear AM business model	Big short-run investment
Time	Help companies to save time in the whole process of medical devices manufacturing	Reducing transportation kilometers, so time consumption. Mass production company, has to manufacture as fast as possible	Use 3D printing machine during the night. Need time to understand this technology	Reducing lead time in general: transportation, inventories, production	AM manufacturing process is longer than the traditional way AM reduces lead time in general: transportation, data exchange, etc.
Vertical Analysis	AM software provider. Waste reduction. Provide trainings and follow up during AM implementation. Mass customization. Recyclable material. Qualitative medical devices.	Mass production. Few 3D printed medical devices but real potential in the future. AM manufacturing time is longer. Not ready to invest in AM and change corporate culture.	AM learning curve is long but real potential. Better waste management with AM. AM manufacturing time is longer than the conventional method. AM requires big investments.	AM is a real potential in medical sector. Adapted technology to each company. Better waste management. Distributed manufacturing.	

Table 5: Interviews analysis matrix according to Sustainable Performance Indicators

APPENDIX 6. Interview guideline with Spentys

I. Introduction

Good afternoon. First of all, I would like to thank you for participating in this study.

Your participation will help me in the realization of my thesis comparing the conventional supply chain and supply chain 4.0 with 3D printing in the medical sector, in order to know which process is the most sustainable.

I'm going to ask you a series of questions. You're completely free in the way you answer them, because there are no right or wrong answers. Just be spontaneous and clear. If you do not want to answer a question, you do not have to.

If you wish your interview remains anonymous, please let me know. I would like to record this conversation so that we can retain all the information that will be useful in our study. Do you have a problem with that?

The interview will last between 15 and 20 minutes.

II. Warm-up

Before we begin, allow me to introduce myself. My name is Mélanie, I am 23 years old and I am in the 2nd year of a master's degree in Business Engineering at the Louvain School of Management. I am currently writing my thesis in order to obtain my degree in management engineering.

- Could you describe yourself as I just did?

III. General questions

- Could you describe your company in two words and what is your function within your company?
- Why did you decide to start a company like this? What opportunities do you see in the 3D printing sector?

IV. Specific issues

- Does sustainable development have an important place in your company? On what do you base yourself to explain and/or prove your environmental, social and economic impacts? (Performance indicators, labels, corporate social responsibility indicators, etc.)

- Could you describe the main steps of your supply chain?
- Could you tell me more about where your raw materials and 3D printing machines come from?
- Are there any specific regulations in Belgium for this type of sector (3D printing, products)?
- In your opinion, what are the advantages/disadvantages of 3D printing in the medical sector?

V. Conclusion

We are nearing the end of this interview. Do you have anything to add? Any conclusions or criticisms you would like to make?

Thank you for the time you have given me and for your participation in my study, it will help me a lot.

APPENDIX 7. Interview guidelines with Giglio Orthopédie

I. Introduction

Good afternoon. First of all, I would like to thank you for participating in this study.

Your participation will help me in the realization of my thesis comparing the conventional supply chain and supply chain 4.0 with 3D printing in the medical sector, in order to know which process is the most sustainable.

I'm going to ask you a series of questions. You're completely free in the way you answer them, because there are no right or wrong answers. Just be spontaneous and clear. If you do not want to answer a question, you do not have to.

If you wish your interview remains anonymous, please let me know. I would like to record this conversation so that we can retain all the information that will be useful in our study. Do you have a problem with that?

The interview will last between 15 and 20 minutes.

II. Warm-up

Before we begin, allow me to introduce myself. My name is Mélanie, I am 23 years old and I am in the 2nd year of a master’s degree in Business Engineering at the Louvain School of Management. I am currently writing my thesis in order to obtain my degree in management engineering.

- Can you describe yourself as I just did?

III. General questions

- Could you describe your company in two words and what is your function within your company?
- How did you get started using 3D technologies and why using this technology?
- Did you directly see the potential for your business?
- What concrete applications have you developed or are you currently developing within your practice?
- What are the main technologies of additive manufacturing?

IV. Specific issues

- What are for you the biggest advantages of 3D technology today, but also for your colleagues?
- What are the drawbacks of implementing 3D technology and what are the barriers?
- Do you see in today's society a fear of this technology?
- In terms of financial but also human investment, what investment does this represent for a company that wants to start manufacturing 3D orthotics?
- How many medical devices do you produce thanks to 3D printing on a monthly or annual basis? Is it faster than traditional methods?
- What percentage does this represent in relation to the rest of the products made using traditional techniques and do you think you can gradually increase this percentage? By increasing the number of machines or by improving the process?

V. Conclusion

We are nearing the end of this interview. To conclude, what are the 3 big challenges you had to overcome for the implementation of 3D printing?

Do you have anything to add? Any conclusions or criticisms you would like to make?

Thank you for the time you have given me and for your participation in my study, it will help me a lot.

APPENDIX 8. Interview guideline with Alpha Company

I. Introduction

Good afternoon. First of all, I would like to thank you for participating in this study.

Your participation will help me in the realization of my thesis comparing the conventional supply chain and supply chain 4.0 with 3D printing in the medical sector, in order to know which process is the most sustainable.

I'm going to ask you a series of questions. You're completely free in the way you answer them, because there are no right or wrong answers. Just be spontaneous and clear. If you do not want to answer a question, you do not have to.

If you wish your interview remains anonymous, please let me know. I would like to record this conversation so that we can retain all the information that will be useful in our study. Do you have a problem with that?

The interview will last between 15 and 20 minutes.

II. Warm-up

Before we begin, allow me to introduce myself. My name is Mélanie, I am 23 years old and I am in the 2nd year of a master's degree in Business Engineering at the Louvain School of Management. I am currently writing my thesis in order to obtain my degree in management engineering.

- Could you describe yourself as I just did?

III. General questions

- Could you describe your Company in few words and what is your function within this company
- Does 3D printing play a role in your manufacturing process in your medical products? If yes why, if not, why not?
- Could you broadly map your supply chain by explaining the main actors and stakeholders from raw material to finish product (life cycle assessment of one of your product)?

IV. Specific issues

- Does your company care about sustainability (economic, environmental and social impacts)? If yes, How?
- What do you rely on to explain and/or prove your environmental, social and economic impacts? (Such as key performance indicators, labels, global reporting initiatives, …).
- Does it exist specific Belgian regulations on the sale of such products (quality test, label, insurance…)?
- What are the main barriers and the advantages for the implementation of such a technology inside your manufacturing process?

V. Conclusion

We are nearing the end of this interview. Do you have anything to add? Any conclusions or criticisms you would like to make?

Thank you for the time you have given me and for your participation in my study, it will help me a lot.

APPENDIX 9. Guideline interview with Laurent Voets, SIRRIS

I. Introduction

Good afternoon. First of all, I would like to thank you for participating in this study.

Your participation will help me in the realization of my thesis comparing the conventional supply chain and supply chain 4.0 with 3D printing in the medical sector, in order to know which process is the most sustainable.

I'm going to ask you a series of questions. You're completely free in the way you answer them, because there are no right or wrong answers. Just be spontaneous and clear. If you do not want to answer a question, you do not have to.

If you wish your interview remains anonymous, please let me know. I would like to record this conversation so that we can retain all the information that will be useful in our study. Do you have a problem with that?

The interview will last between 15 and 20 minutes.

II. Warm-up

Before we begin, allow me to introduce myself. My name is Mélanie, I am 23 years old and I am in the 2nd year of a master's degree in Business Engineering at the Louvain School of Management. I am currently writing my thesis in order to obtain my degree in management engineering.

- Could you describe yourself as I just did?

III. General questions

- Could you describe your company in two words and what is your function within your company?
- Which industrial sectors are the most appropriate and/or most open to additive manufacturing at present? (in terms of proportion?)
- Why do companies decide to move into additive manufacturing, what opportunities do they see in the 3D printing sector?

IV. Specific issues

- Could you explain what are the main barriers to the implementation of additive manufacturing for companies?
- What are the main changes in the supply chain of companies, in terms of moving to additive manufacturing as opposed to traditional manufacturing?
- Does the sustainable development of a company and the implementation of 3D printing within it is compatible from an economic, environmental and social point of view?
- At the social level, I have a few people who have told me that additive manufacturing is replacing trades. They are machines that work in the place of man. What do you think about that?
- Knowing that SIRRIS is a company that advises companies to turn to additive manufacturing, what is your main basis for explaining performance improvement, from an environmental, social and economic point of view? (Performance indicators, global reporting initiatives, labels, etc.).
- In five years, how do you see this technology in business?

V. Conclusion

We are nearing the end of this interview. Do you have anything to add? Any conclusions or criticisms you would like to make?

Thank you for the time you have given me and for your participation in my study, it will help me a lot.

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