LISBON SCHOOL OF ECONOMICS & MANAGEMENT
UNIVERSIDADE DE LISBOA

MASTER

GESTÃO E ESTRATÉGIA INDUSTRIAL

MASTER´S FINAL WORK

DISSERTATION

ADDITIVE MANUFACTURING ADOPTION IN PORTUGUESE COMPANIES: CASE STUDY ANALYSIS

ANA ISABEL MIRA LOPES

OCTOBER - 2019

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SUPERVISION:
PROF. DOUTOR MANUEL DUARTE MENDES MONTEIRO LARANJA

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ABSTRACT

Throughout the years, additive manufacturing has been in constant development and has been proving itself to be a true production technology. However, even though it is not a new technology, it still lacks research, and therefore, with its increased acceptance it becomes relevant to enlarge academic literature on the theme, hence the purpose of this exploratory study being the research on the adoption of additive manufacturing in Portuguese companies, primarily to uncover the motivations for its adoption, the company's experience in the implementation process, experienced benefits and limitations, and future prospects for this technology.

The findings appear to show that motivations for additive manufacturing adoption are mostly influenced by strategic and technological factors, and that the main challenge is the general lack of knowledge about the technology. The findings also show that all interviewed companies have experienced benefits in autonomous abilities, short time-to-market of new products, production flexibility, design freedom, capabilities of high-level customization, increase in the company's competitiveness, boost in product and processes' innovation, capability of reaching new customers and customer involvement in the creation process. As for limitations, the ones identified by all companies were the short production rate offered by the technology and the general lack of knowledge. Regarding prospects for the future, findings show that all companies recognized that the technology's potential is unmeasurable, however there is still a need to increase the offer in additive manufacturing education and trainings, spread awareness of this technology, improve printing speed and quality, progress in the development of hybrid technologies and increase certification.

Key Words: Additive manufacturing; 3D Printing; Adoption; Production Technology.

RESUMO

Ao longo dos anos, a manufatura aditiva tem estado em constante desenvolvimento e tem mostrado ser verdadeiramente uma tecnologia de produção. No entanto, embora não seja uma tecnologia nova, ainda carece de investigação e, portanto, com a sua crescente aceitação torna-se relevante estender a literatura sobre o tema, daí o objetivo deste estudo exploratório ser a análise da adoção da manufatura aditiva em empresas portuguesas, principalmente para descobrir as motivações para a adoção, a experiência da empresa no processo de implementação, os benefícios e limitações experienciados, e perspetivas futuras para esta tecnologia.

Os resultados parecem mostrar que as motivações para a adoção da manufatura aditiva são influenciadas maioritariamente por fatores estratégicos e tecnológicos, e que o principal desafio é a falta geral de conhecimento sobre a tecnologia. Os resultados também mostram que todas as empresas entrevistadas experienciaram benefícios em capacidade de autonomia, curto tempo de colocação no mercado de novos produtos, flexibilidade de produção, liberdade de design, capacidade de alto nível de customização, aumento da competitividade da empresa, aumento na inovação de produtos e processos, capacidade de alcançar novos clientes e envolvimento dos clientes no processo de criação. Quanto às limitações, as identificadas por todas as empresas foram a baixa taxa de produção oferecida pela tecnologia e a falta geral de conhecimento. No que respeita às perspetivas para o futuro, os resultados indicam que todas as empresas reconheceram que o potencial da tecnologia é imensurável, contudo mostra-se ainda necessário aumentar a oferta de educação e formações em manufatura aditiva, elevar a consciencialização acerca desta tecnologia, melhorar a velocidade e a qualidade da impressão, progredir no desenvolvimento de tecnologias híbridas e aumentar a certificação.

Palavras-Chave: Manufatura aditiva; Impressão 3D; Adoção; Tecnologia de Produção.

GLOSSARY

2D – Two-Dimensional

3D – Three-Dimensional

AM – Additive Manufacturing

GDPR – General Data Protection Regulation

R&D – Research and Development

TABLE OF CONTENTS

LIST OF TABLES

1 INTRODUCTION

Additive manufacturing is a manufacturing technology that has been developing since the 1980's, more commonly known as 3D printing (Gibson, Rosen & Stucker, 2015; Martens, 2018). This technology has been consistently evolving throughout the years, to the point where it is believed that it will mark the new industrial revolution (Hopkinson, Hague & Dickens, 2006). Many authors, such as Gibson *et al.* (2015) and Tuck & Hague (2006) believe AM can become a standard for production in the upcoming years, and trust that if AM continues to evolve and develop, manufacturing, and even our economy, may be transformed beyond measure. However, even though additive manufacturing is not a new technology, academic research is only now emerging (Ortt, 2016), therefore there is a clear need to increase investigation on the theme (Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor, Hao & Zhang, 2014; Rogers, Pirner & Pawar, 2018).

This exploratory study aims to contribute to the literature on AM, by analysing how Portuguese companies are adopting the technology, focusing in their motivations, the challenges encountered throughout the process, experienced benefits and limitations, and future prospects for AM. This research was conducted through case studies, and a total four companies were interviewed, all of which are Portuguese companies that have already or are at the moment adopting AM technologies.

Following this introduction, a literature review for additive manufacturing is displayed, which is sectioned in five parts, being additive manufacturing definition, adoption, benefits and limitations, current applications and development prospects. On chapter 3, the methodology applied in this research is presented, describing the methods for case selection and for data collection and analysis. In chapter 4 there is a brief presentation of the four companies that integrate this case study. Chapter 5 displays case findings and discussion, where the results from the interviews are presented and compared to current literature. Finally, the last chapter contains the conclusions of this study, mentioning its limitations and providing recommendations for future research.

2 LITERATURE REVIEW

This chapter presents the current literature on additive manufacturing, starting from the definition, to its adoption, benefits and limitations of the technology, current applications and development prospects. As it is an emerging technology that is evolving at great speed, this study tried to compile the most recent and relevant literature, using Mendeley to better organize and optimize the information collected from each author. One important remark is that this dissertation will not explore neither compare the specific additive manufacturing technologies and materials.

2.1. Additive Manufacturing Definition

Additive manufacturing is the term given to a manufacturing technology that begun to be developed in the 1980's as a result of advancements in many other technologies (Gibson *et al.*, 2015; Khajavi, Partanen & Holmström, 2014). Its basic principle is to build three-dimensional products by adding several 2D layers, directly from a 3D computer-aided design system (Attaran, 2017), therefore differing from the traditional subtractive and formative production processes (Conner, Manogharan, Martof, Rodomsky, L., Rodomsky, C., Jordan & Limperos, 2014; Gibson *et al.*, 2015; Ortt, 2016). AM is a set of several production technologies (Ford & Despeisse, 2016), and these tend to differ in cost, in the materials than can be processed, build volume, layer thickness, accuracy, part quality, speed of production and maintenance process (Conner *et al.*, 2014; Gibson *et al.*, 2015).

AM was firstly introduced as rapid prototyping, which reflected the initial purpose for the technology, being the rapid building of a prototype that would serve as a base model to study the final product (Attaran, 2017; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Mellor *et al.*, 2014). Now-a-days this technology is commonly known as 3D printing (Gibson *et al.*, 2015; Martens, 2018), however throughout this study the term adopted is additive manufacturing, given that it is the most accepted among authors and the official term given by the Technical Committee within ASTM International (2009). Besides being called 3D printing and additive manufacturing, over time many other terms have been used to describe AM, usually to enhance some particular approach to the technology (Gibson *et al.*, 2015), being the most known automated fabrication, additive/layer-based fabrication, freeform/solid form fabrication, rapid prototyping, stereolithography, direct digital manufacturing, and 3D printing (Attaran, 2017; Gibson *et al.*, 2015). However, most of the terms became inadequate, for not fully describing the capabilities, benefits and applications of the technology that arose due to improvements and advancements (Gibson *et al.*, 2015).

Conner *et al.* (2014) drew a comparison of AM with conventional manufacturing, where the authors stated that traditional manufacturing tends to focus on mass production, therefore producing large volumes of standardized products at lower costs. The mentioned authors stress that this business model is cost-driven and not value-driven. Huang, Riddle, Graziano, Warren, Das, Nimbalkar, Cresko & Masanet (2016) summarized the top advantages of AM when compared with traditional manufacturing, which are the easiness in producing complex geometries, the environmental-friendly processes, and the performance and environmental advantages in the product applications. Gibson *et al.* (2015) add that production using AM may not be a fully additive process, since some stages might need to resort to subtraction. Conner *et al.* (2014) state that when product complexity increases, the more difficult it is to produce it with conventional manufacturing.

In what regards how the production will change from now on, some organizations will be able to directly replace conventional manufacturing for AM technologies (Ford & Despeisse, 2016), while most organizations will not be capable of substituting conventional manufacturing, but will instead complement it with AM (Attaran, 2017; Ford & Despeisse, 2016; Rylands, Böhme, Gorkin III, Fan & Birtchnell, 2016). Some authors such as Gibson *et al.* (2015) consider AM has already become a common process in the production of products in low quantities with unique designs, especially in niche sectors (Attaran, 2017; Ortt, 2016; Tuck & Hague, 2006).

Additive manufacturing has indeed come a long way since its introduction and is improbable to be substituted in the near future (Rogers *et al.*, 2018). What once was a technology merely used to create prototypes, now has been used for direct digital manufacturing (Ford & Despeisse, 2016; Gibson *et al.*, 2015). Many authors consider AM as a disruptive innovation for its ability to create new businesses and present a threat to current ones (Amshoff, Dülme, Echterfeld & Gausemeier, 2015; Gibson *et al.*, 2015; Martens, 2018), as by definition disruptive innovations are the ones with new attributes able to disrupt existing markets (Bower & Christensen, 1995). Other authors even believe AM marks the new industrial revolution (Hopkinson *et al.*, 2006).

AM is therefore presenting new opportunities for manufacturing, providing the means to introduce new innovations (Attaran, 2017), and inspiring companies to change their business model (Bogers, Hadar & Bilberg, 2016; Ford & Despeisse, 2016). Rogers *et al.* (2018) even affirm that inter-industry competition between firms that integrated 3D printing in their business model is already high and is expected to increase as time goes by, as can be supported by the findings in Sculpteo (2018), where 74% of over 1000 respondents on the study confirmed that their competitors already use 3D Printing, following the 59% result in the previous year.

2.2. Adoption

Although AM has been increasingly adopted over the years, Martinsuo & Luomaranta (2018) believe it will take time until it is diffused on a large scale, as its adoption is not merely a technological matter.

Mellor *et al.* (2014) proposed that contemplation to adopt AM is both affected by the companies' internal strategy and external forces, and that AM implementation is influenced by five types of factors, them being strategic, technological, organizational, operational and supply chain factors. The mentioned authors acknowledge strategic factors as the ones associated with the specific features of markets and products that align with the companies' strategy, technological factors as the ones linked to the benefits resultant from the technology, organisational factors as the ones related to the company's dimension, structure and culture, operational factors as the ones related to its operational structure changes, mainly in product design, production planning, quality control and cost accounting system, and finally supply chain factors as the ones allied with the collaboration and interaction processes within the supply chain in regards to the accommodation of the technology.

Conner *et al.* (2014) state that business leaders can determine if AM will bring more value for a product when compared to conventional manufacturing, by mapping it through its complexity, customization and production volume. Through their case studies, the mentioned authors found that the higher the customization and/or complexity of the product, also higher is the probability of AM being more competitive than traditional methods. However, for cases in which the three parameters are low, the authors affirm AM will only prevail if it reduces lead times and costs.

Rogers *et al.* (2018) identified the trends that are leading to the increased adoption of additive manufacturing, them being personalization, democratization, and sustainability. The above-mentioned authors believe that the unlimited possibilities of personalisation, the reduction of design and production barriers and the increased sustainability of this production method will impact many industries.

Gibson *et al.* (2015) recognized that the centralization of product development, production and distribution is a common approach for many companies who recur to conventional manufacturing, but with AM that can change since this technology allows the transformation of digital designs into physical products in any location in the world, consequently eliminating costs in development, production and distribution.

Many authors have listed challenges that companies face while adopting additive manufacturing technologies, such as the lack of collaboration models amongst firms

(Martinsuo & Luomaranta, 2018), lack of experience working with AM (Gibson *et al.*, 2015; Mellor *et al.*, 2014), technological limitations (Mellor *et al.*, 2014; Weller *et al.*, 2015), absence of adoption strategies (Martinsuo & Luomaranta, 2018), partial perceptions of the technology influenced by its original limited purposes (Ford & Despeisse, 2016; Mellor *et al.*, 2014) and failure in the business adaptation to the technology (Martens, 2018).

One main aspect that has been influencing AM adoption is the cost of AM machines, also known as 3D printers, and many authors still consider it to be a limitation (Attaran, 2017; Ford & Despeisse, 2016; Khajavi *et al.*, 2014; Khorram Niaki & Nonino, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014). When these machines were first introduced in the market their cost was extremely high, but they still succeeded in capturing the interest of early adopters (Gibson *et al.*, 2015). However, the patents that were protecting the technology started to expire and that allowed the emergence of more models at lower prices (Gibson *et al.*, 2015), therefore encouraging AM adoption (Bonneau, Yi, Probst, Pedersen & Lonkeu, 2017). As the cost of AM machines will continue to drop (Ford & Despeisse, 2016; Gibson *et al.*, 2015; Rogers *et al.*, 2018), Gibson *et al.* (2015) trust that adoption by individuals will increase, and therefore will uncover more of the potential of AM. On the equipment supplier side, Rogers *et al.* (2018) add that the continued price reduction will lead to the reduction of the supplier's margin, and therefore will lead to market consolidation and increased entry barriers.

2.3. Benefits

Although AM has been developing since the 80's (Gibson *et al.*, 2015), academic research is only now emerging (Ortt, 2016), and there is a clear need for investigation in order to exploit all of its potential (Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor *et al.*, 2014; Rogers *et al.*, 2018). At the time when AM first came to market, the first benefits that could be seen through prototyping were the enriched visualization, the capability to discover imperfections and errors, cost reductions due to early detection of flaws, and the short prototyping time (Gibson *et al.*, 2015). Nonetheless, due to the advancements over the years, AM has developed to be a feasible production technology (Bogers *et al.*, 2016).

Most AM benefits uncovered by scientific research are operational, them being cost minimization for low-volume production (Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Holmström, Partanen, Tuomi & Walter, 2010; Khajavi *et al.*, 2014; Tuck & Hague, 2006), autonomous abilities (Attaran, 2017), short time from design to production (Ford & Despeisse, 2016; Gibson *et al.*, 2015), reduced time and cost of production ramp-up (Holmström *et al.*, 2010), reduction in the number of steps in production (Conner *et al.*, 2014; Gibson *et al.*, 2015), workflow optimization (Bonneau *et al.*, 2017), short time-to-market of new products (Attaran, 2017; Conner *et al.*, 2014; Khorram Niaki & Nonino, 2017; Weller, Kleer & Piller, 2015), reduced assembly time and cost (Ford & Despeisse, 2016; Weller *et al.*, 2015), production flexibility, as in the opportunity to introduce changes mid-production (Attaran, 2017; Bonneau *et al.*, 2017; Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Pour, Zanardini, Bacchetti & Zanoni, 2016), design freedom (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khorram Niaki & Nonino, 2017; Martens, 2018; Mellor *et al.*, 2014), better product functionality (Ford & Despeisse, 2016), and capability of high-level product customization (Attaran, 2017; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Holmström *et al.*, 2010; Mellor *et al.*, 2014; Oettmeier & Hofmann, 2016; Pour *et al.*, 2016; Tuck & Hague, 2006; Weller *et al.*, 2015). This customization ability enables the rise of mass customization (Attaran, 2017; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Deradjat & Minshall, 2017; Gibson *et al.*, 2015; Tuck & Hague, 2006), being the mass production of individually customized products. Martinsuo & Luomaranta (2018) make the remark that AM benefits will be heightened with broader supply chain adoption of the technology.

One of the main advantages AM brought is the facilitation of decentralized production (Attaran, 2017; Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Pour *et al.*, 2016), meaning production can happen in any geographic location as long as there is a 3D printer (Gibson *et al.*, 2015), which allows companies to move their production closer to their main customers (Bogers *et al.*, 2016). This way, AM also offer many advantages for logistics management, such as reduced inventories (Bogers *et al.*, 2016; Holmström *et al.*, 2010; Khajavi *et al.*, 2014) due to on-demand production (Attaran, 2017), short lead times (Attaran, 2017; Bogers *et al.*, 2016; Holmström *et al.*, 2010), reduced transportation costs (Bogers *et al.*, 2016; Ford & Despeisse, 2016), reduced complexity on supply chains (Attaran, 2017; Bogers *et al.*, 2016; Holmström *et al.*, 2010), and improvements on supply chain efficiency (Attaran, 2017).

One other great advantage of AM technologies is sustainability, mainly because of resource efficiency (Attaran, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Martens, 2018), reduced waste (Bonneau et al, 2017; Ford & Despeisse, 2016; Holmström *et al.*, 2010), and improvements in energy consumption (Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017).

Ford & Despeisse (2016) also add that although there are still not enough studies on the matter, AM might bring health benefits over traditional methods of manufacturing, resulting from better work environments, with less exposure to toxicities.

Overall, AM technologies increase the companies' competitiveness (Bonneau *et al.*, 2017; Khorram Niaki & Nonino, 2017; Weller *et al.*, 2015), by opening the doors to both product and process innovations (Attaran, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017), and therefore providing the means to reach new customers (Mellor *et al.*, 2014), as it allows the opportunity to involve customers in the creation process (Mellor *et al.*, 2014; Oettmeier & Hofmann, 2016; Rylands *et al.*, 2016).

Although the perspective of several authors on the benefits of AM was already presented, Sculpteo (2019) on their study about the current state of 3D Printing evaluated the perceptions of over 1300 respondents, obtaining the following results in what the respondents considered to be the main benefits of this technology: complex geometries (over 65%), quick iteration (about 45%), lead time reduction (about 40%), mass customization (over 30%), cost savings (over 30%), weight reduction (above 20%), simplified assembly (over 10%), and supply chain management (about 10%).

Many authors, such as Ford & Despeisse (2016), Gibson *et al.* (2015), Ortt (2016) and Tuck & Hague (2006) believe that if AM continues to evolve and develop, manufacturing, and even our economy, may be transformed beyond measure.

2.4 Limitations

Even though AM has presented solid growth over the years, there are still many limitations that are restricting its applications (Huang *et al.*, 2016).

Similarly to the benefits, most of AM limitations are production-related, being the limited choice of materials (Attaran, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014), limited material resistance (Attaran, 2017), size-limited production (Attaran, 2017; Martinsuo & Luomaranta, 2018), lower production precision when compared with conventional methods (Attaran, 2017; Wong & Hernandez, 2012), quality-related challenges (Bonneau *et al.*, 2017; Martinsuo & Luomaranta, 2018), short production rate (Attaran, 2017; Khajavi *et al.*, 2014; Martinsuo & Luomaranta, 2018), high costs in high-volume production (Attaran, 2017), cost of AM machines (Attaran, 2017; Ford & Despeisse, 2016; Khajavi *et al.*, 2014; Khorram Niaki & Nonino, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014) and difficulty in certification (Ford & Despeisse, 2016).

Authors also highlight as limitations the general lack of knowledge and proficiency in AM (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor *et al.*, 2014), as it still is an emerging technology and still lacks maturity (Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014). Additionally, two of the major topics on AM at the moment are the lack of regulation (Attaran, 2017; Bonneau *et al.*, 2017; Gibson *et al.*, 2015) and intellectual property concerns (Attaran, 2017; Bonneau *et al.*, 2017; Gibson *et al.*, 2015). For one, lack of regulation may lead to the production of firearms and other unsafe objects (Attaran, 2017; Gibson *et al.*, 2015), as no legal barriers have been established yet (Attaran, 2017; Bonneau *et al.*, 2017). Regarding intellectual property concerns, Bogers *et al.* (2016) emphasise the need for protection against replication and file sharing on the internet.

Sculpteo (2019) advocates that the respondents of the study considered the main limitations for adoption to be the following: cost of entry (over 60%), knowledge gap (about 50%), type of materials (over 35%), operating cost (about 35%), availability of materials (about 30%), regulations (over 20%) and environmental impact (over 15%).

2.5 Current Applications and Development Prospects

Additive manufacturing has been changing the way products are created, from design to distribution (Bonneau *et al.*, 2017), but it is also transforming the way industries operate (Attaran, 2017). Curiously, the most common purpose for the technology remains rapid prototyping (Bonneau *et al.*, 2017; Gibson *et al.*, 2015).

Regarding the possible applications for the technology, early adopters saw potential in AM as a way to prototype products, detect flaws and reduce costs (Gibson *et al.*, 2015), nevertheless the developments in additive manufacturing led to the broadening range of possible applications for this technology (Attaran, 2017). Now-a-days, the key industries using additive manufacturing are the automotive industry, to print spare parts on-demand, the aerospace industry, for the ability to manufacture lighter structures, and medical and healthcare industry, to develop new customized solutions for patients, and to improve the preparation for procedures (Attaran, 2017; Bonneau *et al.*, 2017; Gibson *et al.*, 2015; Wong & Hernandez, 2012).

According to Gartner (2017), as cited in "Gartner Predicts 2018: 3D printing changes business models" (2017), by 2021 "75% of new commercial and military aircraft will fly with 3D-printed engine, airframe and other components, (…) 25% of surgeons will practice on 3D-printed models of the patient prior to surgery, (…) 20% of the world's top 100 consumer goods companies will use 3D printing to create custom products, (…) 20% of enterprises will establish internal start-ups to develop new 3D print-based products and services, (…) and 40% of manufacturing enterprises will establish 3D printing centers of excellence".

In Sculpteo (2019), the highest response for applications was prototyping, with over 70% of the respondents selecting it, followed by proof of concept (over 60%), research/education/R&D (nearly 50%), production (above 45%), mechanical spare parts (about 40%), personal interest/hobby (over 30%), tooling (above 25%), marketing samples (over 20%), art/jewellery/fashion (above 15%), medical/dental/prosthesis (about 15%), mass production (over 10%), retail sales (nearly 10%) and "other" (under 10%).

Numerous authors, such as Attaran (2017), Gibson *et al.* (2015), Tuck & Hague (2006) and Wong & Hernandez (2012) believe AM can become a standard in the upcoming years, but there is still a lot of research to be done in order to improve it (Wong & Hernandez, 2012), as we are only now discovering all of its potential applications (Gibson *et al.*, 2015; Martinsuo & Luomaranta, 2018).

In order for AM to continue developing and being increasingly adopted, authors believe there should occur improvements in AM machines and in production processes (Rogers *et al.*, 2018), improvements in the accuracy of production (Conner *et al.*, 2014; Wong & Hernandez, 2012), usage of new materials (Rogers *et al.*, 2018), creation of standards related to the technology (Bonneau *et al.*, 2017), improvements in the protection of intellectual properties (Bonneau *et al.*, 2017), and improvement and proliferation of education about the technology (Ford & Despeisse, 2016).

3 RESEARCH METHODOLOGY

Following the example of many other countries, additive manufacturing technologies are growing as a production method in Portuguese companies. Hence, the purpose that underlies the realization of this research is the study of the adoption process of AM technologies in Portuguese companies, primarily to uncover the motivations that encourage the adoption, the challenges that companies encounter, the benefits and limitations experienced through the usage of the technology, and their future prospects. Thus, this research is exploratory and was conducted through case studies, as it proves to be the best method for studying real perspectives (Yin, 2014).

3.1. Case Selection

In order to select and present relevant case studies for this dissertation, a market research was conducted for companies that are adopting or have already adopted AM. Through this research, it was possible to identify thirteen suitable companies in many regions of the country, and three others were recommended by the first interviewees, totaling sixteen suitable companies. According to Eisenhardt (1989), when resorting to case studies, and in order to balance the amount and complexity of data, one should aim to display between four and ten case studies. Following the author's recommendation, in total seven companies were approached via email and LinkedIn for their best fit to this research, but only four of them showed availability to be part of the study.

3.2. Data Collection and Analysis

As previously mentioned, this research was led through case studies, therefore the data was collected through interviews. Prior to the interviews, a conversation guide was developed in order to structure them. This script was based on the literature review for the theme and contained 23 open questions and 2 closed questions. The questions were designed to acquire basic knowledge about the company, in how they incorporated AM into their business, in how has been their experience working with the technology, and to gather their perceptions of its potential.

The interviews were conducted in Portuguese, and occurred in the third week of September 2019, two of them in the companies' headquarters and the other two through online platforms, as presented in table I. This study trusts that the interviewees understood all the questions and answered them truthfully to the best of their ability.

Table I – Case Studies' Interviews

Date and Location	Company	Interviewee	Position	Duration
16-09-2019, Lisbon	3D Ways	Francisco Tenente	Co-Founder and CEO	70 minutes
16-09-2019, Lisbon	Siemens iExperience Centers	João Queiroz	Digital Enterprise Coordinator	55 minutes
17-09-2019, via Zoom Meeting	Diverte	Pedro Ribeiro	Co-Founder and Creative Director	85 minutes
19-09-2019, via Skype	Company X	Person Y	Engineering and Processes Director	75 minutes

Source: Own elaboration

All the interviewees gave their permission to record the interview, for facilitation of data collection purposes. However, one interviewee asked for anonymity as a requirement to participate in this research. In order to facilitate data analysis, all the interviews were later transcribed, except the one from Company X, as a request from the interviewee.

Finally, after analyzing all the data collected, all of the information displayed in this study regarding each company was compiled and sent for their final validation on the week prior to the dissertation submission, and all companies consented on it.

4 CASE STUDIES PRESENTATION

This chapter presents the four case studies that will be further analyzed in this dissertation, providing information about the company, its history and the context for its adoption of additive manufacturing technologies.

4.1. 3D Ways

Francisco Tenente and his business partner João Rosa founded 3D Ways in 2016 with the goal of creating and commercializing fans for camping tents that would turn themselves on automatically when the temperature reached a certain degree. In order to develop the fan, Francisco and João hired a product-development company that was already using additive manufacturing, and from the contact with said company, Francisco began developing ideas of what else he could produce. The founders then decided to acquire 3D Printers to experiment with the technology and assess possibilities, decided to dismiss the fan project, and focused on developing and commercializing customized accessories for airsoft guns, using only additive manufacturing processes. During this period, the company also decided to create their own 3D printers in order to overcome the challenge of finding AM machines capable of providing the printing quality they desired.

Shortly after initiating activity, the company had already grown considerably and acquired enough knowledge of the technology to embrace new markets. Therefore, the founders changed the company's business model and started providing personalized solutions to the specific customer's needs, not focusing in any particular market. The company also provides *in loco* printers, remotely controlled by a software that 3D Ways developed, to some of their bigger customers who require more of the service.

Now-a-days, 3D Ways counts with more than 300.000 printing hours and over 5.000 developed products. The company has four full-time employees, a large network of freelancers, and has already developed solutions for many industries, including healthcare, hotel management, archeology, footwear, art, and many more.

4.2. Siemens iExperience Centers

The Siemens iExperience Centers project began two years ago during the company's participation in the strategical committee for the industry 4.0, promoted by the Portuguese government. This initiative gathered over 60 Portuguese companies to engage in discussion over many topics concerning the theme and figure out the measures and means necessary to embrace the new technologies, one of these being additive manufacturing. One main concern exposed by the majority of the companies was the necessity of creating a specific space that would provide the means to experiment with all of the new technologies that are emerging and perceive its real potential value for their processes. Siemens then decided to accept the challenge and develop this concept, partnering initially with BeeVeryCreative and CADflow to implement these centers.

The project began developing, and currently there are already two centers, one in Alfragide (open since February 2018) and the other in Freixieiro (open since July 2019), but the plans are to open another five in the near future. Regarding the partnerships for the centers, there are now over twelve with different companies in different areas. The purpose of the centers remains the elaboration of projects that support digitalization, while sharing knowledge and developing competences with other companies, universities and other institutions.

4.3. Diverte

Diverte is the name of the brand created in 2016 by Pedro Ribeiro and his business partner, although they had been developing it already for about a year in incubation. The initial business plan that the founders had in mind was to build mini sculptures of children in schools, just like a photographer takes their pictures. However, this idea was not achievable, mostly because of the bad timing as the school year was almost ending. The founders then decided to embrace their experience in 3D printing with their local historical culture and created a project in which they produced sculptures of the traditional costumes worn by the locals of the city of Viana do Castelo during their annual festivities. Initially, said project was a way to continue working and generating income during the summer, as it was the break from the school year for their initial idea, yet the founders realized that the product they had developed was the way to success, and decided to name the project "Printing Traditions". The company then emerged with an artistic imprint and reached a level of detail that did not seem possible to the founders, leading the company into the artistic direction.

Now-a-days, although the company also attends to customers who come in contact with them for specific requests, Diverte focuses on developing and being part of artistic projects, such as what Pedro Ribeiro believes was the largest artistic installation using 3D printing, developed for the Viana do Castelo shopping center.

4.4. Company X

Company X is a fictional name for a Portuguese company with over 65 years of existence acting in the consumer goods sector, with a B2B business model. The company is a wholesaler but also has its own products, and has great international dimension, as it exports around 90% of them for more than 70 countries. This year, the company expects around 60 million euros in revenues from the Portuguese production unit only.

This company was one of the three which were referenced by others for this study, and the reason for its request for confidentiality lies in the fact that they recently adopted additive manufacturing technologies into their processes in order to launch a new business line that is not yet of market knowledge. This new business line will only come to market in 2020, thus the importance of keeping the data private. Regarding their use of the technology for production, the company does not expect it to substitute their other processes, but rather use it as a differentiation factor for its existing products.

5 CASE FINDINGS AND DISCUSSION

This chapter displays the findings resultant from the interviews with all four companies, while discussing and comparing them to what is presented in the literature review for this study. The discoveries are displayed in sections as motivations for AM adoption, adoption process, experienced benefits and limitations, and future prospects.

5.1. Motivations for Additive Manufacturing Adoption

In order to uncover the companies' motivations for the adoption of additive manufacturing technologies, the interviewees were questioned in an open way, thus allowing them to explain and illustrate these motivations for their specific scenario.

3D Ways states that additive manufacturing was the right solution for the company due to technological benefits, specifically because of the ability to easily scale the production capacity, reduce costs and time spent in the ramp-up of production, and overall reduction of costs and efficient time-to-market.

Regarding the Siemens iExperience Centers, as previously mentioned, they were created for the development of solutions, and creation of different projects, with different partners, supported by different types of technologies. Therefore, the main motivation for the adoption of additive manufacturing processes was not only the opportunity to experiment with the technology, but mainly the integration of these technologies into the assortment that the centers already had, complementing it with their other processes, in order to provide more aggregated value to the customers who seek specific solutions.

As for Diverte, Pedro Ribeiro states that the business was a 3D printing company from the very start, and the main motivation for it was the fact that it was a new business opportunity, different from everything that was being done at the time.

For Company X, the decision to adopt additive manufacturing technologies came as a result of the strategic view of the CEO, in an attempt to be pace to pace with market trends and customer needs. The company recognized the potential in AM and believed that the initial investment was now low enough to explore the technology, and therefore it seemed a good opportunity to gain know-how and experience, and, consequently, for staying ahead of competitors when they start adopting AM.

The findings seem to corroborate with the framework developed by Mellor *et al.* (2014), as AM implementation in the interviewed companies was at least influenced by one type of factor identified by the authors. From the interviewees' answers, the most common factors appear to be strategic and technological factors, given that contemplation for adoption seem to have occurred most often due to its alignment with the companies' business strategy, and perception over technological benefits.

5.2. Adoption Process

In order to assess how the companies experienced the adoption journey, the interviewees were inquired on the specific strategies implemented to succeed in the adoption, the challenges encountered, their use for the technology, and its connection with other production processes in the company.

Strategies for adoption

From all interviewed companies, only Diverte and Company X seem to have developed specific strategies to succeed in the technology adoption. For Diverte, the strategy was always focusing on a path to follow, specifically on pursuing artistic projects. In the case of Company X, the company decided to face the adoption process as exploratory, but one strategy implemented was to partner with an already established additive manufacturing company, that acts as their supplier and helps the company in the acquirement of know-how and experience with AM.

In the case of 3D Ways and the Siemens iExperience Centers, both did not implement any specific strategy. João Queiroz, manager of the Siemens iExperience

Centers, affirms they decided to be led by the market, in the sense of following their clients' needs and always being open to new challenges.

Adoption Challenges

Regarding adoption challenges, all companies identified lack of market awareness/knowledge about the technology and its possibilities, also recognized by Bonneau *et al.* (2017), Ford & Despeisse (2016), Khorram Niaki & Nonino (2017) and Mellor *et al.* (2014). João Queiroz affirmed that some clients of the Siemens iExperience Centers do not think of the technology as a possible solution for their needs, however the opposite also happens, when clients get to know the technology and start to believe it is the solution for every problem, which is also a challenge. Siemens overcomes the challenges they face frequently with their clients by analyzing, researching and filtering the requests they receive, and usually saying "no" to 30 up to 40% of them.

In the case of Diverte, the company listed the specific challenges they faced, starting from the moment they found it was becoming more difficult every day to execute their first idea in children schools due to the new general data protection regulation (GDPR), and the communication barrier with the customers, who lack knowledge about the technology. This led the company to focus even more on the artistic path and becoming unique in Portugal in what they do. Though, even after many communication strategies, that include going on TV to present their services, the company still finds that communication barrier with the common citizen, and even with companies. The company also went to explain that during a certain period they had an open store, where only 2 or 3 clients would enter. Diverte named them "the 10 euros client", since usually they would require a simple design and spend only 5 to 10 euros. Other times, clients would sometimes arrive with an idea that was not completely feasible or easy to execute and it was not easy to explain that the design would cost more than the actual production. Due to this, the company made the decision to close the store and now only opens it by arranging specific appointments with clients that approach them via email, which was a strategy that drove away “the 10 euros clients” but turned out better for the company. These experienced challenges also seem to include themselves in the general lack of knowledge about the technology (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor *et al.*, 2014).

3D Ways additionally recognized the difficulty in hiring employees with knowledge of the technology as a challenge, as it is particularly difficult to find people specialized in it due to the lack of available trainings and education on the theme. This challenge was previously identified by Ford & Despeisse (2016), and the authors emphasized its importance for skill development and competences acquirement. To overcome the mentioned challenge, 3D Ways acquired know-how through experimentation with the technology and trainings, using the knowledge of the employees that had a 3D printing background to educate others who did not.

Company X asserts that the main challenges experienced so far were the limitations of the technology for mass production and the value perception of the printed products, especially in the quality/price comparison. Being a large company that commercializes over 900.000 different products, the challenge Company X identified makes it extremely difficult for the company to replace their processes with AM in the present day, and therefore, the company states they will only exploit 3D printing to differentiate and/or complement their existing products, and is not interested in selling separate 3D printed products. These findings support Conner *et al.* (2014), as the level of customization and complexity of most products Company X commercializes is low, and the production volume is high, additive manufacturing is not likely to prove itself to be more competitive than conventional manufacturing.

When questioned if at any time they felt doubt and concerns about how the technology was performing against their expectations, 3D Ways and Diverte said yes. For 3D Ways, that moment occurred when the company was not satisfied with the 3D printers available at the price level they could support and decided to develop their own. Diverte states that this still happens when the company finds times when they need to complement their activities with additional technologies because sometimes AM is just not enough. This need to sometimes resort to other technologies was also identified by Gibson *et al.* (2015).

Company X confirmed that, as they were perceiving the viability of the technology with an exploratory approach, their expectations were not high, but at the moment they believe it is possible to generate income from the use of the technology, not because it is more competitive than what they thought, but rather because there is some market demand specifically for this technology and the market price is still quite high when compared to its cost.

João Queiroz affirms that the adoption of additive manufacturing technologies in the iExperience Centers has been a constant learning experience, as none of the employees had experience with the technology, and the centers have been investing in trainings and competencies development.

AM Purposes in the Company

When questioned about the purpose the company gives to their prints, 3D Ways affirmed that they mostly use the technology for prototyping, production and investigation on automation systems for the software that they have been developing. In the iExperience Centers, the prints are mainly for proof of concept, prototyping and components production. As previously mentioned, Company X uses the technology for small production, and considers that the technology will also be significantly used for production support and internal maintenance, for example through the production of supports and adapters for their machines. Diverte cannot pinpoint all the purposes because the company states that they use it for everything, from research to production. These findings on AM purposes seem to coincide with the most common ones found in Sculpteo (2019), being prototyping, proof of concept, R&D, and production.

Besides additive manufacturing, 3D ways estimates that in about 15% of their production they need to recur to other conventional processes, such as mold injection, thermoforming and CNC machining. In the iExperience Centers, since they use the technology to prove its value and discover solutions and not for product production, all of their prints are 100% made through additive manufacturing. Diverte states that they do not usually recur to other production methods, but occasionally do so when the specific project requires it. These findings support Gibson *et al.* (2015), in the affirmation that production using AM may sometimes require other production methods.

5.3. Experienced Benefits and Limitations

In the interest of assessing how the benefits and limitations experienced by the interviewed companies relate to the ones found in the literature review, the interview guide contained two closed questions in which each one displayed the respective list with the enumeration of benefits and limitations found in the literature, so the company could select those which they experienced. As the benefits and limitations were being listed during the interview, there was openness for answer elaboration, and therefore this section will also include the most relevant remarks made by the interviewees in regard to their experience and opinion.

To improve cognitive visualization, the result tables display a full circle (●) in the spaces where the company stated they experienced said benefit or limitation, an empty space in the ones not experience, and an outlined circle (○) for the cases where they confirm it can be experienced but only depending on the specific situation.

The findings can be seen in the two tables bellow.

Table II - Benefits Experienced by the Interviewed Companies

Benefit	3D Ways	Siemens iExperience Centers	Diverte	Company X
Cost minimization for low-volume production	●	●	●	

(Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Tuck & Hague, 2006)				
Autonomous abilities (Attaran, 2017)	●	●	●	●
Short time from design to production (Ford & Despeisse, 2016; Gibson *et al.*, 2015)	●	○	●	●
Reduced time and cost of production ramp-up (Holmström *et al.*, 2010)	●	○	●	
Reduction in the number of steps of production (Conner *et al.*, 2014; Gibson *et al.*, 2015)	●	○	●	○
Reduced assembly time and cost (Ford & Despeisse, 2016; Weller *et al.*, 2015)	○	○	●	
Workflow optimization (Bonneau *et al.*, 2017)	●		●	○
Short time-to-market of new products (Attaran, 2017; Conner *et al.*, 2014; Khorram Niaki & Nonino, 2017; Weller *et al.*, 2015)	●	●	●	●
Production flexibility, as in the opportunity to introduce changes mid-production (Attaran, 2017; Bonneau *et al.*, 2017; Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Pour *et al.*, 2016)	●	●	●	●
Capability to discover imperfections and errors, due to early detection of flaws (Gibson *et al.*, 2015)	●	●	●	
Design freedom (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khorram Niaki & Nonino, 2017; Martens, 2018; Mellor *et al.*, 2014)	●	●	●	●
Capability of high-level product customization (Attaran, 2017; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Holmström *et al.*, 2010; Mellor *et al.*, 2014; Oettmeier	●	●	●	●

& Hofmann, 2016; Pour *et al.*, 2016; Tuck & Hague, 2006; Weller *et al.*, 2015)				
Facilitation of decentralized production (Attaran, 2017; Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Pour *et al.*, 2016)	●	●	●	
Reduced inventories due to on-demand production (Attaran, 2017; Bogers *et al.*, 2016; Holmström *et al.*, 2010; Khajavi *et al.*, 2014)	●	●	○	
Short lead times (Attaran, 2017; Bogers *et al.*, 2016; Holmström *et al.*, 2010)	○	●	●	
Reduced transportation costs (Bogers *et al.*, 2016; Ford & Despeisse, 2016)	●	●	○	
Reduced complexity on supply chains (Attaran, 2017; Bogers *et al.*, 2016; Holmström *et al.*, 2010)	●	●	●	
Improvements on supply chain efficiency (Attaran, 2017)	●	●	●	
Resource efficiency (Attaran, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Martens, 2018)	●	○	●	
Reduced waste (Bonneau et al, 2017; Ford & Despeisse, 2016; Holmström *et al.*, 2010)	●	●	●	
Improvements in energy consumption (Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017)	●	●	●	
Health benefits due to less exposure to harsh work environments (Ford & Despeisse, 2016)		○	○	
Increased company competitiveness (Bonneau *et al.*, 2017; Khorram Niaki & Nonino, 2017; Weller *et al.*, 2015)	●	●	●	●

Boost in product and process innovations (Attaran, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017)	●	●	●	●
Capability of reaching new customers (Mellor *et al.*, 2014)	●	●	●	●
Customer involvement in the creation process (Mellor *et al.*, 2014; Oettmeier & Hofmann, 2016; Rylands *et al.*, 2016)	●	●	●	●

Source: Own elaboration

Table III - Limitations Experienced by the Interviewed Companies

Limitation	**3D Ways**	**Siemens iExperience Centers**	**Diverte**	**Company X**
Cost of entry (Attaran, 2017; Ford & Despeisse, 2016; Khajavi *et al.*, 2014; Khorram Niaki & Nonino, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014)		○		
Limited choice of materials (Attaran, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014)		●	●	●
Limited material resistance (Attaran, 2017)		○	●	●
Size-limited production (Attaran, 2017; Martinsuo & Luomaranta, 2018)	●	●	●	
Lower production precision when compared with conventional methods (Attaran, 2017; Wong & Hernandez, 2012)	○	●	●	
Quality-related challenges (Bonneau *et al.*, 2017; Martinsuo & Luomaranta, 2018)	●	○	○	●
Short production rate (Attaran, 2017; Khajavi *et al.*, 2014; Martinsuo & Luomaranta, 2018)	●	●	●	●

High costs in high-volume production (Attaran, 2017)	●	●	●	●
General lack of knowledge in AM (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor *et al.*, 2014)	●	●	●	●
Lack of technology maturity (Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014)			●	●
Lack of Regulation (Attaran, 2017; Bonneau *et al.*, 2017; Gibson *et al.*, 2015)	●	○	●	
Intellectual property concerns (Attaran, 2017; Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Gibson *et al.*, 2015)	●	○	○	

Source: Own elaboration

Overall, the findings on the experienced benefits and limitations appear to confirm what is found on the literature. All companies affirm to have experience benefits in autonomous abilities (Attaran, 2017), short time-to-market of new products (Attaran, 2017; Conner *et al.*, 2014; Khorram Niaki & Nonino, 2017; Weller *et al.*, 2015), production flexibility (Attaran, 2017; Bonneau *et al.*, 2017; Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Pour *et al.*, 2016), design freedom (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khorram Niaki & Nonino, 2017; Martens, 2018; Mellor *et al.*, 2014), capabilities of high-level customization (Attaran, 2017; Bonneau *et al.*, 2017; Conner *et al.*, 2014; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Holmström *et al.*, 2010; Mellor *et al.*, 2014; Oettmeier & Hofmann, 2016; Pour *et al.*, 2016; Tuck & Hague, 2006; Weller *et al.*, 2015), increase in the company's competitiveness (Bonneau *et al.*, 2017; Khorram Niaki & Nonino, 2017; Weller *et al.*, 2015), boost in product and processes innovation (Attaran, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017), capability of reaching new customers (Mellor *et al.*, 2014) and customer involvement in the creation process (Mellor *et al.*, 2014; Oettmeier & Hofmann, 2016; Rylands *et al.*, 2016).

As for limitations, the only ones identified by all companies were the short production rate offered by the technology (Attaran, 2017; Khajavi *et al.*, 2014; Martinsuo & Luomaranta, 2018), high costs in high-volume production (Attaran, 2017) and general lack of knowledge in AM (Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Khorram Niaki & Nonino, 2017; Mellor *et al.*, 2014).

3D Ways highlights as top benefits the reduction of time and costs in the production ramp-up, the production flexibility and design freedom. The top limitations for the company are the quality-related challenges, the short production rate and the lack of knowledge in AM. Francisco underlines that the quality challenge experienced in 3D Ways is not due to material quality, but rather quality stability in production repeatability.

Diverte emphasizes the support that the technology provides into product development, as the costs are low, the process is much faster, and allows for personalization. In terms of limitations, Pedro Ribeiro affirms that the most noticeable are the limited choice of materials and its limited resistance, the size-limited production, lack of technology maturity, and also the communication barrier caused by the lack of AM knowledge.

Company X considers that the top benefits are not being a costly technology to experiment with, the fact that it provides an agile way to do it, and its flexibility in applications. As top limitations, the company considers them to be the fact that even though the cost of entry is no longer high, it still is costly when compared to alternatives in quality/cost comparison, and the lack of awareness about what can or not be done in the market.

The main advantage highlighted by João Queiroz, manager of the Siemens iExperience Centers, was the decentralization of production, as recognized by many authors (Attaran, 2017; Bogers *et al.*, 2016; Bonneau *et al.*, 2017; Ford & Despeisse, 2016; Gibson *et al.*, 2015; Khajavi *et al.*, 2014; Pour *et al.*, 2016).

Additionally, all companies believe that adopting AM technologies increases the companies' competitiveness, as stated by Bonneau *et al.* (2017), Khorram Niaki &

Nonino (2017) and Weller *et al.* (2015). Diverte adds that although it elevates the company's competitiveness, it is more notable for companies that switch from conventional manufacturing to additive manufacturing.

As can be visualized in the tables presented above, on the majority of the lines, the findings seem to confirm what is found in the literature. However, one important remark is that blank spaces do not indicate that the company does not believe the benefit or limitation exist, but rather they just do not experience it. Nonetheless, the interviewees made a few observations concerning some of the benefits and limitations, where their opinion goes against what is found in the literature review.

One particularly interesting finding is that none of the interviewed companies consider the cost of entry as a limitation, identified by many authors as such (Attaran, 2017; Ford & Despeisse, 2016; Khajavi *et al.*, 2014; Khorram Niaki & Nonino, 2017; Martinsuo & Luomaranta, 2018; Mellor *et al.*, 2014). 3D Ways believes that the cost is not high, as there is an increasing offer of AM machines at very different price ranges, and one can escape that investment by renting the machines. João Queiroz, manager of the Siemens iExperience Centers, agrees with the latter, and believes that while for some companies this is still a limitation, companies now have the opportunity to collaborate with others and associate themselves with a supplier partner.

Regarding the limited choice of materials and its limited resistance, still identified as a limitation by Attaran (2017), Martinsuo & Luomaranta (2018) and Mellor *et al.* (2014), 3D Ways believes that a few years ago this was a constraint, but not now-a-days, as there is an increasing offer of materials, such as over 80 types of plastics, metals, ceramics, *etc*. In what concerns material resistance, the company states that weak materials offer weak resistance, and that is a question of material quality, that can be obtained at higher prices. João Queiroz, manager of the Siemens iExperience Centers, considers that limited choice of materials is still a limitation, but it is progressively becoming less of a it as time goes by.

In what concerns health benefits, when compared with conventional manufacturing work environments, listed as a possible benefit by Ford & Despeisse (2016), 3D Ways does not consider they exist, as the exposition to toxic materials (if used in production) still happens. Diverte acknowledges that there is still a gap in research surrounding this question, as it depends on the material being printed, and the amount of microplastics released during the printing that are then inhaled by the employees.

Furthermore, the findings show conflicting results in what regards intellectual property concerns and lack of regulation. João Queiroz, manager of the Siemens iExperience Centers, affirms that both these questions depend on the market in which the companies operate, and how the solution is being applied. Pedro Ribeiro, from Diverte, believes that the lack of regulation, identified by many authors (Attaran, 2017; Bonneau *et al.*, 2017; Gibson *et al.*, 2015), does not show itself more because even though AM is becoming increasingly adopted, there are still few companies operating with the technology. Pedro considers regulation as an action step, since the reduction of price and increase in quality on 3D printers led to the widespread of the technology, which poses as a challenge for companies as everyone can now have a printer at home and print upon request. This encouragement for adoption was previously identified by Bonneau, *et al.* (2017), and Pedro considers this is "destroying" the market for companies with this kind of business model, because there is no certification nor regulation for controlling competition. Regarding intellectual property concerns, shown by Attaran (2017), Bogers *et al.* (2016), Bonneau *et al.* (2017) and Gibson *et al.* (2015), Pedro does not see these concerns very worrying at the moment as there have not been many creators in the 3D printing field and the market has been functioning well as a community.

Regarding technological maturity, 3D Ways does not believe it is a limitation, as opposed to Martinsuo & Luomaranta (2018) and Mellor *et al.* (2014), since we are already in a situation where the technology has started maturing, just not to the point of scaling to even more competitive prices. João Queiroz, manager of the Siemens iExperience

Centers, agrees that lack of technology maturity is no longer a limitation, as improvements are advancing at a rapid speed.

5.4. Future Prospects

This section aims to provide the interviewees' insights into the expected evolution of the interviewed companies' investment, the expected progress of the technology, and top priorities for technology improvements.

Expected Evolution of Investment

Regarding evolution of investment, 3D Ways was the only company to share their future plans. The company has already invested over 300.000 euros but intends to invest 500.000 euros more in the next year, not only in machines, but mostly on advertising and commercial teams, in order to increase sales. Francisco emphasizes the importance of always continuing the investment in education and know-how, as also considered fundamental by Ford & Despeisse (2016).

In the case of Company X, even though the company preferred not to disclose the value of their investment, Person Y trusts that in the near future they will stabilize and take advantage of the investment already placed in the technology.

Expected AM Evolution

Concerning the expected evolution of the technology, 3D Ways agrees that the technology is developing at great speed, and while there are still many things that need improvement, a lot of capital is being invested into technology research. Francisco Tenente affirms that just like the internet started some time ago and now-a-days it is almost impossible to live without it, in a few years the same will happen with AM. In what concerns market awareness, 3D Ways believe that when more large companies adopt the technology, it will spread even more. The company believes that Portugal is falling behind in AM adoption, but soon more companies will want to implement this technology. Francisco Tenente trusts that there will be a decrease in price in the consumables for AM machines but also in the machines with more recent technologies, an increased offer for new materials, also more innovation such as in the software, and more efficient use of the machines.

João Queiroz, manager of the Siemens iExperience Centers, thinks there will be evolution in materials, printing speed and scale, and also introduction of mechanisms for multi-material printing. João believes that print shops will start to spread, especially in the consumer market, and more companies will start supplying 3D printing solutions. João also trusts that 2020 will be a year of major advancements in many new technologies, and therefore it will be possible to observe a major increase in their adoption.

Diverte recognizes that AM has giant potential, and that today the technology is not even close to where it will evolve. The company considers that the market for the "10 euros clients" will exist, and will start spreading in the future, but is not something they want to explore. Regarding education on AM, Pedro Ribeiro states that even with trainings on the theme, the real experience is acquired through printed hours, not by training hours. In the near future, Pedro Ribeiro expects the technology to mature and develop an higher quality standard, also with developments on market regulation, and increased market awareness with less communication barriers.

Company X agrees with the huge potential of AM, and while believing that there are methods this technology will never replace, the company trusts that with some advancements AM could really substitute a significant part of them, as acknowledge by many authors (Attaran, 2017; Ford & Despeisse, 2016; Rylands *et al.*, 2016). The company has hopes for some evolvements in machines in the near future, in the sense of becoming faster and more reliable, and also reductions on the price for metal printing.

As mentioned above, all companies seem to recognize AM's enormous potential and believe in a great evolution for the technology, which corroborates with the predictions of many authors, such as Ford & Despeisse (2016), Gibson *et al.* (2015), Ortt

(2016), Rogers *et al.* (2018) and Tuck & Hague (2006), that believe AM has the potential to transform manufacturing beyond measure.

Regarding next steps for the technology, Company X considers that in order for AM to grow and spread even further, there is a need for technological advancements, specifically in the sense of increasing printing speed and increasing quality, which supports the need for improvements in AM machines and processes identified by Rogers *et al.* (2018). João Queiroz highlights the promotion of these new concepts, but also the increase of the connection between the 3D printing concept, production management and network operation, and perception of 3D printing as part of the company's value chain. 3D Ways lists three priorities for the future, which are certification, increased awareness and hybrid and faster technologies development. Francisco Tenente also mentions that a great step to increase market awareness is increasing education on the theme, by increasing the amount of trainings and courses in universities about AM, also emphasized by Ford & Despeisse (2016).

6 CONCLUSIONS

This chapter intends to provide the main conclusions drawn from this case study, as well as acknowledge its limitations, and offer recommendations for future research.

6.1. Main Conclusions

This dissertation had the purpose of exploring how Portuguese companies are adopting additive manufacturing, through the analysis of their motivations, their journey through the adoption process, their experienced benefits and limitations, and their future prospects for further technology developments. Therefore, this exploratory study contributes for the current literature on the theme, providing an insight of AM adoption in Portuguese companies.

Through this study, and using the framework developed by Mellor *et al.* (2014), it was possible to identify that the main motivations for adoption seem to be most often related to strategic and technological factors, as contemplation for adoption seem to have occurred most frequently due to its alignment with the companies' business strategy, and perception over technological benefits.

In what concerns the adoption process, there were several findings. Beginning with strategies for adoption, only two out of the four interviewed companies state there was an implemented strategy to succeed in the adoption. Regarding adoption challenges, one which all companies identified was the general lack of knowledge about the technology. Other challenges identified by the interviewees were the hiring of specialized employees due to lack of available trainings and education on AM, limitations in mass production, and the low value perception of 3D printed products.

Considering the purposes given to AM by the interviewed companies, the findings appear to coincide with the ones identified by Sculpteo (2019), in which the most common are prototyping, proof of concept, R&D and production. Moreover, only one of the four interviewed companies affirm to not resort to any other traditional process on their prints.

Overall, the findings on the experienced benefits and limitations, appear to confirm what is found on the literature. The benefits that all companies state to have experienced are autonomous abilities, short time-to-market of new products, production flexibility, design freedom, capabilities of high-level customization, increase in the company's competitiveness, boost in product and processes innovation, capability of reaching new customers, and customer involvement in the creation process. As for limitations, the only ones identified by all companies were the short production rate offered by the technology, high costs in high-volume production and general lack of knowledge in AM. Other highlighted benefits by the interviewees were the reduction of time and costs in the production ramp-up, improvements in product development, and decentralization of production. As for limitations, the interviewees also emphasized quality-related challenges and size-limited production. The findings show conflicting results in the perception over limitations in materials, intellectual property concerns and regulations.

Regarding the interviewed companies' prospects for the future, all companies recognized that AM's potential is unmeasurable, but there are still many improvements necessary for further developments. Some of the priorities for the future identified by the companies were the need to increase the offer in AM education and trainings, increase technology awareness, improvements on printing speed and quality, development of hybrid technologies, and certification.

6.2. Limitations and Future Research

There are three main limitations in this exploratory study. The first one is the small number of interviewed companies, as only four companies were interviewed. The second limitation is the singular country analysis, as the study was conducted to analyze only the Portuguese context on AM adoption. The final limitation is the fact that only qualitative data was gathered and analyzed.

As for recommendations for future research, there are a number of interesting studies that could be done, such as applying the methodology of this dissertation but focusing only on companies that change from a conventional method of manufacturing to additive manufacturing. Another possibility is the study of the impact of AM adoption in one specific industry, or also the impact on the supply chain when one Portuguese company adopts the technology. Additionally, it would be curious to include quantitative data, and study the financial impact on the company after AM adoption.

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APPENDIX

Appendix A – Interview Guide

<u>*Section 1 – Company Introduction*</u>

1. Company Profile: name, industry, years of existence, brief history.
2. Interviewee Profile: name, position in the company, number of years working in the company.
3. Authorization to allow the use of the name of the company and interview results in this study.

<u>*Section 2 – AM Adoption Process*</u>

4. How did your company decide to implement AM technologies?
5. What were your main motivations to do so?
6. Did you develop any specific strategy in order to succeed in this adoption?
7. What challenges did you encounter through the process of adoption?
8. How did you overcome the challenges?
9. Did you at any point felt that the adoption of the technology was not corresponding to the expectations?
10. How long have you been using 3D printing?
11. Did you had anyone in the company that had used 3D printing before?
12. How many years of experience would you say the company has in average working with AM processes?
13. Can you estimate how much has your company invested in 3D printing?
14. What purpose does your company give to the 3D prints?
15. To what degree do you use 3D printing?
16. Do you use any other methods of production besides 3D printing?
17. From the list below can you tell me which benefits has the company experienced:

Benefit	**Experienced?**
Cost minimization for low-volume production	
Autonomous abilities	
Production speed	
Reduced time and cost of production ramp-up	
Reduction in the number of steps of production	
Reduced assembly cost	
Workflow optimization	
Short time-to-market of new products	
Production flexibility, as in the opportunity to introduce changes mid-production	
Capability to discover imperfections and errors, due to early detection of flaws	
Design freedom	
Capability of high-level product customization	
Facilitation of decentralized production	
Reduced inventories due to on-demand production	
Short lead times	
Reduced transportation costs	
Reduced complexity on supply chains	
Improvements on supply chain efficiency	
Resource efficiency	
Reduced waste	
Improvements in energy consumption	
Health benefits due to less exposure to harsh work environments	
Increased company competitiveness	
Boost in product and process innovations	
Capability of reaching new customers	
Customer involvement in the creation process	

18. From this list below can you tell me which limitations has the company experienced:

Limitation	**Experienced?**
Cost of entry	
Limited choice of materials	
Limited material resistance	
Size-limited production	
Lower production precision when compared with conventional methods	
Quality-related challenges	
Short production rate	
High costs in high-volume production	
General lack of expertise in AM	
Lack of technology maturity	
Lack of Regulation	
Intellectual property concerns	

19. How do you perceive the success of your use of the technology?
20. How is AM integrated in the company's strategy?
21. How do you expect your investment in 3D printing to evolve in the next year?

Section 3 – Future Predictions

22. How do you perceive the potential of the technology?
23. How do you expect the technology to evolve in the next five years?
24. What do you feel should be the top priorities for the 3D printing industry growth?

Section 4 – Additional Information

25. Do you have any other information you see relevant for this study that we did not discuss?