ADDITIVE MANUFACTURING AS A MANUFACTURING METHOD: AN IMPLEMENTATION FRAMEWORK FOR ADDITIVE MANUFACTURING IN SUPPLY CHAINS

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Prof. Ing. Matteo Kalchschmidt, Ph.D) Principal Advisor

I certify that all of the material in this dissertation which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other university.

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Approved for the University Committee on Graduate Studies.

Abstract

The supply chain is changing speedily and on a continuous basis to keep up with the rapid changes in the market, which are summarized as increased competition, changes in traditional customer bases, and changes in customers' expectations. Thus, companies have to change their way of manufacturing final products in order to customize and expedite the delivery of products to customers. Additive manufacturing, the new production system, effectively and efficiently increases the capability of personalization during the manufacturing process. This consequently increases customer's satisfaction and company's profitability. In other words, additive manufacturing has become one of the most important technologies in the manufacturing field. Full implementation of additive manufacturing will change many well-known management practices in the production sector.

Theoretical development in the field of additive manufacturing in regards to its impact on supply chain management is rare. There is no fully applied approach in the literature that is focused on managing the supply chain when additive manufacturing is applied. While additive manufacturing is believed to revolutionize and enhance traditional manufacturing, there is no comprehensive toolset developed in the manufacturing field that evaluates the impact of additive manufacturing and determines the best production method that suits the applied supply chain strategy. A significant portion of the existing supply chain methods

and frameworks were adopted in this study to examine the implementation of additive manufacturing in supply chain management. The aim of this study is to develop a framework to explain when additive manufacturing "3D printing" impacts supply chain management efficiently.

To build the framework, interviews with some companies that already use additive manufacturing in their production system have been carried out. Next, an online survey and two case studies evaluated the framework and validated the results of the final version of the framework.

The conceptual framework shows the relationship among supply chain strategies, manufacturing strategy and manufacturing systems. The developed framework shows not only the ability of additive manufacturing to change and re-shape supply chains, but its impact as an alternative manufacturing technique on supply chain strategies. This framework helps managers select more effective production methods based on certain production variables, including product's type, components' value, and customization level.

Acknowledgement

It is a great honor for me to express my gratitude to the person who has guided me throughout my research and made this thesis possible. I am extremely grateful to my academic and research advisor professor Matteo Kalchschmidt for providing me invaluable guidance throughout my research work. Prof. Kalchschmidt has always motivated me to pursue my ideas and rectified my mistakes under his watchful eyes. His greatest contribution taught me how to think in an organized manner and evaluating and solving problems one step at a time.

I would also like to thank my parents for being with me, always. I dedicate this thesis to them and I hope they will find happiness in my achievements.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

New technologies are able to create strategic opportunities for companies to build competitive advantages and enhance performance in many functional and managerial areas including supply chain management. Technology has great positive impact on the success of supply chain management by improving the efficiency and effectiveness of the manufacturing process. However, the degree of success depends on the right application of the technology in accordance to the applied business strategies, products type and level of customization.

3D printing is specifically a manufacturing technology that depends on computerized design files to manufacture three-dimensional (3D) objects. It creates layers of materials over each other's which makes it an additive process in contrast to subtractive or formative processes [Nyman and Sarlin (2014)]. Because 3D printing is still in the early stages of implementation in manufacturing businesses, it is difficult to be fully compared to the capabilities of traditional manufacturing repetitive process system. However, the development of 3D printing and its applications have been accelerated strongly in recent years [Wohlers

(2015)]. The technology has dramatically transformed from simple prototyping to fully integrated utilizations in direct manufacturing. According to Manners-Bell and Lyon (2012) 3D printing became one of the most significant industrial developments of this decade, due to its many forms of applications.

As Cohen et al. (2014) stated, the rapid development of 3D printing has affected all industries including aerospace, medical, consumer goods, architecture, fashion, education, and business development and design. Consequently, 3D printing has a great impact on supply chains and supply chain management. This impact gives rise to new opportunities in supply chain management. Researchers like Basiliere et al. (2013), as well as, Wohlers report [Wohlers (2015)] have forecasted a huge inflation in the global market size of 3D printing through the years from 2013 – 2018. They expected it to grow from 3 billion USD to 13 billion USD. Moreover, Wohlers report of 2015 [Wohlers (2015)] went further in expectation to expect the market size in year 2020 will exceed the 21 billion USD. These expectations make it clear that experts in this field believe the market of 3D printing keeps growing, rapidly. Accordingly, this makes 3D printing a hot topic in the field of business, in particular supply chain management. The motivation of this PhD thesis is based on these expectations of experts and the confident beliefs in the opportunities this technology has to affect supply chain management.

3D printing gains its trust from manufacturers to become not only a prototyping method in developing departments but to be specialized machines produces finished components or final goods [Cohen et al. (2014)]. However, it is not feasible and/or applicable to all business firms in all industries. That depends on several variables such as the types of products or output levels of production, level of customization, and applied supply chain strategy.

Nevertheless, a lot of companies with different nationalities from different sectors or industries are implementing 3D printing in their production system. This implementation of this technology gives a positive indicator to its success in variant industries. Manufacturers like General Electrics had invested vastly in 3D printing to produce more than 85,000 fuel nozzles for the new Leap Jet engines [Gilpin (2014)]. Lenovo, the world's largest PC company has acknowledged their intent to enter the 3D printing world [Arora (2015)]. Boeing Airline Company was one of the early adopters of 3D printing technology. Boeing has 3D printed more than 20,000 parts for 10 different military and commercial planes [Gilpin (2014)]. Intel, the world's largest computer chip producer has created RealSense which is become the best budget 3D scanner available [Arora (2015)]. Other manufacturer like Ford has been using this technology since 1980's [Gilpin (2014)]. Ford declared on its website that due to 3D printing technology they could save time and money in each printed part. While traditional manufacturing process would take four months in addition to half million dollars, 3D printing reduced the process to four days only with no more than 3,000 USD. In food industry, Hershey's started to use 3D printers to print chocolate and other edible products. However, with their Sugar Lab the company was able to print icing and other sugary confections depending on 3D printers [Arora (2015)]. In toys industry, MakieLab also use 3D printing system in creating personalized dolls and dolls' fashion. MakieLab declared that 3D printing enabled them to reduce waste through the production process [Arora (2015)].

As 3D printing has become an important pillar in manufacturing field, it also has a great impact on supply chains and supply chain management. Thus, 3D printing must get some attention in academic researches to clarify this impact on the supply chain. For that reason, this PhD thesis is aiming to study when and under which conditions 3D printing is more applicable to be implemented as a manufacturing method.

1.1 Research Context

The stretched process of activities starting from the very first point of converting natural resources, components and raw materials into final goods until the point where these final goods are delivered to the end customer is called "The Manufacturing Supply Chain" [Chandra and Kumar (2000); Cooper et al. (1997)]. Manufacturing supply chain management is universally referred to as the harmonization of transportation of goods and both upstream and downstream flow of information and capital between suppliers and customers [Duclos et al. (2003)]. Managing supply chain is an essential duty in all companies and organizations. Proper management of supply chain results in success for the organization, and poor supply chain management results in failing the business firm. Referring to Nyman and Sarlin (2014), organizations' success or failure depends on getting the right product to customers, at the right time and at the right price. This leads the firm to pay more attention to managing its supply chain properly and reevaluating the implementation of its supply chain strategies. Supply chain strategies can vary to include all possible strategies that have an effect on enhancing the delivery of products and information from suppliers to customers and vice versa [Lee (2002)].

Fisher (1997) proposes one of the most famous frameworks that links supply chain strategy with product's type and shows the relationship between both of them. Fisher's framework has been cited by large number of researchers and scholars. Fisher (1997) suggests having an alignment between supply chain strategy and the type of product manufactured. Fisher's framework proposes the two supply chain strategies and attached each of them to one type of products.

The two types of products in Fisher's framework are:

1. Functional products which characterized by long product life cycle and low product variety, and
2. Innovative products which are characterized by shorter product life cycle and higher product variety.

The external environment has never been stable. Companies always have to keep up with these changes in order to survive in the competitive market. Nevertheless, when the company changes its strategy, it must also have its supply chain prepared for these changes.

Lee (2002) discussed in his article "Aligning Supply Chain Strategies with Product Uncertainties" that the prosperity of companies is underscored by an understanding that the right supply chain strategy is depending on understanding the inherent variety in the needs of customers. Thus, one-size-fits-all strategy will never lead to success. Managers, practitioners and researchers all work together, hand in hand, to figure out ways and methods of innovating supply chain in a way that adds value to manufactured goods. Cutting costs also results in reducing the price for consumers when the final product arrives their hands.

Supply chain should match the degree of demand uncertainty [Fisher (1997)]. Implemented strategies of supply chain can be either Pull or Push strategy, and often a mixture of both together [Cachon (2004)]. Push strategy in supply chain is typically the method used to reduce customer waiting time; customers get what they need from the shelf with no time wasted. Ferguson et al. (2002) labeled this as "Early-commitment" system. In this method, companies manufacture and deliver the products to shelves before they get orders from customers, so final customers can find what they need immediately. However, this strategy could never be an ideal fit for all types of products; that is because one critical point is missed in this approach. Customization is the critical issue that companies fail to satisfy with the Early Commitment approach. Innovative and, sometimes, functional products need to be customized to customers' preferences. Push supply chain cannot give customers the opportunity to customize their goods. Pull supply chain is the preferable strategy in such cases when customization is requested. Pull supply chain refers to letting the customer order first in order to manufacture what he/she wants, then deliver them the product [Iyer and Bergen (1997)]. This strategy is the exact opposite of the push supply chain, where customers have to wait between the point in time when they order the product and the point when they actually receive it. Some other companies rely on a hybrid method where a combination of push and pull strategies are implemented, in order to both satisfy customer needs and save time. Other strategies focus on cutting costs by removing all unnecessary and non-value adding steps in manufacturing supply chain. The focus of this research is on strategies that both add value and cut costs.

Since the industrial revolution, manufacturing expression is an interchangeable one with factories, machines, tooling, assembly lines, production lines and economies of scale or supply chain. Nevertheless, additive manufacturing has changed the meaning of manufacturing in the modern manufacturing. Additive manufacturing is completely different from repetitive process traditional manufacturing. Additive manufacturing is also called "Instant Manufacturing" due to its ability of being perpetual of making and manufacturing.

Additive manufacturing is an industrial manufacturing system based on systematic processes. It is a broad term that includes many additive methods such as 3D printing. More recently, additive manufacturing has become nearly synonymous with 3D printing [Gao et al. (2015); Wong and Hernandez (2012); Noorani (2006); Kochan (1997)], and most people, authors and researchers in the field use the two terms interchangeably.

In a way to link 3D printing with supply chain strategies, we found that there are several common characteristics between them. Lipson and Kurman (2013) emphasize on the efficiency of 3D printing, while Wong and Hernandez (2012) and Noorani (2006) affirm its ability to increase customization. Following are the common characteristics of supply chain strategies and 3D printing:

1. Reducing Waste. Unlikely traditional manufacturing, 3D printing can cut costs in manufacturing by reducing wastes. 3D printing can reduce fixed and variable costs [Berman (2012)], such as:

    (a) Wasted Material. Since 3D printing is an additive manufacturing system, waste in used material could be eliminated to minimum, and no by-product would be produced [Berman (2012); Sealy (2012)].

    (b) Wasted Time. 3D printing is able to minimize waiting time by reducing lead time, cutting unnecessary transportation and unnecessary processes like assembly, and eliminating overproduction and excess inventory [Lipson and Kurman (2013)]. And,

    (c) Inventory Costs. Reducing the risk of overproduction and having unsold finished goods in inventory [Lipson and Kurman (2013); Berman (2012)].

2. Ease of Creating Products. 3D printing facilitates the manufacturing process because it does not require high degree of specific skills or specialization to operate the machinery used. 3D printers are easier to operate compared to other traditional operating machines. In addition, 3D printers can print any required product, regardless of the physical object's complexity [Sealy (2012)]. Unlike repetitive process in traditional manufacturing, 3D printer needs only the design file of the product in order to produce it. Thus, there is no difference between simple and complex products in 3D printing.

3. Flexibility of Production. 3D Printers can be adjusted to produce any required product without the need to change the production process, and without the need to change or retrain personnel, as is required with traditional machinery. This, in turn, helps reduce total production time. In contrast to traditional manufacturing, in which machines produce products with fixed dimensions, 3D printers allow for product differentiation, because they have the ability to flexibly produce any size or shape required [Wong and Hernandez (2012); Noorani (2006)].

4. Better Customization. 3D printing is a very flexible production tool. Products can be produced to meet customer's exact requirements. Materials used, shapes, sizes and any other features can be adjusted on the spot to accommodate the customer's requirements [Wong and Hernandez (2012); Noorani (2006)].

While, 3D printing is a new applied technological and manufacturing revolution in this era [Berman (2012)]. The idea of 3D printing is not novel; experiments had started to bring 3D objects into existence in 1960's by Herbert Voelcker [Sealy (2012)]. Operations did not come true until pioneers such as Charles Hull, the founder of 3D Systems Corporation, and Scott Crump, the founder of Stratasys, developed together, in early 1980's [Kodama (1981)], a framework of technologies that are based on additive processes by creating fixed commodities layer over another of liquefied materials onto a powder bed with ink-jet printer heads. Nonetheless, this idea faced critical improvements during the last decade to arrive to the shape that it is at today. Dimitrov et al. (2006) expressed 3D printing as an innovative production of 2D printing.

The original term of 3D printing refers to the process of layering material onto a powder bed with ink-jet printer heads. However, the term has widened recently to include a wider variety of techniques. In this way, 3D printing becomes called Additive Manufacturing [Berger (2013)]. Extrusion and sintering based processes are some newly techniques that the term has included.

1.2 Research Problem

"Hydroelectricity and oil," the new sources of energy, were the driving forces behind the 2^{nd} phase of industrialization in the early 20^{th} century. When the demand behavior in the market changed because of the rapid changes in customers' tastes, the need for getting the product faster than before, and sometimes the need for highly customized products, the third industrial revolution became the main characteristic of this new century. This, indeed, affected and changed manufacturing performance. However, traditional manufacturing techniques lack the capacity to adapt the rapid changes in customer demand and reduce the production cycle duration.

Appleton (2014) stated that improvements in additive manufacturing technology are growing rapidly. Additive manufacturing has been dramatically developed through the past few years to overcome its technical limitations and limited capabilities, in addition to its high cost. However, manufacturers still underestimate additive manufacturing ability to enhance manufacturing processes or business operations, especially because additive manufacturing is not as cost effective as repetitive process of traditional manufacturing when it comes to large scale of production.

Literature shows a significant expansion in the additive manufacturing market. However, on one hand, it is still not easy for top managers to accept the adoption of this technology in manufacturing [Cohen (2014)]. On the other hand, there is no clear model in literature body shows which business strategy best fits the adoption of additive manufacturing, and/or if additive manufacturing is applicable to all types of products and/or how additive manufacturing can change or re-shape businesses and supply chains. Thus, managers are facing some difficulties on how to implement this technology in their manufacturing system.

Presently, manufacturers are trying to adopt additive manufacturing technology that is characterized by being efficient in energy and material consumption and, at the same time, being very flexible and very fast with regards to:

1) following the changes in the market demand and

2) delivering the product to the customer.

The adoption of this technology, in its turn, requires fundamental changes in the applied business models. Changing production systems in manufacturers has to result in the amendment of the business model's operational strategy. Optimizing operations in manufacturers can be done by focusing on enhancing the main elements of operations which are: 1) decreasing costs, 2) increasing quality, 3) reducing both manufacturing and lead time, 4) increasing production flexibility and 5) increasing innovation.

Traditionally, internal performance improvements are what companies worried about and keep working to achieve. However, in this globalized market, customers do not really differentiate between a company and its suppliers. Thus, companies have to worry about the improvements in their suppliers businesses, in order to achieve better performance in the market, since the performance of one company directly influences the others in the same supply chain. Literature suggests performance improvements through additive manufacturing [Cohen et al. (2014); Wohlers (2014); Manners-Bell and Lyon (2012)]. In addition, literature shows that additive manufacturing affects supply chain management. Nyman and Sarlin (2014) argued that additive manufacturing is powerful and makes manufacturing processes easier and customization less expensive. Wong and Hernandez (2012) and Ashley (1991) assured that 3D printed products are characterized by being higher quality, lighter, customizable, stronger, already assembled and having lower costs. Conerly (2014) confirmed that a very low volume of raw materials and work-in-progress will be in inventory, and no finished goods will be stored in inventory. Ugochukwu et al. (2012) stated that 3D printing technology can help in delivering the right product, at the right time and at the right price to customers. Even though, that all suggest a great positive impact on supply chain management; additive manufacturing applications are still not fully expanded to cover the supply chain management, yet.

The research problem is focused on the relationship between supply chain strategies and product types. Specifically attention is given to the specific conditions that would make 3D printing applicable. It is because there is lack of contextualized, structured and generalized framework that illustrates the best fit supply chain strategy and product type manufactured that make the adoption of additive manufacturing applicable. The existing literature has limited developments in terms of the conceptualization of additive manufacturing in supply chain management. In addition, previous studies lack to evaluate and consolidate supply chain management with additive manufacturing in terms of efficiency of production and responsiveness to market strategies and to link it with the type of products manufactured.

1.3 Research Objective

This PhD thesis aims at developing a framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy. While additive manufacturing is believed to revolutionize and enhance traditional manufacturing, there is no comprehensive toolset developed in the manufacturing field that evaluates the impact of additive manufacturing and determines the best production method that suits the supply chain. This study adopts a qualitative descriptive methodology and uses 3D printing as a case study to examine not only the ability of technology to change and re-shape businesses, but also the potential impact of 3D printing as an alternative manufacturing technique on supply chain strategies.

1.4 Research Questions

Following is the research question which systematizes the theoretical discussion of this PhD thesis:

Under which conditions, in the supply chain, additive manufacturing technology replace traditional manufacturing system?

Additive manufacturing, which is also known as rapid manufacturing or 3D printing [Gao et al. (2015); Wong and Hernandez (2012); Noorani (2006); Kochan (1997)], has emerged as an innovative and disruptive manufacturing technology that has major implications for companies and industries [Phaal et al. (2011)]. According to Wohlers (2014) additive manufacturing industry is currently assessed at more than $3 billion, with an expected rise to $13 billion by 2018 and $21 billion by 2020, additive manufacturing technologies have an enormous potential, although they also imply important and necessary changes to the management of supply chains. Additive manufacturing provides highly customized and personalized products. Thus, it also provides a specific set of opportunities and challenges in managing the supply chain.

The objective of this PhD thesis is to develop a comprehensive toolset evaluates the impact of additive manufacturing and determines the best production method that suits the supply chain.

Manufacturers of customized products in domains as toys, jewelry, fashion and apparel, dental, and biomedical have so far successfully adopted additive manufacturing technologies. The flexibility of additive manufacturing technologies allows for customized shapes, digital interaction with consumers and direct manufacturing, which gives benefits in terms of lower costs, reduced supply chain complexity and lead times, etc. However, despite the potential, many questions apply to the justification for mass manufacturers of commodity products to use additive manufacturing technologies, the types of production methods that they would have to employ to capitalize on the flexibility that additive manufacturing offer, and how these changes would affect their supply chain structures. Accordingly, we designed the following sub-questions to precisely define the impact of additive manufacturing on supply chain management to include supply chain strategies and supply chain structure, as the following:

1. Does additive manufacturing fit both "efficiency in production" and "responsiveness to market" supply chain strategies?

   Additive manufacturing in this context is referred to the utilization of additive technologies for the production of final goods. In contrast to rapid prototyping which is the use of additive technologies for the purposes of manufacturing prototypes, additive manufacturing is in principle repeatable and scalable as a production process. Because additive manufacturing have recently emerged as a viable manufacturing technology due to significant improvements in part quality, price and manufacturing process time, principles such as “lean” and “agile” can also be considered here in the context of full-scale small batch production, with a focus on the customer and creating value, with less cost possible [Tuck et al. (2006)].

2. How can additive manufacturing change or re-shape supply chains in terms of customization?

   Additive manufacturing enabled manufacturing processes to be more flexible in terms of customization. Thus, manufacturers have to be closer to final consumer, which means that there is high potential to eliminate retailer’s roles in supply chains. At the same time, additive manufacturing enabled the production of complex products that are already assembled, which means that the number of suppliers can be reduced. These new possibilities and challenges that additive manufacturing presents to manufacturers’ supply chain with a particular focus on the potential to open up to a higher degree of consumer involvement and on the associated implications for the organization of production activities.

1.5 Thesis Structure

This PhD thesis consists of seven chapters; after this introduction which includes the research problem, research questions and illustrates the main objective of this doctoral thesis, chapter two clarifies the application of procedures and techniques used to identify, select, and analyze information applied to understand the research problem and developing the solution framework then shows the process of how it was evaluated. Chapter three reviews the general characteristics of both supply chain management and manufacturing. In addition, this chapter reviews the conceptual views of production and supply chain management. Chapter four of this thesis presents four exploratory interviews that were the base of collecting the inputs for developing the proposed framework. Chapter five displays the framework that was developed based on the collected inputs from chapter four. Chapter six provides a qualitative report generated from a survey questionnaire that evaluates the proposed framework. Then, the collected data from the survey questionnaire were validated through a creation of two case studies for three companies that are using additive manufacturing. The last chapter discusses the research conclusion and describes the research limitations. Figure 1.2 illustrates the sequence of the chapters with brief descriptions.

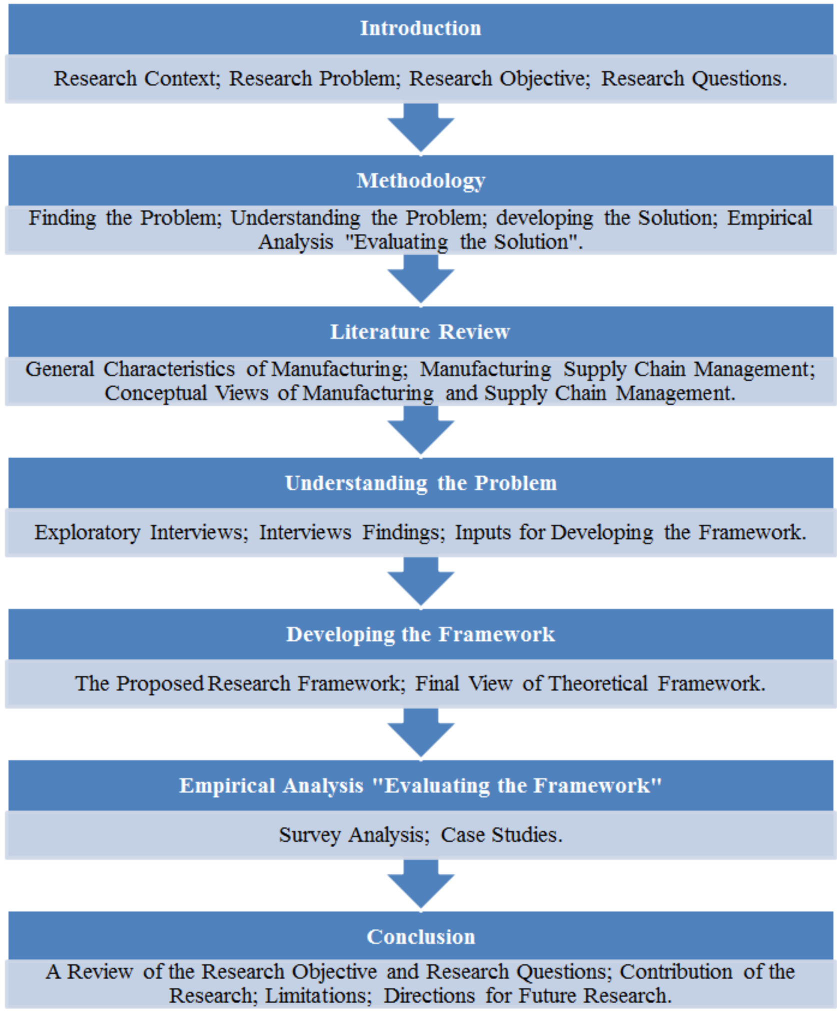

Figure 1.1: Thesis Structure

Chapter 2

Methodology

2.1 Introduction

This chapter details out the epistemological and methodological approaches that are followed in this PhD research. The nature of this PhD research allowed us to adopt the exploratory research design. As the latter provides a comprehension insights into an issue that has not been clearly defined. Since this research is based on finding out a contextualized, structured and generalized framework that helps manufacturers to take decisions of when and how to adopt additive manufacturing and what are the best fit supply chain strategies with this technology, an exploratory research design is an appropriate method in this study.

2.2 Methodology

This PhD research is consisted of four sequential and interdependent steps as shown in Figure 2.1. Methodology of each step will be discussed in full in the following subsections.

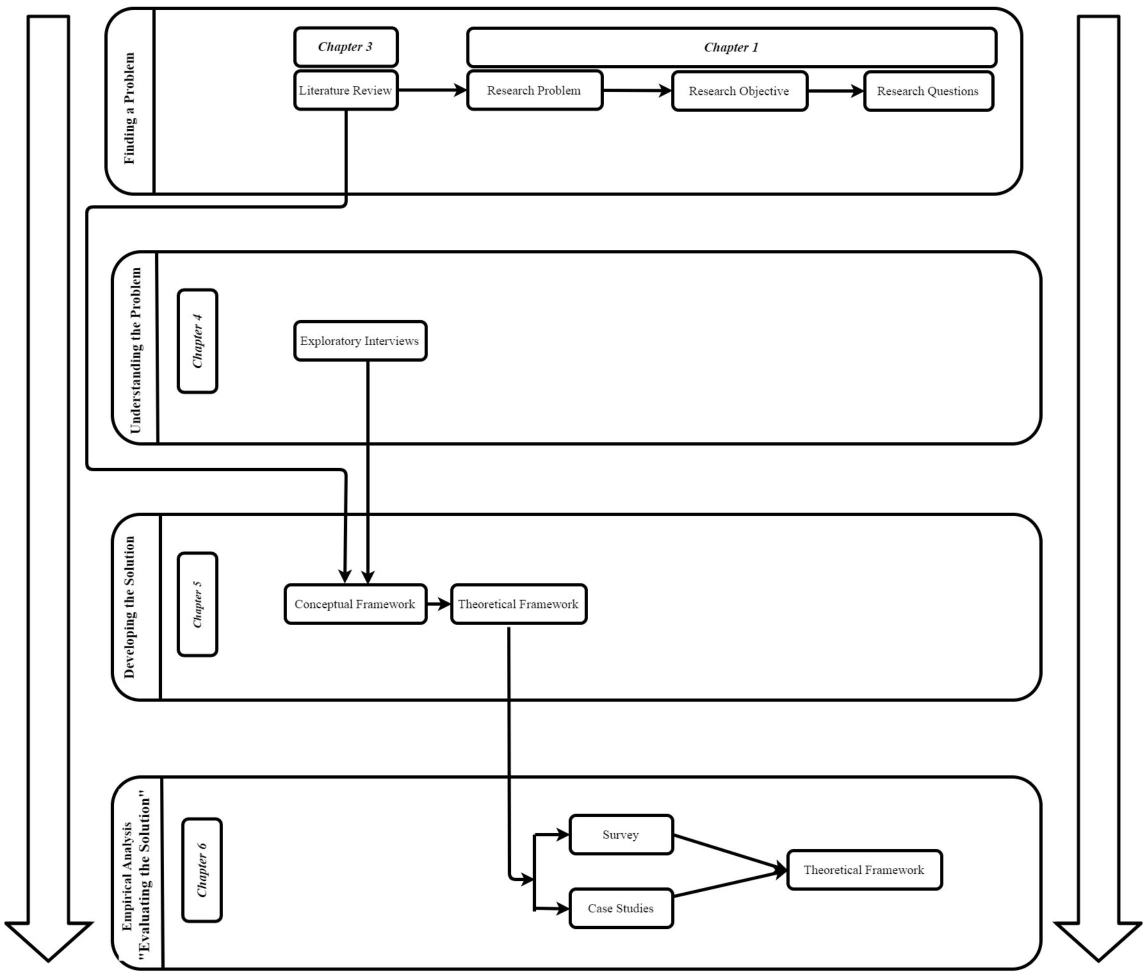

Figure 2.1: Research Method

2.2.1 Finding a Problem

This phase is consisted of four steps as follows:

1. Reviewing the literature
2. Defining the research problem
3. Describing the research objective
4. Formulating the research questions

2.2.1.1 Literature Review

Coherently to what suggested by Tranfield et al. (2003), the Systematic Literature Review is the adopted method in reviewing literature in this thesis. The authors affirmed that this method assures a structured reviewing of literature. On the other hand, the authors claimed that this method gets the best of any other literature review methodology because it depends on providing detailed process which reduces bias through exhaustive literature search.
In order to increase the validity of the methodology in reviewing the literature, we agreed upon using the “Four-step Process Model” by Mayring (2003) [Philipp (2003) as cited in Kache and Seuring (2013); Ugochukwu et al. (2012); Wilding et al. (2012); Gold et al. (2010); Kohlbacher (2006)] in the research process of the systematic literature review. The reason behind adopting this particular model to systemically review the literature is because that it was found that many researcher in the supply chain management field depended on it. Moreover, this model serves our objective better than any other model can be used in reviewing the state-of-art.

Figure 2.2 summarizes the Systematic Four-step Process Model as presented by Mayring (2003).

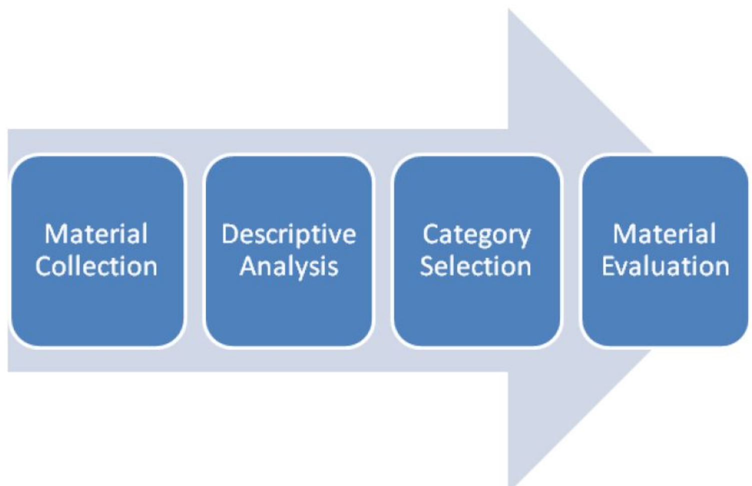

Figure 2.2: Four-step Process Model - Adopted from Mayring (2003)

Following is a detailed description of the systematic four-step process model used in reviewing the literature:

The first step in this process was the material selection. In this step we planned and defined the material we want to collect for each of the fields we want to study. In this step, the proposed required material for the research was defined and research boarders was planned to keep the research in the required area of focusing on our research objective. This step comprises the identification of keywords and publications.

First, a set of keywords were identified by the author. The main keywords are: “Lean Supply Chain”, “Lean Management”, “Supply Chain Management”, “Supply Chain”, “Open Source Manufacturing”, “3D Printing” and “Additive Manufacturing”. The keywords were checked in different databases including the following but not limited to them: Web of Science, Elsevier, Science Direct, JStor, EBSCO, Emerald, and Google Scholar. In the aim of avoiding broad results, keywords were combined with simple special characters such as quotations ("exact word") and boolean operators (AND, OR).

The initial search with keywords in all the information sources resulted in more than 2,000 hits. Quick scanning of the titles and abstracts reduced the number of these articles by more than 50%. The limitation was based on the good relevance of the title and abstract to our research interest. Articles with perceived irrelevant titles were excluded. Articles that did not have at least one of our suggested keywords in its title and abstract were eliminated, too. A quick scanning of the reference lists of each of the remaining articles suggested more relevant articles. The same exact process was repeated several times for different keywords and databases. At some point in this process, it became so clear to us that the same set of articles kept reappearing, and the search process was stopped.

The second step was the descriptive analysis where we studied the basic characteristics of the selected materials. The following are the basic characteristics we looked at:

1. Year of Publication: Since Womack et al. (1991) popularized lean in 1990 in their book “The Machine that Changed the World” [Womack et al. (1991)] and researches on supply chain management started at the beginnings of 1990’s [Hanna and Rocky Newman (1995)], all predating papers were excluded from our search. Thus, just journal articles that were published between the years of 1990 and 2016 were considered as the main source of information in reviewing the literature for this doctoral thesis.

2. Journal Name: Journals were verified to be with compliance to Journal Citation Reports® and Social Sciences Citation Index® in order to base our research on objective quality material.

The list of journals investigated in this thesis includes the following but it is not limited to them:

1. American Journal of Engineering and Technology Research
2. International Journal of Business and Management
3. International Journal of Operational Research
4. International Journal of Operations and Production Management
5. International Journal of Production Economics
6. International Journal of Production Research
7. International Journal of Quality and Reliability Management
8. International Journal of Supply Chain Management
9. Journal of Operational Management
10. Journal of Product Innovation Management
11. Journal of Sustainable Development
12. Operations and Supply Chain Management

In addition to the previous list of journals, a number of books were used as key points in the literature during the development of the PhD thesis.

Category selection was the third step in this model, where decision was made on the choice of categories and dimensions to be used in structuring the collected materials. This third stage was followed by material evaluation, which involved a review and classification of the selected materials according to the chosen structural dimensions and categories.

After this classification a further screening of the articles was made to each category by scanning through the abstracts, introduction and body contents of each article to make sure that the remaining articles are a good source of information to our research and they are satisfying our research objective. The literature was then summarized and presented in Chapter 3.

2.2.1.2 Research Problem

The research problem was presented in Chapter 1. After reviewing the literature, the body of knowledge supporting this thesis was developed. The research problem is presented as follows:

"The research problem to be addressed in this research is the lack of contextualized, structured and generalized framework that illustrates the best fit supply chain strategy and product type manufactured that make the adoption of additive manufacturing applicable."

2.2.1.3 Research Objective

The objective of this PhD research is to develop a framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy.

2.2.1.4 Research Question

After reviewing the literature some research questions have been developed in order to guide the investigation of the research problem. Answering the research questions, the research objective of this research should be achieved. The following question was developed on the bases of the existing gaps in literature:

Under which conditions does additive manufacturing technology impact supply chain management?

2.2.2 Understanding the Problem

Due to the qualitative nature of the information needed, exploratory interviews method was adopted in this step of the research in order to achieve a better understanding of the problem.
To better understand the problem, two sets of inductive interviews were held. The first one was conducted with a supply chain optimization consultancy. The aim of this interview is to explore which initiatives, practices, problems and guidelines exist in managing supply chains in general. In addition, to refine the interview questionnaire that was set for the manufacturing companies and to get benefit from their experience in dealing with companies that already adopted additive manufacturing.

The second set of interviews was conducted with three different companies from different industries in several geographical locations. The reason behind this variety is due to that 3D printing becomes famous in so many fields, such as but not limited to: healthcare, aircraft, automotive, technology, food sector, jewelry, and cloths and footwear. All interviews were conducted through Skype calls and each interview lasted for approximately 45 - 50 minutes.

The criterion that was followed in selecting the interviewees was based on random sampling. As we first checked “All3DP Magazine” which is a leading 3D printing online magazine that ranks the 3D printing companies worldwide. Besides, All3DP magazine clusters these companies into different groups according to their geographical areas, industries, printing software, services, etc. From All3DP magazine, we randomly collected contact information for 20 companies from different industries in different geographical locations and different company sizes. Only four companies (three manufacturing companies and one consultancy firm) accepted to be interviewed and each suggested a convenient date and time for the interview according to their time schedule.

In order to support the interviews, a semi-structured questionnaire was prepared. The questionnaire and the interviews were aimed at exploring the guidelines in managing the supply chains and how additive manufacturing is applied in these companies and how it affects their supply chains. Further details regarding the interview questionnaire and the invitation letter that was sent to the participants are presented in Appendices A and B, respectively. On the other hand, the interviews helped in pointing out and identifying the relevant elements for designing the conceptual framework for adopting the best fit manufacturing method based on supply chain strategies.

2.2.3 Developing the Solution

The aim of this step is to develop an initial conceptual framework. Based on literature review and the exploratory interviews, the conceptual framework was developed. The detailed information of developing the conceptual framework is presented in chapter 5.

Two fundamental elements were necessary to develop the solution:

1. Conceptualization of manufacturing supply chain: the objective of the research is to develop a framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy. In order to develop such a framework, a previous conceptualization is required. The key elements considered for conceptualizing manufacturing supply chains are the essential characteristics of manufacturing companies and the specific features of manufacturing supply chains in this sector. In addition, current frameworks for applied supply chain strategies were analyzed in order to understand how additive manufacturing can affect them and to understand whether some of their components could be adapted in the framework. Two fundamental components are then proposed for conceptualizing manufacturing supply chains, which are the product types and the components' complexity.

2. Practices for manufacturing supply chain: after conceptualizing the manufacturing supply chains, it was found that an additional factor is essential for supporting the conceptualization. This factor is the design of the supply chain that affects the inventory level that should be kept on hand. Based on the existing literature two supply

chain designs were proposed in this framework, namely pull supply chain and push supply chain.

Based on these finding the theoretical framework was presented.

2.2.4 Empirical Analysis “Evaluating the Framework”

The final step in this research method was empirical analysis step which aims to evaluate the developed solution. In order to evaluate the framework that was presented in the previous step, and to be confident with results of the evaluation, a triangulation method consists of two different methods of collecting data were used. The two methods are: survey questionnaire and case studies based on interviews. The reason behind using triangulation method of collecting data is that it is a method-appropriate strategy of founding the credibility of qualitative analysis [Creswell and Clark (2007)].

A deductive survey evaluation method was used as a first step of the triangulation method. Data collected from the survey was analyzed through a qualitative method of analyzing data. The findings of this method are presented in details in Chapter 6. A raw report generated from Google Forms of collected data is presented in Appendix F. The second method of collecting data in this triangulation method was case studies based on interviews with different companies. Following are detailed description of the two used methods:

2.2.4.1 Survey

Survey method in collecting data is the most used technique in social sciences. According to Scheuren (2004) survey questionnaire is a measurement tool to gather information from a sample group of individuals about a certain subject. In order to efficiently use the survey method, a questionnaire was developed. Questionnaire method provides a major source of knowledge. The development process of the questionnaire was adopted from Churchill and Iacobucci (2006), as in Figure 2.3.

Step 1: Determine the purpose of the questionnaire and what the needed information is

The purpose of collecting data at this stage of the research is to measure the validity of the proposed theoretical framework. Thus, information is needed concerning the used supply chain strategy, the level of customization, the type of inventory system used, and the supply chains length in terms of number of suppliers and retailers in the supply chain.

Step 2: Determine the method of distributing the questionnaire

An online questionnaire was designed through Google Forms and it was sent via email. Scholars, such as Sheehan (2001), remarked the benefits of email over postal mail method of distributing the survey, specifically to its speed in reaching the selected sample group and its cost efficiency, as well. An informed consent email detailing the purpose of the investigation, the way in which the data would be used, and assuring the confidentiality of collected data by keeping respondents anonymous, was sent with each questionnaire. The informed consent email is presented in Appendix D.

Step 3: Determine the content of each question

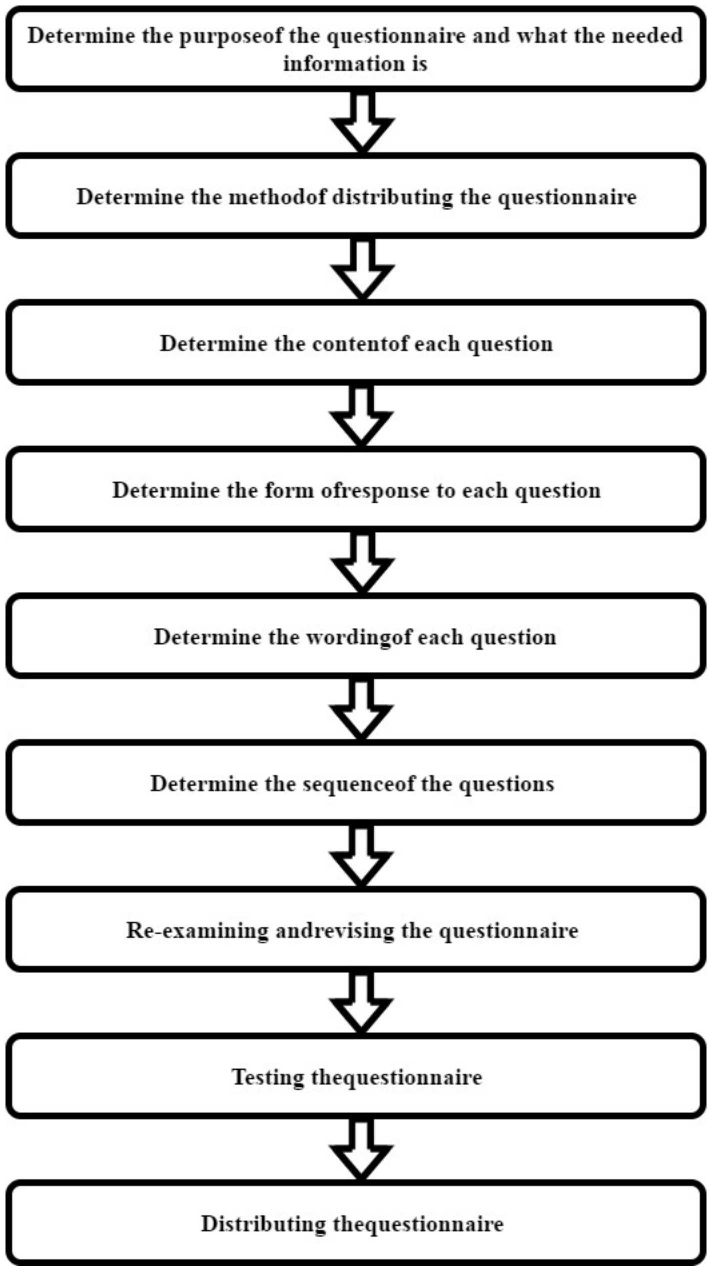

Figure 2.3: The development Process of the Questionnaire - Adopted from Churchill and Iacobucci (2006)

Based on the proposed framework, essential points were highlighted and clustered in topics. Through an iterative revision process the general content for each question was decided.

Step 4: Determine the form of response to each question

The questionnaire survey was designed to have two types of closed questions as a means of facilitating the analysis process of the collected data. The first type of questions is multiple choice questions, while the second one is a 5-point Likert scale questions, where '5' refers to "Extremely Good" or "Very High" or "Always" or "Very Often" and "1" refers to "Extremely Worse" or "Very Low" or "Rarely".

Step 5: Determine the wording of each question

Questions were carefully worded in order to avoid complex terms or jargons. It was taken into consideration that some of the participants are non-native English language. So questions were worded in a way to clarify the main point asked in each question to avoid misunderstanding the question.

Step 6: Determine the sequence of the questions

Questions were clustered into three groups. The first group of questions aims in collecting data about the respondent's company, such as the nature of the business, the geographical scope of their operations, their customers, and the number of suppliers and retailers they deal with. The second group of questions was developed to check whether they use additive manufacturing in their operating system and how long it has been implemented. While the third group of questions mainly focus on the cost efficiency, lead time, and type of inventory system the companies implement. Thus, questions were carefully sequenced to ensure clarity to respondents. Some questions were marked by asterisk (*) to identify them as required questions. However, some questions were left optional, since answering these questions depend on their previous answer. Links between questions was determined in this step to ensure facilitating the analysis process, later on.

Step 7: Re-examining and revising the questionnaire

All previous steps (from step 1 – step 6) were re-examined and revised if necessary. Then the overall questionnaire was reviewed carefully checking for errors, such as typos, grammar, etc.

Step 8: Testing the questionnaire

Before sending out the survey questionnaire to manufacturers, a pilot test, on academicians and few practitioners in the field, was done to ensure that everyone in the sample not only understands the questions, but understands them in the same way.

Step 9: Distributing the questionnaire

Wholers Report, an annual report concerning about additive manufacturing firms worldwide which provides up-to-date review of the nature of additive manufacturing industry, was our base to identify survey participants. Thus, contact information for 100 companies was gathered from Wohlers (2015) and Wohlers (2014). The selection of the companies was done carefully to ensure that the sample includes different business sizes, different geographical areas, and different industries. A copy of the questionnaire survey is included in Appendix C.

2.2.4.2 Case Studies

As an alternative to traditional criteria like reliability and validity, we used the triangulation method to validate our collected data from the survey. Thus, the final step in evaluating the theoretical framework was done through creating two case studies based on information gathered from three companies. However, since Croft LTD and Croft AM are sister companies owned by the same managers, Neil Burns and his brother Mark Burns, we used the generated information to form one case study. Following is a description on how we created each of the case studies.

Information regarding companies is summarized in Table 2.1.

	Case Study No. 1		Case Study No. 2
	Croft LTD	Croft AM	MakieLab
Country	UK	UK	UK
Number of Employees	25	7	41
Yearly Revenue	2 million US Dollars	260 thousand US Dollars	2.3 million US Dollars
Manufacturing System	Traditional/ Hybrid Manufacturing	Additive Manufacturing	Additive Manufacturing
Supply Chain Strategy	Push Supply Chain	Push Supply Chain	Pull Supply Chain

Table 2.1: Information Summary of Companies

The aforementioned companies are located in United Kingdom in which the additive manufacturing has a major impact on the manufacturing industry. The selection of the companies was based on the following underpinnings: applied manufacturing system and the adopted supply chain strategy.

Croft Filters LTD Case Study

Croft Filters LTD is one of the most interesting companies in adopting additive manufacturing technology to produce customized industrial filters. Needed information about the company was collected through a Skype interview with Neil Burns; director of Croft and co-founder. This case study was formed on the bases of two sister-companies; Croft LTD and Croft AM. Croft Filters case study illustrates a perfect example on companies adopting push supply chain strategy to utilize efficiency in production to produce either personalized products with high value components through additive manufacturing technology, or to produce mass customized filers using a hybrid manufacturing system of traditional manufacturing machineries and additive manufacturing technologies.

MakieLab Case Study

MakieLab is a famous doll brand that sells dolls fully designed by customers and manufactured through 3D printers. MakieLab is based on pull supply chain strategy where it gives their customers the roll of designing, creating and styling their dolls. When customers order the doll, the unique item is fabricated with the help of laser sintering 3D printers. Information about MakieLab was gathered from ALL3DPrinting website (https://all3dp.com/makie-doll-makies-dolls). This case provides good example of companies that are based on pull supply chain strategy and are highly responsive to market by using 3D printing technology to personalize final products.

The aforementioned case studies are presented in details in chapter 6 of this PhD thesis.

Chapter 3

Literature Review

Introduction

This chapter is formulated to generate knowledge of the specific and general backgrounds of the existing body of literature. The author of this research focused in this chapter on discussing, analyzing and summarizing three subject matters that provide a theoretical basis for this research. Firstly, the general characteristics of manufacturing is presented and discussed. Then, the context of supply chain management including in practice manufacturing supply chain models and theories of best practices in supply chain management are discussed. Finally, the conceptual views of manufacturing and supply chain are presented and discussed as they are the practical literature in this field.

3.1 General Characteristics of Manufacturing

3.1.1 Characteristics of Manufacturing

Performance objectives, manufacturing processes and strategies and customer order point are the general characteristics every manufacturing company has to be aware of when managing its operations. Thus, this section presents and discusses each of these characteristics as presented in the literature body.

3.1.1.1 Performance Objectives

Slack et al. (2010) argues that manufacturing performance exceeds the efficiency in production or achieving lower cost levels, but it is measured by achieving customer's perspective of the product. Thus, manufacturers have to identify key measurement objectives in order to satisfy customer's requirements.

Many authors have investigated these objectives and their implications. However, each author has presented them in a different way, in terms of organizing or sub-dividing them in their researches. In addition, these objectives vary in practices within a company or among companies [Malhotra et al. (2007)]; some firms need to apply more objectives than others to comply with their needs.

Among all authors, Slack et al. (2010) proposed five generalized objectives that are applicable to all types of operation. The following are the five objectives:

1. Quality: According to Slack et al. (2010) quality is defined as the accordance of production and customer's expectations. While Malhotra et al. (2007) defined quality as two divisions; the first one which they called "top quality" is defined as providing best features in the product as well as affording well after sales services. The second division is related with conformance to the manufacturing process. However, Ward et al. (1998) extended in defining quality to include the product's performance, features, reliability and durability in addition to its conformance with the customer's expectation and after sales service.

2. Lead Time: is defined as the time period between placing the order and its actual delivery. Authors such as Slack et al. (2010); Malhotra et al. (2007) and Ward et al. (1998) agreed that reducing the lead time will lead to an over whole improvement of the company which will be noticed by inventory reduction as well as reduction in cost.

3. Reliability: according to Slack et al. (2010) reliability is defined as providing the right product at the right time. In addition the authors argue that reliability is the most important objective among others since it is essential in the planning stage of production to predict what customers need and when they need it. In the same sense, Ward et al. (1998) state that reliability increases the companies' competitiveness.

4. Flexibility: is defined as the adaptability level of production to the change in customers' needs. Slack et al. (2010) defined it as the ease of changing the production process. While Ward et al. (1998) defined its dimensions to include the ease in changing the material, modifying the product, changing the production volume

or the product mix or even the rerouting the production process. Moreover, Malhotra et al. (2007) emphasized on flexibility to capture the rapid change in customer's requirements.

5. Cost: according to the reviewed literature, cost is the main objective for all companies. Malhotra et al. (2007) stated that companies are eager to lower the production cost to satisfy their customers. However, it is well known that production is not the only cost driver since productivity, inventories and so many others are factors affect the cost [Ward et al. (1998)].

3.1.1.2 Manufacturing Processes and Strategies

From reviewing the literature it was found that there is a strong relationship between choosing the appropriate production process and the type of product or the product features. The level of customization, the volume of production, the mix of products and others are the main characteristics lead to make a choice of what manufacturing process is the most appropriate to be applied in order to achieve operational efficiency.

Malhotra et al. (2007) discussed the product-process matrix, which was originally found by Hayes and Wheelwright (1979). Hayes and Wheelwright (1979) argue that the emphasis given to product customization have to be in accordance with the process choice. They clarified their framework based on the agreement between the business strategy, product plan and the choice of the manufacturing process. Figure 3.1 presents Hayes and Wheelwright (1979) product-process matrix. According to Malhotra et al. (2007) product-process matrix is based on linking the appropriate production process with the features of the manufactured product. This matrix suggests five major processes as follow:

1. Continuous flow process: this process is the most appropriate to high volume of production. Commodity products such as fuel and metal are examples for products that require this type of production process.

2. Line process: is the most well know applied manufacturing system. It is applied in many different industries that have high demand volume such as technology, clothes and others.

3. Large batch process: is suitable for moderate to high volume of production especially for heavy industry, such as steel and cement.

4. Small batch process: in contrast to the previous process, this one is suitable for low to moderate volume of production. It is usually applied when manufacturing product's parts and/or components. Scholars, such as, Kemppainen et al. (2008) and Malhotra et al. (2007) agreed that this type of process is done with disconnected line flows; whereas one batch of product is produced each time.

5. Job process: Malhotra et al. (2007) state that this type of process is characterized by flexibility because it aims at producing a variety of products at different levels of quantities and at high levels of complexity tasks or steps through the production process.

Each of the above processes needs a specific strategy to be properly operated. However, Fisher (1997) argues that the product characteristics must be the base of choosing the proper manufacturing strategy. In addition, Slack et al. (2010) state that in addition to the products

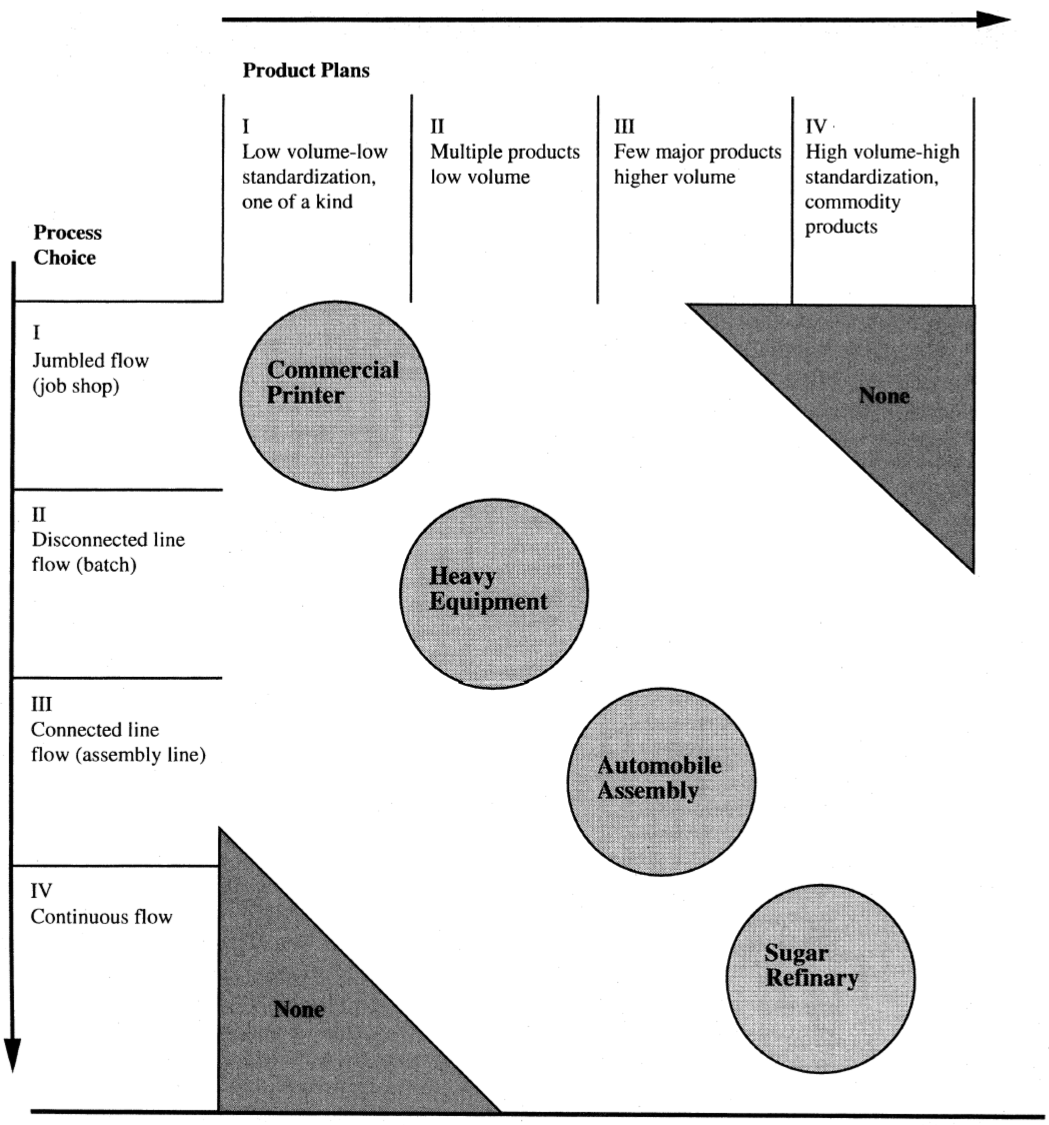

Figure 3.1: Product-Process Matrix - Adopted from Hayes and Wheelwright (1979)

characteristics, the demand patterns and other factors such as the degree of customization and types of production process affect the selection of the manufacturing strategy.

Scholars in the production field have identified five production strategies. Based on the characteristics of these five strategies, clustering has been done into three groups of marketing strategies. The following are the three clusters of marketing strategies that include the five manufacturing strategies:

1. Push strategy which is useful for increasing efficiency and ensuring compliance

    (a) Make-to-stock: Slack et al. (2010) argue that the product has to be manufactured before the customer demands it. Malhotra et al. (2007) argue that this strategy is more effective when the demand can be forecasted and the product is standardized. Thus, this strategy suits best the line process of production. Since the latter does not require any level of customization and production is made in high volumes.

2. Pull strategy which is more person-centered and is useful for increasing effectiveness and integrating the customer in the manufacturing process.

    (a) Make-to-order: Slack et al. (2010) present this strategy as not to produce until the customer orders the product with the required specifications. Such a strategy requires small volume of production and high level of customization. In addition, Slack et al. (2010) state that a high level of flexibility is also required through the production process. Thus, in accordance with these requirements, job process and small batch process are the most suitable to be applied for this strategy. Engineer-to-order: this strategy allows customers to place orders for specific design of the product or specific technical requirements. According to this characteristic of this strategy, a high level of customization is needed. However, none of the above production processes is suitable for this strategy. Thus, Gosling et al. (2013) proposed the project-based process which is characterized with high customization in production and low level of production volume.

3. Hybrid strategy which combines the characteristics of both pull and push strategies

   (a) Assemble-to-order: this strategy is the most suitable for products that are produced by combining pre-assembled and standardized products. Malhotra et al. (2007) emphasize that production of parts or components must be done first then a combination process is done after the customer's order is received. In compliance with this strategy, large and small batch processes should be applied.

3.1.1.3 Customer Order Point

This concept has been proposed by Olhager and stlund (1990) as the point in the manufacturing process where the customer orders the product. It also can be interpreted as the point where customers can interfere with the manufacturing process to customize the product. In addition, the authors raised a point of the need to have two different production approaches in the customer order point; upstream and downstream approaches. The upstream approach means that the customer has to place the order first, while the downstream approach is based on forecasting the demand [Olhager (2003)].

Olhager (2003) suggests three categories of factors affect the customer order points. Following are the three categories:

1. Factors that are related to the market: required delivery lead time, the order size and frequency, demand volatility and seasonal demand are market-related factors that affect the customer order point. Thus, when manufacturers face high rates of such factors, such as, high lead time variability or high seasonal demand, make-to-stock strategy is the best to be implemented to reduce the risk of having stock-out. In contrary, low rates in these factors leads to nominate engineer-to-order strategy in manufacturing.

2. Factors that are related to the product itself: such as customization, product design, product feature and product structure influence the customer order point. When the customer needs to customize the product, or requires specific features in the product, assemble-to-order production strategy severs best [Da Silveira et al. (2001)].

3. Factors that are related to the manufacturing process: are presented as flexibility of the manufacturing process and production lead time. When a manufacturer lacks of manufacturing process flexibility or needs high manufacturing lead time, push strategy serves best. Conversely, manufacturers can choose any of the other three strategies when manufacturing lead time is low or manufacturing processes are flexible.

3.1.2 Characteristics of Additive Manufacturing

Because additive manufacturing has initially been developed as a prototyping tool [Wong and Hernandez (2012)] which is an open source technology [Grimm (2004)], this section briefly presents general overview of open source and open source manufacturing then presents the literature of additive manufacturing.

3.1.2.1 General Overview of Open Source

The idea of free sharing and exchanging knowledge goes back to the mid of the century 19^{th}, specifically between the years 1850 - 1870, when the Pig Iron Industry of Cleveland (UK) had the idea of fostering free exchange of information about new techniques and plant designs among firms within a specific industry [Allen (1983)]. Then this movement has been called as “Collective Invention”. Interestingly, this movement of freely exchanging of knowledge rose back in the 20^{th} century holding the name of “Open-Source Software” (OSS). This idea is to develop software that is freely redistributable and its source code available for modification or enhancement by anyone. Even more interestingly, recently, a new movement just appeared that is called “Open-Source Manufacturing” (OSM), which is defined by users on (openmanufacturing.net) as “bringing free and OSS development methodology and philosophy to the design and construction of the physical world”.

In the open community, the definitions of the terms “OSM” and “Open-Source Culture” (OSC) must be agreed upon in order to determine the factors that allow the OS community to alter imagination and creativity. People in this field should be able to distinguish between the two terms, as well. Linda Naiman, founder of the website Creativity at Work, clarified that “*Creativity is the act of turning new and imaginative ideas into reality*”. According to Banzi, one of the co-founders of Arduino, imagination and creativity are supported by a creative Do-It-Yourself (DIY) community. That is based on OS online cooperation, in addition to some online magazines and websites like “Instructables”, where users of OSM teach each other about their projects and share knowledge and experiences. According to Berthon et al. (2007) the creative customer is defined as an individual (or group) who has the ability to adapt, modify, or transform a proprietary offering, such as a product or service. Creative consumers are now surrounded by a modern business environment that provides unparalleled opportunities for them to know more and open up new modes of thinking about how to better satisfy their needs. The internet permits the rapid spreading of information about customer innovations, and fosters rapid communication among consumers about these innovations. This means that having a creative customer requires a creative product. Creative products represent the production of viable, original solutions to problems that call for, or permit, creativity [Mumford (2000)].

The main idea of OS movement and OSC is illustrated as “the hacker ethic,” with some common values of sharing, openness, decentralization, free access and world improvement [Levy (1984)]. This idea has been facilitated by accepting and involving in the sharing culture of OS, where the individual’s appreciation is determined by the amount of knowledge and information given away. In this system, more you give, and the more valuable the gift, the richer you are and the more respect you gain [Pearce (2014)].

OS community gives the opportunity for creative people and businesses to enhance their businesses or their business models, and to generate huge profits, by allowing them cut costs and better serve their customers. The OS community allows businesses to satisfy their customers’ needs in a more efficient way by providing customers with a fully customized product in less time that the applicable manufacturing system needs.

3.1.2.2 Open Source Manufacturing

The movement towards OS which is “making instead of buying” has been increased [Matzler et al. (2015); Belk (2014); Asay (2005)]. The current technological innovation and network evolution facilitates changes in business interactions, as well as the ways that people manage their work, live, socialize and exchange knowledge. These changes are continued and supported by the emergence of Open Source Manufacturing (OSM) that moved the technological advancement from computer interplay toward physical interaction with its users. OS innovation is a consequence of studying innovation processes through several decades and building off of the research of previous scholars [Chesbrough (2006)]. OSM consists of physical pieces of technology designed and offered in the same manner as free OSS. OSM is part of the OSC movement and it applies to a variety of components. The expression means an increased ease of exchange and understanding of information about manufacturing products. Product design, (i.e. mechanical drawings, schematics, bill of materials, and integrated circuit layout data) in addition to software that drives hardware, is all released using the OS approach as well [Pearce (2013); Barbulescu et al. (2011)]. The idea of an open community is to share knowledge and ideas. Koschatzky (2001) found that firms which do not cooperate and which do not exchange knowledge reduce their knowledge base on a long-term basis and lose the ability to enter into exchange relations with other firms and organizations. Open source business can rely on Open Innovation (OI) which has been defined by Chesbrough (2006) as the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation.

Moreover, to understand the OSM, one should look at the definition of OSS. Programmers often explain OSS like this: “When you hear the term “free software”, think free speech, not free beer [Weber (2004)].” The case of the OSM is not far from this simple explanation. “Free” in this field does not mean free of charge or zero prices, but rather a freedom of use, where the code in the OSS is open to the public, and is non-proprietary. Stallman (2002) defines freedom in OSS to include the right to run the program for any purpose, to study how it works and adapt it to the user’s own needs, to redistribute copies to others, and to improve the program and share the improvements with the community so that all benefit. OSM is also the same, by definition, where the design and business model have been released to the public in such a way that anyone can make, modify, distribute, and use them.

Despite the fact that OSM was primarily a result of the creativity of the founders, imagination and creativity of customers and hobbyists added some innovative customization and prospects to final products that are produced to the market. Both the imagination and the creativity of users are very important to increase the success of lower cost customization that may change the way businesses work from both the management side and the production side. OI can open the way towards entry into new businesses and new business models, too [Chesbrough and Crowther (2006)]. In addition, it may affect the meaning of innovation in the very near future, with this unprecedented way of production that could result an industrial revolution. Banzi says that Arduino OSM is the industrial revolution that is inspiring thousands of people around the world to make the coolest things they can imagine.

In an experimental study by Paulson et al. (2004), that compared OS and close source software products, evidence was presented to support the hypothesis which claims that creativity is more predominant in OSS. The concept of OS projects is powerful, and was very successful, due to the simplicity of interacting among users and sharing knowledge and experiences among people [Weber (2004)], which makes innovation easier and customization less expensive for customers. So, we can conclude that the foundation of OS is dependent upon three main features that need to be defined. First, source code must not be a secret but should be publicly spread. Secondly, anyone has the freedom to redistribute the software without royalties or licensing fees. Finally, anyone may modify the software or derive other software from it and then distribute the modified code under the same terms [The Open-source Definition, Version 1.9, 2002]. In the same sense, as for OSM the main three requirements are: 1) making the interface openly public in order to be used freely, 2) the design has to be made public in order to allow learning and implementation, and 3) the tools used to create the design must also be free to allow others to develop and improve the design. In general, OSM is "creating a product with a design that is made publicly available so that anyone can study, modify, distribute, make, and sell the design or the product itself based on that design."

3.1.2.3 General Overview of Additive Manufacturing

In 1987 Carl Deckard, a researcher at the University of Texas, used Voelcker's solid modeling techniques to create a new manufacturing process [Sealy (2012)] based on three dimensional (3D) objects created by stacking one layer onto another using Computer-Aided Design (CAD) [Wong and Hernandez (2012)]. That process was called "Rapid Prototyping" [Grimm (2004); Skinner (1985)]. At the time, this technology was used only for creating prototype parts or models to help designers and engineers turn their concepts into tangible 3D objects [Skinner (1985)], which is why it was called Rapid Prototyping [Grimm (2004)].

We refer to additive manufacturing as the utilization of additive technologies for the production of final goods, in other words, in contrast to rapid prototyping which is the use of additive technologies for the manufacturing of prototypes, we employ the additive manufacturing term, in this PhD thesis, as a repeatable and scalable production process. Additive manufacturing is also called “Instant Manufacturing” due to its ability to simultaneously make and manufacture products. It is going to revolutionize traditional manufacturing [Bogers et al. (2016); Huang et al. (2013); Berman (2012); Phaal et al. (2011); Tuck et al. (2006)]. However, additive manufacturing will not replace traditional processes of manufacturing; it will enhance them. There are many processes in additive manufacturing that are similar to the ones in traditional manufacturing, such as extrusion deposition, granular fusion, lamination and photopolymerization. These processes depend on using materials, such as thermoplastics and thermoplastics powders, metal alloys, paper, liquid resins and more. The most common use of additive manufacturing at this point is for prototyping, but it is becoming more commonly used in the automotive, aerospace and medical industries for the purpose of producing certain parts and tools [Horn and Harrysson (2012)]. It is also increasingly familiar to scientists, market researchers, students and professors in colleges and universities, and artists, [Wong and Hernandez (2012); Noorani (2006)] and it is being more frequently used in the manufacture of customizable products such as jewelry and toys because of its ability to create and produce almost any shape, including shapes that are very difficult to construct with traditional machines [Wong and Hernandez (2012)].

Additive manufacturing is an industrial manufacturing system based on systematic processes. Additive manufacturing is a broad term that includes different additive manufacturing platforms and technologies. Table 3.1 summarizes 7 different leading additive manufacturing technologies. More recently, additive manufacturing has become nearly synonymous with 3D printing [Gao et al. (2015); Wong and Hernandez (2012); Noorani (2006); Kochan (1997)], and most hobbyists, authors and researchers in the field use the two terms interchangeably. Thus, and in accordance to literature and practitioners in the field, this PhD thesis uses 3D printing term as a synonym to additive manufacturing. As additive manufacturing helps to develop prototypes faster, it has the ability to improve production as well [Wong and Hernandez (2012)]. In addition to production improvement, it enables manufacturers to save time and reduce costs [Berman (2012); Wong and Hernandez (2012); Ashley (1991)].

Since the industrial revolution, manufacturing expression is an interchangeable one with factories, machine tool, tooling, assembly lines, production lines and economies of scale or supply chain. Nevertheless, 3D printing has changed the meaning of manufacturing in the modern manufacturing.

While, 3D printing is a new applied technological and manufacturing revolution in this era [Berman (2012)]. The idea of 3D printing is not novel; experiments had started to bring 3D objects into existence in 1960's by Herbert Voelcker [Sealy (2012)]. Operations did not come true until pioneers such as Charles Hull, the founder of 3D Systems, and Scott Crump, the founder of Stratasys, developed together, in early 1980's [Kodama (1981)], a framework of technologies that are based on additive processes by creating fixed commodities layer over another of liquefied materials onto a powder bed with ink-jet printer heads. Nonetheless, this idea faced critical improvements during the last decade to arrive to the shape that it is at today. Dimitrov et al. (2006) expressed 3D printing as an innovative production of 2D printing. For example, Inkjet 3D printing is one of the youngest additive manufacturing technologies currently available on the market [Bogers et al. (2016)]. The technology uses a familiar concept of inkjet printing, as used by 2D printing companies worldwide. However, instead of using ink, the print head ejects a photo-polymer material which is then hardened by a UV light which is connected to the print head on both its sides.

AM technology	Description
Fused Filament Fabrication (FFF)	A process in which a string of plastic is fed to a heating element (the nozzle) and is then semi-molten in order to be able to dispense the plastic as desired [Dumas et al. (2014)].
Selective Laser Sintering (SLS)	A process during which thin layers of polymer are being distributed in the building chamber and are bound with the use of a laser deflection system (mirrors deflect the laser beam to a desired location) [Tan et al. (2003)].
Stereolithography Apparatus (SLA) (also: SL)	A process of solidifying liquid resin by photo-polymerization using a controlled laser beam [Kataria and Rosen (2001)].
Direct Light Processing (DLP)	A process, very similar to SLA, that is also based on a photo-polymerization process; however instead of using a laser beam, a light projector is projecting images onto the polymer surface [Tesavibul et al. (2012)].
Polyjet Matrix (PJM) (also: Inkjet 3D printing)	A process that uses the familiar concept of inkjet printing, as used by 2D printing companies worldwide. Instead of using ink, the print head ejects a Photo-polymer material that is then hardened by a UV light that is connected to the print head on both its sides [Bogers et al. (2016)].
Inkjet ZCorporation technology (Zcorp)	A powder-binding process based on a liquid binder that is dispensed on to a bed of plaster powder, layer by layer, using an inkjet multi-nozzle printing mechanism [Bogers et al. (2016)].
Selective Laser Melting (SLM) and Metal Selective Laser Sintering (MSLS)	A process uses a laser to melt successive layers of metallic powder (Kruth, 2004) to make strong or hard metallic models for tools and dies directly from metallic powders [Patil and Yadava (2007)].

Table 3.1: Summary of Different Leading Additive Manufacturing Technologies

In addition to the building material applied by the print head, a wax based support material is applied in order to expand the range of geometries achievable by the machine. The support material can be removed using pressurized water [Brajlih et al. (2006); Vaupotic et al. (2006)].

Even though the technology was originally advertised as specialized tool for rapid prototyping but not for manufacturing processes, it became one of the fastest and more accurate free forming 3D printing technologies in the market [Bogers et al. (2016)]. The speed of the process is attributed to two characteristics of the technology. The first is the multiple ejection of material from the print head and the second is the dual UV light system in both sides of the print head. These two attributes enable the production of multiple parts simultaneously and a faster curing process [Melchels et al. (2010)].

The original term of 3D printing refers to the process of layering material onto a powder bed with ink-jet printer heads. However, the term has widened recently to include a wider variety of techniques. In this way, 3D printing becomes called “Additive Manufacturing” [Berger (2013)]. Extrusion and sintering based processes are some newly techniques that the term has included.

3D printers are now able to produce any parts, tools and even whole appliances with the click of the button, provided that there is a valid 3D CAD file. This kind of files contains the dimensions and the design of the intended product. Basically it tells the printer what the final product is supposed to look like [Berman (2012)]. Such ease of printing greatly lowers the technical barrier towards 3D printing [Wong and Hernandez (2012)]. Major companies have caught onto the benefits of 3D printing processes with many already incorporating 3D printing manufacturing methods to their production chain. 3D printing can offer great opportunities to businesses where the currently applied manufacturing system can never offer. Lipson and Kurman (2013) referred these opportunities to its ability of reducing cost and decrease the manufacturing lead time. While Wong and Hernandez (2012) and Noorani (2006) emphasized on the ability of 3D printing to increase the customization level as well as 3D printers have the ability to flexibly produce any size or shape required, in contrast with traditional manufacturing, in which the machine is only capable of producing products of uniform size.

3.1.3 Conclusion

At the early years of production management, the focus was concentrated on high volume of production. Thus, continuous flow, line and large batch processes were the focal points. These process types are linked to the make-to-stock strategy that is based on demand forecasts for production planning. Nevertheless, recently customer tastes and requirements have been changed. Thus, customers start to demand more customized products. This created good attention to the positioning of the customer order point and its effect in production and supply chain planning. In this context, high production volume, such as mass production, does not fit well in such markets and thus the related processes and strategies are not preferable anymore. However, manufacturers should adopt low volume production strategies, such as assemble-to-order and market-to-order production strategies. Once these strategies are adopted, the appropriate production process should be linked to them.

Additive manufacturing fits well in this concept as it is a mass customization and personalization-enabling technology [Gibson et al. (2010); Hague et al. (2003)]. Additionally, 3D printers enable the free forming processes which in their turns enable the manufacturing of almost unlimited geometries at once without special tools and equipment.

Furthermore, additive manufacturing makes it possible to manufacture various parts in the same batch [Gibson et al. (2010)]. This leads to allow the mass customization [Reeves et al. (2011); Tseng and Piller (2011)], and facilitates the production of low volume without having to invest in expensive tools and machineries, such as molds. Accordingly, implementing additive manufacturing can reduce the sunk costs and general investments in equipment [Hopkinson et al. (2006)]. Besides, the reduction and elimination of traditional tooling, additive manufacturing will potentially increase a company's product introduction rate. Since machineries, molds and tool development and testing time can be reduced, companies will be able to generate more rapid test concepts and release them to the market [Bogers and Horst (2014); Wong and Hernandez (2012); Mortara et al. (2009)]. Thus, additive manufacturing enables faster, more agile and better responsiveness to market and trend changes [Hopkinson et al. (2006)].

Porter (1981) proposed technology as a major source of gaining competitive strategy among competitors, and so increasing the market share. In addition, Skinner (1984) cited in Mellor et al. (2014) proposed that innovation in production technology can be used strategically as a powerful competitive weapon, suggesting that it can bring to bear many other strategic factors besides achieving low costs including, superior quality, shorter delivery cycles, lower inventories, lower investments in equipment, shorter new product development cycles and new production economics.

By looking at the previously discussed problem of the shift in customers' requirements toward customization, manufacturers can notice that 3D printing has been applied to low volume production. The output in this production system can be of higher rank than traditional manufactured output; that is 3D printed products characterized by higher quality, lighter, customized, stronger, already assembled and have lower costs [Wong and Hernandez (2012); Ashley (1991)] than if produced by repetitive process of traditional manufacturing system, due to its ability to control precisely the used material quantity.

3.2 Manufacturing Supply Chain Management

3.2.1 General Characteristics of Supply Chain Management

Supply chain management is defined as: "Integrated group of activities and processes that starts with an idea to be designed in the form of goods or services that fits consumer's demands and ends in the delivery of these goods or services into consumers' hands" [Christopher et al. (2004)]. This includes many internal and external integrated and networking parties, entities and/or managers, all work together in a sequential process to transform inputs into outputs, to manage materials, information and money flows, and to end with the delivery of the final output to the customer. Supply chain management is defined as a constantly developing management philosophy [Ross (1998)] that manages and coordinates efficient and effective [Nyman and Sarlin (2014); Agus and Shukri Hajinoor (2012)] movement of materials, goods, services, information and capital among all internal and external supply chain members to include suppliers, manufacturers and customers [Duclos et al. (2003); Beamon (1998)], in order to add value for customers and stakeholders [Beamon (1998)]. Authors have defined four main objectives for supply chain management. Thus, anyone can have the same understanding of supply chain management when it is defined by these objectives which are summarized as follows:

1. Add value for customers and stakeholders. Supply chain management, like any other type of business management, aims to create value through financial benefits. Value is broadly defined as the worth of an item, good, or service. Adding value to a good or service is the responsibility of each entity and every process in the supply chain [Beamon (1998)].

2. Enhance customer service. In terms of the supply chain, customer service is the ability of a company to address needs and requests from customers [Beamon (1998)]. It also can be explained as the measure of delivery of the product to customers at the time specified. The basic characteristics of customer services are:

   (a) Availability, which is defined as the ability to have the product when it is requested by customers,

   (b) Operational performance deals with the time needed to deliver the product to customers once the order is placed, and

   (c) Customer satisfaction, which takes into account customer perspectives, expectations and opinions based on the customer's experience and knowledge.

3. Effectiveness and efficiency in using resources in supply chain [Nyman and Sarlin (2014); Agus and Shukri Hajinoor (2012)]. In terms of the supply chain, resources can be defined as the amount of employees, raw materials, equipment and time needed in production and delivery. Being effective and efficient helps organizations achieve their business goals and objectives. In addition, business growth is a result of efficiency and effectiveness in using resources; effectiveness in the supply chain means getting the right product and right quantity to the right customer at the right time [Nyman and Sarlin (2014)]. Efficiency, however, generally means the ability to achieve these goals with minimal wastes. In terms of supply chain, efficiency measures how much is being accomplished, or to what degree accomplishment is being maximized, with the available resources in the supply chain network.

4. Leverage partner strength. The supply chain is a network of different entities; all work together to achieve the same goal of satisfying customers. Partnership in the supply chain is a relationship based on trust and shared risks. A strong relationship among all partners of different functions in the supply chain lets organizations add value to their products, increase technological strength and strengthen operations. Additionally, it lets them increase their market share, improve organizational skills and build financial strength through increasing income and sharing costs [Chandra and Kumar (2000); Lamming (1996)].

3.2.2 The Concept of Supply Chain Management

Supply chain has been discussed intensively in literature. Scholars have presented it and discussed it using different points of view. Their views show the development of supply chain management through the time. Supply chain management has developed from traditional approach that is mainly reflects it as a logistics management to a more complex one that takes it as a multi-organizational process. Some authors like Ellram and Cooper (1990) discussed supply chain management as a logistic approach. They presented supply chain management as a composition of strategies to reduce uncertainty and increase competitiveness. The authors suggested that supply chain management trends to manage inventory not only within one firm but among all suppliers. Balancing inventory requires integration of all parties through the supply chain in exchanging information. They emphasized on cooperation and collaboration to extent of partnership within the parties of the supply chain. In their point of view, such cooperation and collaboration increase efficiency and improve performance. In addition, integration and cooperation results in reducing uncertainties and increase in competitiveness in the market. However, according to Ellram and Cooper (1990) achieving a high cooperation in practice is very difficult.

Scholars after that period of time start to differentiate between logistics and supply chain management. Cooper et al. (1997) positioned such a difference in their research. The authors argued that supply chain is an inter-organizational process. However, at the operational level managing logistics is the bases of supply chain management. They defined logistics as the process of procurement, production and distribution. Nevertheless, they defined the supply chain management and presented it as a framework comprises of structure, business processes and management components. Furthermore, Simchi-Levi et al. (2016) emphasized the need for a structured framework. But they also emphasized that supply chain is a logistic tool management. These authors defined supply chain management as an approach where suppliers, manufacturers, warehouses and stores cooperate all together in order to manufacture and distribute the right product with the right quantity at the right time in the right locations. In their point of view, this integration results in reducing the cost.

Supply chain management definition has evolved in literature to be considered multi-organizational strategic planning. Chopra and Meindl (2007) defined it as multi-organizational decision making approach of designing, planning and operating. In this context, these authors suggested two strategies of supply chain management. These strategies are based on the integration with customers. The first strategy they presented is push strategy, which manufacturers have to respond to customer's order. While the second one is pull strategy, which let manufacturers to anticipate in the customer's order. Moreover, Malhotra et al. (2007) presented supply chain management as a multi-organizational strategy that controls, organizes and motivates the flow of both material and information among all supply chain parties.

More evolution has been noticed in literature of supply chain management. The definition has been extended to include competitiveness. Vachon et al. (2009) stated that cooperation among suppliers is what aligns competitive priorities with supply chain. Schniederjans et al. (2010) have discussed supply chain management as the coordination between partners in the supply chain to achieve competitiveness goals of improving quality by adding value to the product or service, quick response to customer by decreasing leading time and cost reduction. They argued that implementing lean principles in supply chain management leads for higher competitiveness through continuous improvement and waste elimination. In addition, flexibility has been presented by Simchi-Levi et al. (2016) to be an addition key competitive issue. The author discussed the production categorization to be aligned to operations strategies. Simchi-Levi et al. (2016) encouraged the idea of having diverse strategies in supply chain management to be applied for different types of products. Gosling et al. (2012) suggested an idea close to Levi's idea when they criticized the one-size-fits-all approach for managing supply chains. Thus, this proposition indicates the correlation among product type, production strategy and supply chain management approach.

3.2.3 Manufacturing Supply Chain

The aforementioned discussion leads to define the manufacturing supply chain as the stretched process of activities starting from the first point of converting natural resources, components and raw materials into final goods until the point where these final goods are delivered to the end customer. Manufacturing supply chain management is universally referred to as the harmonization of transportation of goods and both upstream and downstream flow of information and capital between suppliers and customers [Duclos et al. (2003)]. Managing supply chain is an essential duty in all companies and organizations. Proper management of supply chain results in success for the organization, and lack in supply chain management means failure for that organization. Referring to Nyman and Sarlin (2014), organizations' success or failure is depending on getting the right product to customers, at the right time and for the right price. This can lead the organization to pay more attention to managing its supply chain properly and reevaluating the implementation of its supply chain strategies. Supply chain strategies can vary to include all possible strategies that have an effect on enhancing the delivery of products and information from suppliers to customers and vice versa [Lee (2002)].

3.2.4 Frameworks of Supply Chain Management

Literature presents several approaches for managing supply chains. These approaches have focused on the business processes [Melnyk et al. (2000); Cooper et al. (1997); Stewart (1997); Davenport and Short (1990)]. Cooper et al. (1997) presented a framework that is based on coordination of activities and processes within and between organizations. Their framework defines business processes chains, network structures and management components. However, Stewart (1997) discussed the Supply Chain Operations Reference (SCOR) model as the first cross-industry framework for evaluating and improving enterprise-wide supply chain performance and management. The author discussed the four main processes in SCOR, namely plan, source, make and deliver. Nevertheless, Davenport and Short (1990) presented the business process reengineering framework which was the result of the organizational transformation into information technology. Such a framework has discussed the analysis, the design and the redesign the work flows within and among organizations. Furthermore, Melnyk et al. (2000) presented a framework that is an extension to SCOR model [Lambert et al. (2005)] which comprises of eight business processes. Lambert et al. (2005) clustered these eight business processes into three groups which are: operational, planning and controlling and behavioral. The eight business processes according to Melnyk et al. (2000) are: plan, acquire, make, deliver, product design and redesign, capacity management, process design and redesign and measurement.

Lambert et al. (2005) emphasized that achieving cross-functional integration can be done by using SCOR model which is based on implementation of business processes that connect customers and suppliers.

The following section describes and analyses SCOR framework in depth.

3.2.4.1 Supply Chain Operations Reference Model

SCOR model is an industry standard framework that was developed by "The Supply Chain Council" (SCC) and has become a reference model for organizations to increase their performance in managing their supply chains [Stewart (1997)]. The SCC which was formed in 1996 is the product of PRTM and AMR consulting firms together with a group of US and multinational firms. According to Bolstorff and Rosenbaum (2007), the goal of forming the SCC is to have an independent organization to develop a supply chain implementation model. As a result, in early 1997 the first version of SCOR model was proposed.

Lambert et al. (2005) stated that the SCC started with an integration of 69 world leading companies. However, Bolstorff and Rosenbaum (2007) show that more than 750 members worldwide have joined the SCC by 2002.

SCOR model is an operational process perspective [Zhou et al. (2011)] it covers everything that managers need to understand about the processes in the supply chain. It gives descriptions of management processes and the relationships among them, it explains the practices that result in superior performance, and it provides metrics to measure the performance of these processes [Hwang et al. (2008)]. SCOR model helps all supply chain members to effectively work together on improving the efficiency of their supply chain management [Hwang et al. (2008)]. The main goal of SCOR model is to provide and improve alignment between the marketplace and the response of a supply chain [Huan et al. (2004)]. Such an alignment increases the supply chain performance such as holding lower inventory levels, improving visibility of the supply chain, increasing the cycle times and improving the access to important customer information [Zhou et al. (2011)]. Moreover, Stewart (1997) stated that SCOR has been developed to evaluate and improve the performance of the supply chain by providing standard process definitions, terminology, and metrics. Nevertheless, Bolstorff and Rosenbaum (2007) argue that SCOR model could combine several elements, such as benchmarking, business process engineering and leading practices, into one framework.

SCOR Overview

"*SCOR model is the first model that can be used to configure supply chain based on business strategy*" [Huang et al. (2005)]. "*It provides unambiguous, standard descriptions for the thousands of activities within the supply chain*" the author states.

SCOR model is based on five management processes which are: 1) Plan 2) Make 3) Source 4) Deliver Stewart (1997) and 5) Return [Zhou et al. (2011); Bolstorff and Rosenbaum (2007); Lockamy III and McCormack (2004); Stephens (2001)]. Some other authors like

Hwang et al. (2008) argue that SCOR is based on six management processes, adding "Enable" as the sixth content of the processes types.

According to Stewart (1997) these processes compass the supply chain and extend across all parts of the manufacturing and delivery process. Thus, scholars agree that SCOR model is a process-centered view of supply chain management. However, Lambert et al. (2005) affirm that each process in SCOR model is analyzed and implemented based on business process reengineering and best practices analysis. Bolstorff and Rosenbaum (2007); Stephens (2001) and Stewart (1997) emphasized that SCOR processes cover all aspects in the supply chain for both customers and suppliers. Thus, it covers all customers' interactions, all physical material transactions and all market interactions. Following are the five basic processes:

1. Plan: scholars have agreed that plan process is the initial and major process in managing the supply chain by forecasting the demand. However, each of them highlighted the plan process in different aspect. Stewart (1997) focused on plan infrastructure aspect in this process. The author discussed plan infrastructure in terms of make and buy decisions, supply chain configuration, and manufacturing process. However, Bolstorff and Rosenbaum (2007) discussed plan process in terms of demand aggregation, inventory and capacity planning, and supply resources. While Zhou et al. (2011) discussed this process in terms of gathering on-time internal and external information in order to balance between aggregate demand and the quantity manufactured and supplied, and to achieve the strategic goals of the firm.

2. Source: is the relationship between the firm and its suppliers with regards to all activities and practices. Some scholars like Bolstorff and Rosenbaum (2007) and

Stewart (1997) focused in their discussions on the activities that take place in this process such as obtaining, receiving, inspecting, holding, and authorizing payment for purchased materials and goods. While other scholars such as Zhou et al. (2011) discussed the best practices that connect manufacturers with suppliers and listed them as the following:

(a) establishing a long-term relationship,
(b) reducing the supplier base,
(c) evaluating supplier's performance and providing programs to develop them, and
(d) implementing just-in-time delivery.

3. Make: according to Bolstorff and Rosenbaum (2007) the make process is the production process and all related aspects such as request and receive material, test product, package and inventory. Stewart (1997) discussed make infrastructure such as engineering changes, equipment, production quality and shop scheduling, among others, as a part of the make process. On the other hand, Zhou et al. (2011) defined that make process as the process of transforming the raw materials into finished goods in an efficient way. Though, the mentioned scholars have all agreed on a set of best practices for the make process. The major best practices that were mentioned in their researches are just-in-time production, quality management, human resource management and preventive maintenance.

4. Deliver: authors have defined this process as a delivery infrastructure. However, Stewart (1997) extended the definition of the deliver process to managing demand, warehouses, transportation and installation. Moreover, Bolstorff and Rosenbaum (2007) included some other activities such as generate quotations, configure product,

create and maintain database for customers, products and prices, manage imports and exports and verify performance. These authors and others such as Zhou et al. (2011) argued that there should be a set of capabilities in the deliver process like real-time information sharing, agility, and information technology enablers and others.

5. Return: according to Lockamy III and McCormack (2004) the return process has been proposed to SCOR model in its fifth version. Bolstorff and Rosenbaum (2007) stated that this process has been developed to deal with warranties, defective products, and excess delivery.

Stewart (1997) suggested that SCOR model includes internal and external supply chain improvement perspectives. The internal improvement perspective suggests best practices to compete more effectively in the range from the immediate supplier to the immediate customer. However, the external improvement perspective suggests best practices to improve the whole supply chain performance starting from the supplier's supplier to end with the customer's customer.

3.2.4.2 Best Practices in Supply Chain Management

Over the last two decades, plenty of researches have been done aiming developing performance management and best practices in supply chain management. There are dozens of best practices for managing supply chains. In this section, best practices are presented and reviewed. The top best practices in supply chain management are organized into the five processes of SCOR model as the following:

1. Plan
   - Performance Measurement and Benchmarking

Supply chain management optimizes all processes in supply chain by minimizing inventory, reducing costs, increasing production and rapid order fulfillment. These areas can be measured by performance measurement and benchmarking. Performance measurement in supply chain management is not an easy task [Estampe et al. (2013)] due to involvement of several parties in the supply chain. On one hand, according to Beamon (1999) a company must focus its efforts on implementing a structured performance measurement approaches in order to gain a competitive advantage. These measurement approaches could be in a form of qualitative and/or quantitative metrics [Beamon (1999)]. Beamon (1999), however, sees that qualitative approaches are more vague than quantitative approaches. The author clarified that as quantitative approaches provide data that can precisely describe a process performance and then analyzing these quantitative data is easier than analyzing qualitative data. On the other, Beamon (1999) defined competitive priorities in which a company's operations are performed. Moreover, other scholars have highlighted several competitive priorities by giving the cost the higher ranked priority. Later on, other dimensions have been added such as quality. In that sense, firms have to produce the products at the lowest cost possible but with higher quality. In addition, other dimensions like flexibility, speed and delivery have been nominated to be competitive priorities besides cost and quality. Later on, other authors such as Melnyk et al. (2010) have argued that innovation, responsiveness, and sustainability are essential dimensions for measuring performance beside what have been mentioned earlier.

2. Resource, Deliver, and Return

   - Supplier relationship Management

   Managing supplier relationship is a critical issue in supply chain management. It gained attention from many scholars because it provides several benefits to the firm from many aspects. According to Ellram and Cooper (1990) supplier relationship management benefits the firm on the economical, managerial, and strategic aspects. These benefits can be translated to cost reduction [Janda et al. (2002)] and gaining higher competitive advantage. Janda et al. (2002) argued that long-term manufacturer-supplier relationship based on sharing information between them results in increasing the performance and flexibility of the supply chain management. In addition, quality of produced items will increase due to suppliers' involvement and suppliers' development.

   - Value Chain

   Because the main goal of businesses is to maximize profit and to increase customer satisfaction, value is the top priority because it benefits both the company and the customer. Porter and Millar (1985) defined value chain as the process whereby the corporation passes value on to the customer with the minimum cost possible to the firm. The author emphasized that value chain provides businesses with competitive advantage. Value can be created in so many ways, such as linkages which are not only connecting value activities inside a company but also among the suppliers [Porter and Millar (1985)]. According to Porter and Millar (1985) information technology makes it easier to coordinate with supplier. This type of coordination leads to order management. Order management leads to efficiency when orders are entered once and order status is visible throughout the chain.

3. Make

- Flexibility Management

Scholars have discussed flexibility management and proposed several frameworks to increase flexibility in the supply chain and to manage it, as well. Lee (2004) proposed the triple-A supply chain. According to Lee (2004) agility, adaptability and alignment are the key aspects for the success of supply chain members. In addition, Dwayne Whitten et al. (2012) agreed that the implementation of triple-A supply chain increases the performance of the supply chain members. Lee (2004) defined agility as the responsiveness and the ability to reduce time to market. Moreover, Dwayne Whitten et al. (2012) claimed that agility includes the capability of suppliers to collaborate and they defined it as the quick react to changes in customers demand. In addition, Lee (2004) defined adaptability as the ability to adjust and modify the design of the supply chain and the supply chain network in order to meet the structural shifts in market. Nevertheless, Lee (2004) referred alignment to the ability to increase the supply chain performance. Dwayne Whitten et al. (2012) suggested a set of practices to increase the supply chain performance such as exchanging information with suppliers and customers, defining clear roles and responsibilities for suppliers and to share risks, cost and gains with them.

3.2.5 Operationalizing Additive Manufacturing as a Manufacturing Process: Implications for Supply Chains

The characteristics of additive manufacturing technologies affect the manufacturer's activities, especially when it comes to the increase in customization levels where customers have to interact in the manufacturing process. Koren (2010) theoretical framework discusses the changing role of the customer when moving from mass production to mass customization to personalized production (as in Figure 3.1). Thus, additive manufacturing creates the potential to change the supply chain structure.

When considering supply chain structures for additive manufacturing, Walter et al. (2004) present two possible models; centralized and decentralized supply chains. According to Walter et al. (2004) centralized supply chain requires centralized manufacturing production and centralized inventory. This means that the company should have the more standardized products on the inventory shelves with high turnover. However, adopting additive manufacturing leads to decentralized supply chain which results in reducing the inventory levels while allowing companies to better fit supply to real demand [Bogers et al. (2016)]. Based on Bogers et al. (2016) opinion inventoried components can be produced based on lean principles and kanban signals to replenish the more standardized components while customized products are manufactured just-in-time based on the additive manufacturing technologies. Tseng and Piller (2011) and Da Silveira et al. (2001) agreed that balancing capacity and inventory reduces complexity in the supply chain, decreases the response time, and increases the efficiency in production.

One of the interesting debates in recent years concerning supply chain strategy is based on “lean” and “agile” philosophies [Tuck et al. (2006)]. The focus of lean thinking has been on the reduction or elimination of waste. It has been suggested that lean concepts

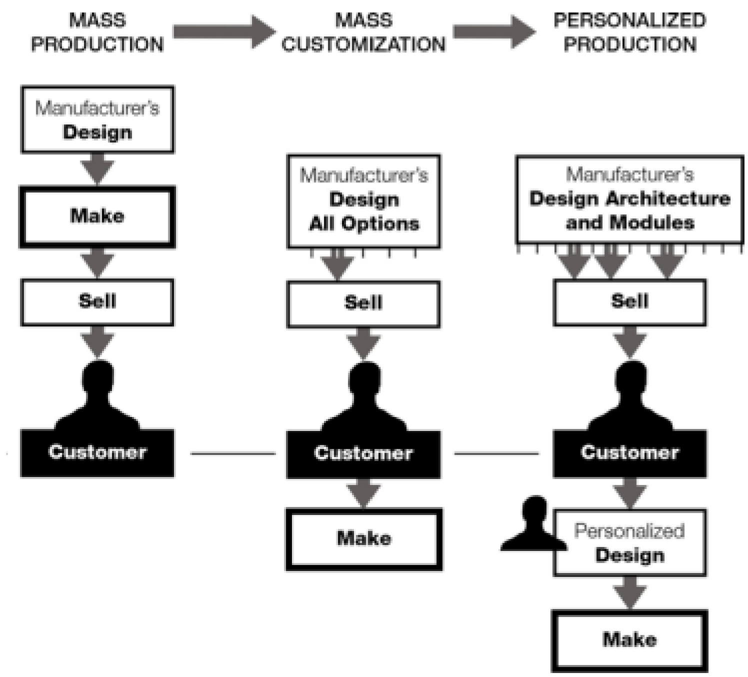

Figure 3.2: The Consumer Role When Moving from Mass Production to Mass Customization to Personalized Production - Adopted and Adjusted from Koren (2010)

work well where demand is relatively stable and therefore predictable and where variety is low [Christopher et al. (2004)]. On the other hand, in environments where demand is volatile and there is high requirement for variety, a different approach is called for. This is the concept of "agility", which is concerned with responsiveness. It is about the ability to match supply and demand in turbulent and unpredictable markets. Fundamentally, agility is about being demand-driven rather than forecast-driven, and in some of these approaches additive manufacturing may fit better than traditional manufacturing. In some cases, the two ideas of lean and agile can be brought together as a hybrid "leagile" solution [Tuck et al. (2006)]. This hybrid solution is to utilize lean principles when designing supply chains for predictable standard product's components and agile principles for customizing the products.

The characteristics of additive manufacturing and its lack of need for tooling enabled decentralized production close to the market. Thus, manufacturers can produce decentralized at production facilities close to their customers with a relatively low investment due to the reduction in dedicated tools and the flexibility of additive manufacturing platforms [Bogers et al. (2016)]. In that sense, inventory is reduced due to the decrease of forecasting. Additionally, implementation of additive manufacturing will decrease lead times in a manufacturer's production while increasing responsiveness for market changes. Walter et al. (2004) give a real example from the aerospace industry, where the manufacturer was able to reduce inventory costs, increase their responsiveness, lower their investments, and increase their ability to customize products to customers' needs when the manufacturers decided to implement additive manufacturing to produce customized parts at decentralized facilities close to their customers.

3.3 Conceptual Views of Manufacturing and Supply Chain Management

3.3.1 Lean Concept in Supply Chain Management

3.3.1.1 Overview of Lean Management

Because of the economic depression which followed World War II, Taiichi Ohno tried to establish a production system, later named the Toyota Production System (TPS), to guarantee the continuity of Toyota Motor Company [Womack and Jones (1996b)]. The main objective of TPS at that time was to ensure the continuity of practices that eliminate waste, resulting in increased production efficiency and reduced production costs. The basic idea behind Ohno's implementation of TPS was to produce only the needed units and amount of products, at the required time of production. By doing so, Ohno could avoid high inventory levels and reduce waste to the lowest possible levels. Even though TPS was used since the mid-20^{th} century, it did not get much attention from other manufacturers until the oil crisis occurred in 1973. During that period, many manufactures and companies closed their businesses [Ugochukwu et al. (2012)]. However, because of TPS, Toyota Motor Company sustained great earnings during that crisis period which resulted in great notice from others [Womack and Jones (1996b)]. As Ohno (1988) claimed, because of the outstanding performance of Toyota Motor Company, many other companies became interested in TPS. In the same year, a researcher named Krafcik from Massachusetts Institute of Technology, USA, used lean as a term to describe TPS. Krafcik elucidated lean as a system that makes products with fewer defects and adjusts production according to customer needs [Shah and Ward (2007); Womack et al. (1991)]. Lean gained popularity in 1990 when Womack et al. (1991) published their book titled The Machine that Changed the World. Hines et al. (2004) compared the use and implementation of lean manufacturing or lean production in the manufacturing shop floor with the modern day implementation of lean concepts in many different industry sectors. In trying to define lean concept, it was found that there is no clear and accepted definition; instead, we found some general ideas clarifying what lean is and what it is not [Mohan and Sharma (2003)]. Thus, in our research we were able to find out what researchers in the field described "lean concept." For instance, Sezen (2009) described lean as a method used to reduce costs and improve efficiency and quality, as well. At the same time, Shah and Ward (2007) described it as a management philosophy. Regardless, from all the reviewed literature, we conclude that all researchers agreed upon one main opinion in defining what the objective of lean concept is. This objective is summarized by reducing costs and improving production efficiency. Moreover, all agreed that the objective of lean could not be achieved without the appropriate implementation of lean principles, practices and tools.

Lean Principles, Practices and Tools

Even though Shah and Ward (2007) have argued that lean is a set of principles, practices and tools, most researchers in the lean field could not give a clear characteristic of each of the three terms. Most of them kept these terms vague by not explaining the dependency of the terms, and some authors use them interchangeably [Ugochukwu et al. (2012)]. On the other hand, Hines et al. (2004) mentioned the hierarchical levels for the principles, practices and tools of lean, where he kept the principle on the highest level and tools at the lowest one. This hierarchical order is implemented based on some logical implementation of each category. Lean principles cannot be properly implemented without putting practices into operation, where practices are the accepted activities that transport improvements into the company. However, practices need a set of tools to be properly implemented [Dean and Bowen (1994)].

Lean Principles

Womack and Jones (1996b) were the first who put forward and discussed the idea of the Five Principles of Lean which focus on the core lean management issues. Later, other authors concentrated their discussions of lean on these five principles because they could enfold all the business logic of what lean could be. By these principles Womack and Jones (1996b) brought to light a new great idea in management, which they called lean thinking. They explained it as a great way to reduce waste. The five principles according to Womack and Jones (1996b) are the following:

1. Value Specification. Specifying value from the end customer's view involves trying to find out what a customer desires in a product or service [Womack and Jones (1996b)]. The first step in lean thinking that a manufacturer should take in any production system is a proper specification of value from the customer's perspective. By doing so, companies can be efficient in providing the right product that satisfies customers' needs and reducing the probability of failure in the market. Thus, when providing any goods or services, companies should depend on the customer's view of expected value of the product before processing. According to Ross David (2000), customer satisfaction depends on the manufacturer's ability to grasp what customers are asking for and provide the expected value.

2. Value stream identifying. The very basic and important step that every company should take to implement lean thinking is to apply this principle to each product the company provides. By doing this, the company can identify the value stream of the

product through every step of the supply chain. Thus, the company can understand each of the activities in the supply chain and identify what activities add value and what activities do not. Consequently, a clear picture of value stream comes to light and waste can be pointed out. Womack and Jones (1996b) claimed that mapping the value stream classifies these supply chain activities into three different categories. First, value adding activities; these activities are essential to the production of goods and, at the same time, adding value from the customer's perspective. Second, activities that are required in the production and delivery process, but do not add value to the product from the customer's perspective. Finally, the third category of activities are those that could be eliminated from the production and delivery processes because of their lack of usefulness, and their negligible effect in adding any value to the product. Accordingly, applying this principle of lean thinking sheds the light on the activities that increase both cost and waste without adding any value. Thus, it helps the company to eliminate such activities and improve the process of manufacturing and delivering the products to the final consumer in more efficient and effective way.

3. Flow. Implementing this principle means that the system should have a clear path of sequential activities. Doing so eliminates the waste in both time and production. As to Womack and Jones (1996b), the flow principle focuses on identifying and arranging value creating activities in a continuous flow. All activities from producing the product until delivering it to the final customer have to be connected. Any source of waste or delay has to be recognized and removed.

4. Pull principle. This principle is simply summarized in letting final customers pull the product. It means companies should produce and manufacture no more than the

demanded quantity of the market. No extra amount of production should be stocked in inventory. Womack and Jones (1996b) explained this principle as no production should occur until customers demand the product.

5. Perfection. According to Womack and Jones (1996b) perfection is continuous, radical and incremental improvement. However, this principle only starts being implemented once the company understands the first four principles.

Lean Practices

Many authors like Wee and Wu (2009); Taylor (1999), and Levy (1997) agreed on numerous activities that exemplify lean practices. These activities should be implemented in companies in order to put lean principles into practice and therefore improving the company's efficiency. These activities are:

1. Reducing waste. Analyzing the chain of activities from the creation of the product until it is delivered to final consumer in order to identify and eliminate the waste is the main objective of implementing lean [Shah and Ward (2007); Ohno (1988)].

2. Striving for perfection. Businesses should look for perfection because it is their only way to achieve longevity in the market. Achieving perfection has never been an easy goal. Nevertheless, looking for real causes of issues in business and fixing them from their roots leads to perfection. Identifying source of problems in the activity chain and fixing these issues reduces wastes and improves the whole process.

3. Right amount at the right time. One of the main ideas of lean production is to produce the minimum required quantity only at the precise time it is needed [Shah and Ward

(2007)]. Excess in production leads to higher costs in inventory; these higher costs are obviously a waste of money. Lean calls for reducing waste. Thus, companies must study their market very well to know exactly what customers need and when they need it.

4. Realizing customer needs. Taylor (2006) claimed that recognizing and understanding customers' needs is the most important step in achieving lean in an organization.

5. Analyzing the value chain. This analysis is discussed by many authors, and there is consensus that it is essential, because it facilitates the methods with which companies can improve their value chain.

6. Organizing. Proper arrangement of shop floor workplace, organization offices and the system used by the company helps in reducing waste time. Coordination improves the production flow, which results in improving the whole chain of activities [Julien and Tjahjono (2009)].

7. Rapport. Long term contracts and sharing information among all members of supply chain, creates trust and successful connections [New and Ramsay (1997)]. Such connections facilitate the flow of activities and reducing wastes, as well.

Lean Tools

Dean and Bowen (1994) stated that lean practices need some specific and detailed tools in order to be effectively implemented. From reviewing the literature, one can find that authors agreed on some approaches that many firms applied in order to put lean in practice. These lean tools can be summarized in the following:

1. Just in time (JIT). No more than the required quantity is to be delivered at the time of production. No excess inventory and no waste are the main points in this technique [Ohno (1988)]. This system calls for fast and timely processes, so waste has to be reduced to the bare minimum.

2. Kaizen. Striving for perfection entails a continuous search to find problems, identify and analyze their roots [Ohno (1988)], and then solve these problems. This engenders continuous, incremental improvements [Womack and Jones (1996b)].

3. System consistency. One accepted methodology has to be adopted by the organization. Well known sequential activities reduce waste and improve efficiency in work [Nicholas and Soni (2005)].

4. Vertical integration. Good relationships with suppliers and customers can enhance the manufacturing process, improving quality and eliminating waste that results from poor quality, storing and delays in both receiving and delivering products [Wee and Wu (2009)]. In addition, these good relationships help in facilitating the implementation of many other lean tools.

5. Concern for employees. In order to achieve the required quality in production with minimum waste and high performance, employees should be engaged in the decision-making process [Nicholas and Soni (2005)]. Employees have firsthand knowledge of how the work process is being implemented. They experience everyday problems of work and know techniques to solve them. Engaging them in the decision-making process can help in getting over these daily work issues and give them incentives to work harder to achieve stated goals.

6. Mieruka. This is a business management technique that companies employ to make all the communicated information visualized in signs, figures and charts instead of written texts [Womack et al. (1991)].

7. 5S Method. Julien and Tjahjono (2009) summarized the 5S method to be the management of inventory, work process and suppliers. This method is based on sustaining, sorting, simplifying, shining and standardizing the workplace.

8. Kanban and Pull System. Antony et al. (2012) argued with regards to lowering the inventory levels, a pull system has to be implemented. This system requires the company to order what they need when they get the order to produce. Kanban is a tool of communication based on attaching small cards to boxes to control pull by indicating the production and delivery [Womack and Jones (1996b)].

Figure 3.2 summarizes lean principles, practices and tools in their hierarchical order. This summary graph is based on understanding the literature review to link the three levels of lean principles, practices and tools/techniques.

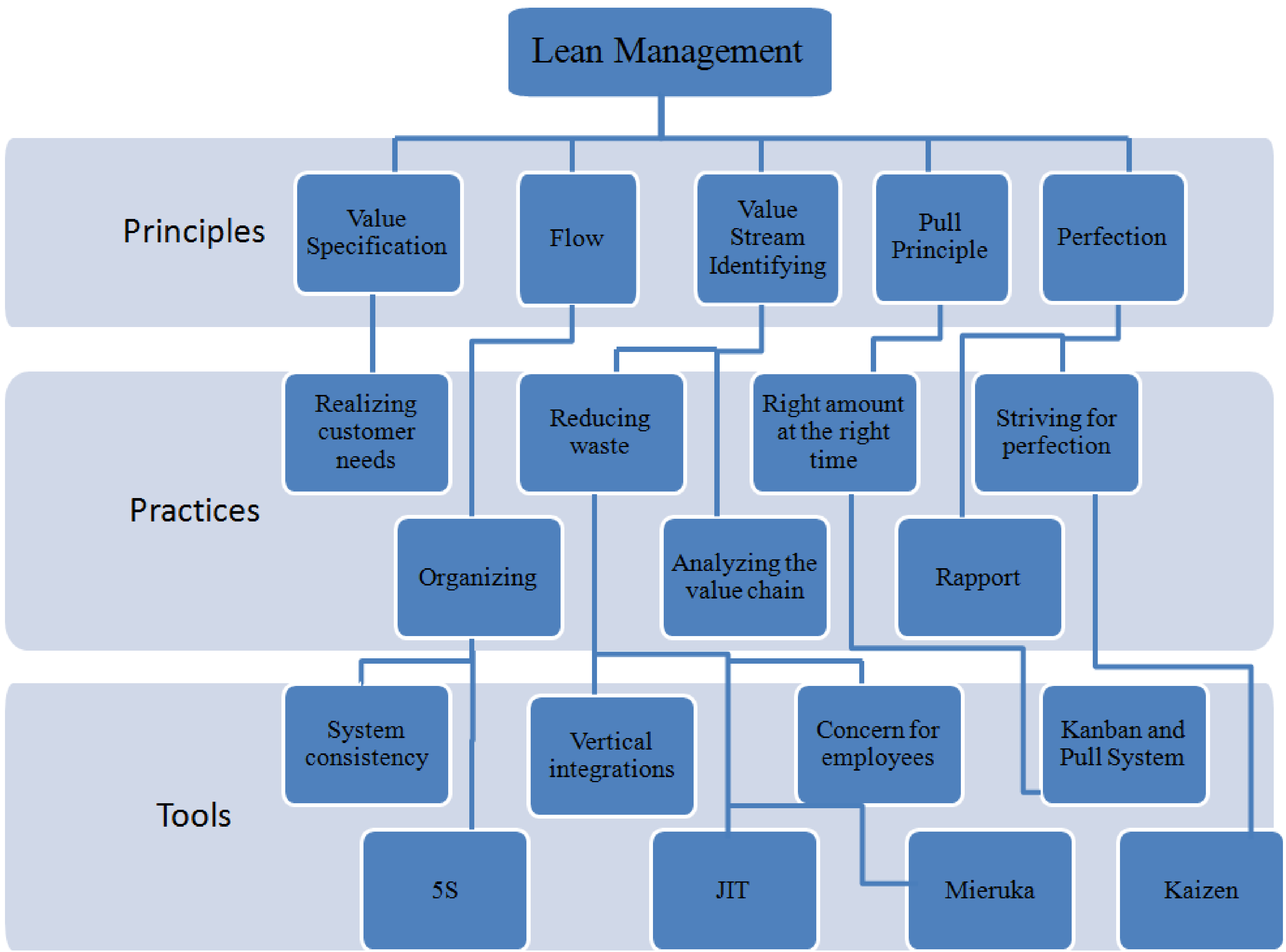

Figure 3.3: Summary of Lean Principles, Practices and Tools

3.3.1.2 Lean Supply Chain

Researchers and practitioners agreed that lean is systematic approach with one goal of increasing the value of the final product to the final customer through identifying all kinds of wastes and eliminating them. On the other hand, supply chain managers are always eager to perform tasks and activities along supply chain in a way that helps their companies stay competitive in the market. Researchers like Agus and Shukri Hajinoor (2012) and Shah and Ward (2007) have claimed that lean implementation in the supply chain gives managers the opportunity to improve supply chain activities as well as enhance managers' performance in managing the supply chain. Performance in this sense could be translated to cost reduction, which in turn could be either identifying activities that do not add value and getting rid of them to increase profits, or augmenting the efficiency of value-adding activities and thus increasing the productivity of the process.

While reviewing literature on lean management, it was noticed that lean implementation has been researched and discussed on a micro level within supply chain. Researchers' main focus on lean implementation was not extended to the whole supply chain; it was to check its effect on a single corporation, or on some critical processes within an organization in the supply chain. Researchers agreed that proper implementation of lean principles, practices and tools increases the efficiency and profitability of organizations, and that it also helps in building competitive advantage. However, implementing lean only at isolated points in the supply chain and using it on a micro level will not be as advantageous as extending its use to cover all activities and entities within the supply chain. Inventory, warehouses, and human and working capital are the main resources in the supply chain. Lean thinking could be implemented in any of these resources to reduce waste and thereby reduce costs. Implementing lean on inventory will result in reducing inventory levels to the lowest possible minimum. In addition, implementing lean on warehouses will result in maximizing the space used for storing inventory. Implementing lean on both human and working capital results in increased productivity, more hedging agreements or contracts with suppliers, and increased profitability ratios as well. Thus, implementing lean in all of these resources at the same time will definitely reduce costs throughout the supply chain and result in a supply chain that is extremely cost-efficient.

Many authors, such as Behrouzi and Wong (2011), Sezen (2009) and Womack and Jones (1996b) supported the idea of implementing lean management throughout the entire supply chain.

Womack and Jones (1996b) have presented in their book, which is entitled "Lean Thinking," that it is appropriate to actualize lean along the supply chain. Furthermore, Womack and Jones (1996b) are not the only ones who support the idea of putting lean into effect along all supply chain activities and entities; Sezen (2009) have also supported this idea. Sezen (2009) argue that enforcing lean along the supply chain will result in reduced costs, increased production quality, and a competitive advantage. Accordingly, when lean is implemented throughout a supply chain, and the supply chain is appropriate for lean production, the activities and processes can be referred to as a "Lean Supply Chain". In addition, according to Behrouzi and Wong (2011) lean must be implemented throughout the supply chain.

Many authors have defined "Lean Supply Chain." No matter what expressions or manner of description the authors used to define lean supply chain, they all agreed on the same characteristics. Effective relationship among all supply chain members is the most important characteristic of a lean supply chain. In any supply chain, members may have to sign long-term contracts in order to guarantee the continuous flow of materials, products and services.

Effective relationships help in establishing an integrated supply chain. However, in order to have an integrated supply chain, effective communication among all supply chain members is needed. Effective communication along the supply chain and the sharing of information among members leads to better supply chain management. This is achieved through cutting costs by lowering inventory levels, continuously improving processes throughout the supply chain, improving the quality of products and services, and increasing customer satisfaction by focusing more on the customer at the end of the chain. Abbott et al. (2005) define a lean supply chain as "*a set of organizations directly linked by upstream and downstream flows of products, services, finances and information that collaboratively work to reduce cost and waste by efficiently and effectively pulling what is needed to meet the needs of the individual customer.*" Moreover, Sezen (2009) define it as "*value stream through customers*." In these definitions, the authors implicitly indicate the effectiveness and efficiency inherent to achieving supply chain goals of enhancing the relationship between all supply chain partners, including end users, and increasing customer satisfaction by delivering the right quantity and quality of the demanded product at the right time.

When implementing lean along the entire supply chain, lean supply chain management is needed to achieve supply chain management tasks and goals. According to Nightingale (2005), lean supply chain management represents "*a new way of thinking about supplier networks*". Implementation of lean principles requires implementation of lean practices, and the latter necessitates a certain set of tools [Dean and Bowen (1994)]. Lean implementation changes traditional supply chain management practices. From literature review it was found that authors agreed upon some changes in supply chain management when lean is implemented. Following are the changes according to the authors:

1. In traditional supply chain management, forecasting is considered the basis in production and delivering products to floor shop to meet the expected customers demand. Historical data as well as current sales rates of a specific product is required to base the production plan on, to manage inventories and to manage logistics. Thus, push system is used to meet the demand in order to let customers find the product on shelves by the time they order it. By lean implementation, push system is no longer an appropriate tool. Push system is in contrast with lean goal of reducing wastes and costs. However, push system is replaced by pull principle which let the customer to pull the product at the time they need it [Sezen (2009)]. Appropriate implementation of pull principle can be done through right amount at the right time lean practice. In addition, an appropriate tool should be employed, such as JIT. JIT tool reduces stocking products in inventory and makes the product to be delivered to customer at the time they request it. Implementation of pull principle in a supply chain gives the opportunity to managers to realize customer needs through identifying value specifications; that all lead to optimizing agile manufacturing, flexibility in production and delivery which in result leads to higher customization. Agile manufacturing refers to the ability of an organization to respond rapidly to changes in customer demand [Verdouw et al. (2011)]. The overall result of pull principle can be seen and noticed in higher customer satisfaction.

2. Supply chain management mainly focuses on delivery and inventory management. When lean implemented across the supply chain, managers must pay more attention on building better relationship among supply chain members through vertical integration. Vertical integration, good relationship, and information sharing among

all members along supply chain results in better management practices in delivering products to customer on the right time [Levy (1997)].

3. Lean management requires managers to analyze value adding activities along supply chain to identify value stream along the supply chain [Womack and Jones (1996a)]. Analyzing activities through supply chain and identifying value adding activities are replacing the old practices of focusing and putting all management efforts on manufacturing and delivery in order to satisfying customers in producing higher quality and on time delivery.

According to Taylor (1999) lean implementation in the supply chain is achieved through six parallel activities. The author argues that implementing lean into the supply chain with sequential activities is not preferable, and that the most appropriate way is to implement lean with parallel activities. The six parallel activities according to Taylor (1999) are:

- Waste identification throughout the supply chain
- Mapping the value stream by identifying value-adding activities and processes
- Improving value-adding activities and eliminating activities that cause waste
- Developing supply chain strategies
- Sharing information and familiarizing managers with all activities throughout the supply chain
- Creating an organizational body composed of supply chain managers to help transform the traditional supply chain into a lean supply chain.

According to Mohan and Sharma (2003), it is very critical to expand lean implementation beyond central manufacturers' internal activities to cover all supply chain activities, in order to optimize the benefit of lean. However, in the course of literature review, it was noticed that researchers tend to focus their research on lean implementation only in main processes or main members of the supply chain; either on central manufacturers' internal activities of manufacturing, production processes, and supply of raw materials, or on final products or management of inventory and the members involved in these activities. All other activities and other members, such as logistics and distribution, design and product development, suppliers, and end customers have not received enough attention in the field of lean implementation research. Focusing on other parties within the supply chain benefits the entire supply chain by cutting costs and increasing customer satisfaction [Behrouzi and Wong (2011)]. Very few authors have posited the argument that competitive advantage could be gained from lean distribution.

Lean implementation across the supply chain is not an easy process to undertake, since there is no general rule of implementing lean throughout the supply chain. That is because lean consists of a set of principles, practices and techniques [Shah and Ward (2007)] which all depend upon each other, and implementing them depends on other economic factors [Nicholas and Soni (2005)].

To sum it up, researchers agree that lean provides many advantages when it is implemented along the supply chain. Moreover, optimized supply chain management, which is called "Lean Supply Chain Management," is the result of implementing lean principles, practices and tools through the supply chain. These advantages include:

1. Lower costs; lean's main objective is to eliminate waste. Waste elimination consists of canceling unnecessary processes and transportation, reducing lead time, and avoiding over production throughout the supply chain; this results in high cost reduction.

2. Lower inventory levels; implementation of JIT and pull system along the supply chain avoids excess in inventory and results in avoiding waste.

3. Higher customer satisfaction; application of value chain analysis throughout the supply chain helps to identify value-adding activities and processes. Identifying such activities improves the quality of production and leads to higher customer satisfaction.

4. Higher efficiency and effectiveness regarding manufacturing and delivery; efficient delivery regarding time, quantity and quality specifications.

5. Higher flexibility; flexibility in terms of delivery and production size or volume as the result of lean tools and techniques implementation.

6. Stronger relationships; through vertical integration along supply chain, suppliers establish better and stronger relationships.

3.3.2 Matching Production and Supply Chain Management

Fisher (1997) proposed a matrix to match the products types and supply chain approaches. This matrix has been proposed as a decision support tool for matching products and supply chain strategies. Fisher (1997) has identified two products categories, which are functional and innovative products. This identification was based on product life cycle, predictability of demand, average margin of error in the demand forecast, contribution margin, stock out rate, and lead time.

Scholars have developed the proposed matrix by Fisher (1997) to include additional product characteristics. Olhager (2003) argued that production volume, needed level of customization, and diversity of raw materials and components must be included in identifying the products types. However, Qi et al. (2009) suggested lead time for production to be added to previous characteristics.

Moreover, Childerhouse et al. (2002) have aligned product life cycle stages with different strategies for managing demand chains. These authors have argued that matching product characteristics with supply chain management benefits the company in many aspects, namely saving time and reducing costs. First of all, the product development time will be reduced as well as delivery lead time. In addition, manufacturing costs will be significantly reduced.

3.4 Conclusion

Additive manufacturing is one of the most disruptive innovations to impact supply chains and supply chain management. Some authors such as Berman (2012) claim that additive manufacturing will revolutionize and replace existing manufacturing technologies, while others like Berger (2013); Lipson and Kurman (2013); Berman (2012) and Sealy (2012) argue that the technology merely enhances some aspects of the production process. However, whether it is evolutionary or revolutionary, additive manufacturing technology is recognized as innovative manufacturing process that will significantly impact supply chains [Skinner (1984) cited in Mellor et al. (2014)].

In this chapter we reviewed the literature on additive manufacturing and supply chain management. Literature emphasizes the core principle of additive manufacturing that materials are added rather than subtracted [Berger (2013)] from a larger raw material object during the manufacturing process, as is the case with conventional manufacturing; therefore, 3D printing is synonymous with the term "additive manufacturing" [Gao et al. (2015); Wong and Hernandez (2012); Campbell et al. (2011); Noorani (2006); Kochan (1997)]. Also, it is agreed that additive manufacturing has successfully disrupted the prototyping industry and gave birth to new fields in the areas of design and manufacturing [Mellor et al. (2014); Lipson and Kurman (2013)]. With the ongoing improvement of 3D printers in terms of accuracy, speed, and quality [Wong and Hernandez (2012)], the potential for future impact is immense [Janssen et al. (2014); Manners-Bell and Lyon (2012)].

Based on this review, we conclude that the supply chain strategies are most likely to be disrupted by 3D printing technology, as the following:

First of all, additive manufacturing impact the responsiveness to market strategy of supply chain management:

3D printing has remarkable impacts on downstream sections of the supply chain, particularly on production and distribution [Wong and Hernandez (2012)]. Nyman and Sarlin (2014), and Lipson and Kurman (2013) argue that additive manufacturing characteristic of offering personalized products hold potential for a shift in priorities of cost and profit management. Thus, 3D printing prioritizes the personalization over mass production. Additionally, customer's involvement in the design and production activities can make the supply chain more agile and flexible to react to changes in the marketplace [Wong and Hernandez (2012)]. In this sense, 3D printing can improve time-to-market, responsiveness, and the degree of agility in the supply chain for small volumes of products, particularly those that require high technological specifications [Lipson and Kurman (2013); Wong and Hernandez (2012); Noorani (2006)].

Secondly, additive manufacturing impacts the efficiency in production strategy of supply chain management:

3D printing has greater resource efficiency compared to most conventional, subtractive production methods [Campbell et al. (2011)]. Authors like Lipson and Kurman (2013); Berman (2012), and Sealy (2012) propose that the success of 3D printing is due to the material savings during production, smart redesign of components, and the ability to utilize recycled materials for the printing process. According to Janssen et al. (2014), 3D printers produce less waste during manufacturing compared with conventional machines, in that way additive manufacturing contributing to a greener, more environmentally sustainable technology. In addition, as additive manufacturing takes production closer to the market; it is able to shorten the supply chain and thus reduces the total cost of the final product [Lipson and Kurman (2013)]. Furthermore, the ability of 3D printing to increase the customization allows to high reduction in overproduction and excess inventory. 3D printing allows for production to happen on demand and at the point of consumption. Consequently, the need to transport physical goods can be replaced by placing manufacturing close to the customer, which would lead to the rationalization of warehousing and logistics [Manners-Bell and Lyon (2012)]. Besides, the movement of physical goods across the globe can be substituted by sending electronic files for the printers [Nyman and Sarlin (2014)]. Digital inventory in the form of 3D model files for the entire product portfolio could replace physical inventory for technically complex products, further reducing the number of SKUs and the total number of stored parts [Lipson and Kurman (2013); Berman (2012)].

The impacts described above illustrate why 3D printing disrupts the supply chain management. Thus, supply chain managers must be aware of these impacts that additive manufacturing technology could have on their organization and accordingly be prepared to react in a flexible and adaptive manner. However, literature lacks to present a framework for managing supply chains in additive manufacturing companies in regards to the implemented supply chain strategies. To fill this gap in literature, this PhD thesis aims at developing a conceptual framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy.

Chapter 4

Understanding the Problem

When thinking about industrial manufacturing, one cannot omit machine tools and factories from manufacturing picture. It became almost impossible to think about manufacturing without mentioning assembly lines, production lines and supply chains or even economies of scale.

Currently, 3D printing is majorly used for prototyping new products which let designers and manufacturers to touch and test the new product with lower costs possible. On the other hand, it assures the functionality of the product before it is reached to the customer. 3D printing for prototyping purposes shortens the development time of the product. Economically, this reduces costs and results in higher profits to the manufacturers. First of all, costs of developing the product is reduced to the minimal, lead time is also reduced which means faster time to reach customers and higher market share is gained. Secondly, cost of defective products, in the development stage, is also reduced.

In this research, the exploratory research strategy is adopted to understand the research problem. Thus, exploratory interviews were the base in having an initial view regarding the field of study. The interviews were carried out with practitioners in several companies in different countries succeeded in implementing additive manufacturing through their supply chains.

4.1 Exploratory Interviews

As discussed previously in chapter 1, the research objective is to develop a framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy. However, after reviewing the literature it was clear that there is no comprehensive toolset developed in the manufacturing field that evaluates the impact of additive manufacturing and determines the best production method that suits the applied supply chain strategy. In this research, a set of exploratory interviews was carried out between January 2016 and April 2016 with practitioners in additive manufacturing industry. We aimed in this research to interview participants from different industries in both United Kingdom and United States of America in order to gather perceptions from people in different environments. The criterion that was followed in selecting the interviewees and the process that was followed in preparing to interview them is mentioned in details in the methodology chapter (Chapter 2).

The purpose of the interviews was not to generalize theory from them, but to collect perceptions from the participants and put them together with findings from the literature. The participants were formally invited to take part in this research. The invitation letter that was sent to them asking them to participate in this research is included in Appendix B.

One of the participants was a consultancy firm specializes in end-to-end supply chain optimization. The others are manufacturers in different industries. The names of participants and companies are disclosed in the following table (Table 4.1).

Following are summarized the background of the interviewed companies. These summaries helped us better understand their work field and how and when they started implementing the additive manufacturing. Full interview questions are illustrated in Appendix A.

4.1.1 ThreeAsfour

ThreeAsfour Company started in 1998 as collaboration between 4 partners with different nationalities; German, Russian, Israeli, and a Palestinian that was born in Beirut. So the company is based on collaboration between the multi-cultural exchanges. ThreeAsfour works in fashion industry mainly creating cloth pieces that are shown in “Fashion Week” in New York twice a year also in a number of art shows each year such as installations in films and performances.

The group split up into three people in 2005 and since then the group became “ThreeAsfour” the previous name was “Asfour” which is the last name of one of the members, after splitting up the company wanted to keep its original name “Asfour” so it became “Three-Asfour”, to show that the three members are open to collaboration with another person. The approach of the members since they come from different backgrounds but living in the same place, New York, is to have different projects dealing with different issues. Some

Interviewee	Company	Job Title	Industry	Country	Years of Experience
Fraser Gleekie	FERCO Ltd	Senior Consultant	Supply-chain Consultancy	United Kingdom	40
Michael Lee	Shapeways	Vendor Operations Manager	Consumable products	USA	9
Gabriel Asfour	ThreeAsfour	Partner	Fashion	USA	18
Annalisa Nicola	xyzbag	CEO & Co-founder	Fashion	Italy	16

Table 4.1: Exploratory Interviews

are human related to nature, connecting geometries from different cultures and different religions together, the company became known as that type of work. In 2011 there was a show called “insalaam inshalom”, happened in Tel-Aviv and a fashion show in New York. Similarly in 2013 the company had another sort at the Jewish museum called Markaba. The shows are kind of the perfect example of the aim of the company, which shows the different kinds of variations. The company now has developed and has a reputation in fashion and technology also in fashion and art. The philosophy of “ThreeAsfour” is summarized in the combination of fashion, technology, art, and the spirituality of the conciseness.

ThreeAsfour has gone through different phases. It used to manufacture in New York and then it got bigger at a certain point because they had a Japanese partner. Then they started manufacturing in china, Korea, Japan and then back to India. Now the company is back to USA. Basically the company opened up before 2008, before the market crash and they were selling internationally; Asia, Russia, Middle East, all over Europe, America and South America. After the crash, the company had pulled back and lowers its distribution to fewer places, mainly in New York and Europe. Recently they are going back into a bigger distribution, slowly.

ThreeAsfour is not a common sort of company. Most people come because they are dedicated to the cause; a lot of them are apprentices that come between three to six months. There are number of assistants as free lancers also a number of tailors are like crafts people. The 3 members that are always in the company are the three who started the company and the rest are either part time paid or apprentices. So the number of the team varies from 3 to 25, usually the average number of people work in the company is 10 members.

4.1.2 XYZBag

XYZbag is an Italian creative brand inspired by the novelty of 3D printing innovative technologies and the revolutionary digital craft manufacturing. It seeks to create new self-design and self-expression fashion 3D bags by revisiting the new tools to personalize a fashion product.

Their goal is to get one style for each customer. XYZBag explore the world of digital production to create a new paradigm of 3D bags manufacturing with the aim to adapt all differences between individuals. XYZBag want to meet customer's specific needs and materialize them into a highly personalized product. XYZBag constantly research new technologies to achieve the maximum of customization.

4.1.3 Shapeways

Shapeways is a marketplace where new ideas come to light. Customers upload designs on the website and Shapeways manufactures them and prints them in various materials. On the other hand, customers can also sell their designs on Shapeways' website. So customers can get their own prototypes for themselves or they can become shop owners and sell parts on Shapeways' website.

Shapeways consider themselves operating in the tech industry; mainly, 3D printing. However, they have ninety factor parts for almost every industry that the one can think of. It can be toy industry, health care, gaming, entertainment and construction industry. Michael Lee (vendor operations manager at Shapeways) clarified that 3D printing is very diverse; it is very useful for anybody to get benefit of in any different type of industries. Thus, people use Shapeways as a manufacturing service for most parts. In addition, when seeing what people sell on Shapeways' website, one can notice that it can be anything from jewelry, to toys, to functional parts.

Shapeways has two factories, one in the Netherlands, which is where Shapeways originated out of, and the other one is in New York. These locations helped them to sell parts all over the world. However, Shapeways do not have stores, and thus no finished goods stocked in inventory. They are considered as click only firm.

4.1.4 FERCO

FERCO specializes in end-to-end supply chain optimization. Within that, FERCO has participating strategists, manufacturing inventory control, warehousing, distribution and customer service expertise that they put together and optimize, either through modeling or through process interventions supply chains widely to manufacturing companies, but not so limited to that.

4.2 Interviews Findings

Based on the interviews, interviewees pointed out that there is a need for a framework for managing supply chains in additive manufacturing companies. The interviewees provided an initial perception in the following areas:

1. The need for a framework for managing supply chains in additive manufacturing companies: based on the interviewees' opinion, a conceptualized framework for managing additive manufacturing supply chains is required, due to the lack of developments in this area. According to Gleekie, a framework is needed to additive manufacturing companies for couple of reasons. Firstly, it helps the traditional companies to evaluate their resources and check whether it is preferable to them to switch partly or totally to additive manufacturing or to stick with their traditional methods of production. Secondly such a framework helps additive manufacturing companies to benchmark themselves to higher accepted standards. Interestingly, the rest of the interviewees agree with Gleekie's opinion regarding the need of the framework.

2. Additive Manufacturing does not work with all products' types: interviewees raised a point through the interviews to be considered in the development of a framework which is additive manufacturing could not be applicable to all types of products. It is the view of interviewees that manufacturing low value products or products with low value components will result in cost inefficiency. In this sense, additive manufacturing is more suitable to high value components.

3. Additive manufacturing increases the supply chain efficiency: interviewees emphasized that using additive manufacturing definitely increase the supply chain efficiency. They claimed that additive manufacturing is able to reduce cost through increasing the product's development, reducing the testing time, reducing lead time, reducing the needed number of suppliers and retailers, decreasing inventory levels, reducing the manufacturing cost and re-work cost, and increasing the responsiveness to changes in demand.

4.3 Inputs for Developing the Framework

1. Adoption of additive manufacturing depends on the product's type. In other words, additive manufacturing is not applicable to all types of products, even though additive manufacturing is applicable to almost all industries. Thus, it is not applicable to all firms in the same industry. Regarding to Asfour, 3D printing is not profitable to be used for all types of dresses, especially the ones that are not personal customized. In addition, it also depends on the used material for the dresses or the shoes. He claims that it is not useful to use 3D printers for all types of materials, since they might cost higher to produce one piece of dress or one pair of shoes, than the traditional manufacturing. In the same sense, Nicola (XYZBags co-founder) agrees that mass production of standardized products is not feasible to be done by additive manufacturing. Nicola suggests using 3D printers for either personal customized products or when the production of the good is too complex to be done by traditional machinery. Moreover, Nicola argues that additive manufacturing is more applicable when it is used for the high valued components rather than low valued ones. Furthermore, Lee from Shapeways sees that additive manufacturing is a better production method to be applied when it is used for personal customization than when it is used for mass customization. Thus, that all leads us to verify the relationships between the two main variable of product type and components value and the production system. All agree on adopting additive manufacturing when having high product complexity and high components value. The opposite is true, as well, which means using traditional manufacturing when producing a product that is characterized by low product complexity and having low components' value.

2. Adoption of additive manufacturing influences the applied supply chain strategy: Interviewees agree that additive manufacturing has an impact on re-shaping the supply chain. Compared to traditional supply chain, when additive manufacturing is in use, the supply chain becomes shorter. Even though all interviewees are operating globally, but it is remarkable that they are dealing with no or a few number of retailers. In addition, the number of suppliers they are dealing with is too low, compared to any other firm in their industry operating with traditional manufacturing system. Thus, the adoption of additive manufacturing as a production method influences the applied supply chain strategy as it increases the speed of delivering the final product to the customer, as well as, it lowers the cost and increases the efficiency of handing in the final product.

Chapter 5

Developing the Framework

5.1 Introduction

This chapter aims to present the development of the theoretical framework investigating the research questions defined in Chapter 1. The development of the framework was based on the results of the literature review and the interviews findings. The chapter is organized as follows: the proposed research framework is presented in the following section explaining how the framework was determined. Then the factors in the framework and the inter-relationships between them are discussed in detail. The last section presents the final view of the theoretical framework.

5.2 The Proposed Research Framework

There is a common acceptance that the researcher must develop a prior view of the general and main factors that are to be studied, and the relationships among them. Voss et al. (2002) suggests such a framework that is known in the form of a conceptual framework, which explains the main variables that are to be studied.

A conceptual model of factors influencing the implementation of additive manufacturing technologies as a production method is presented in Figure 5.1. This conceptual framework has been developed from the literature review and exploratory interviews and it is of a closed loop nature to illustrate the interaction and dependency between the supply chain strategy, manufacturing strategy, and manufacturing method that has to be implemented. Theories that we based our framework on are presented and propositions behind the framework are explained in this section.

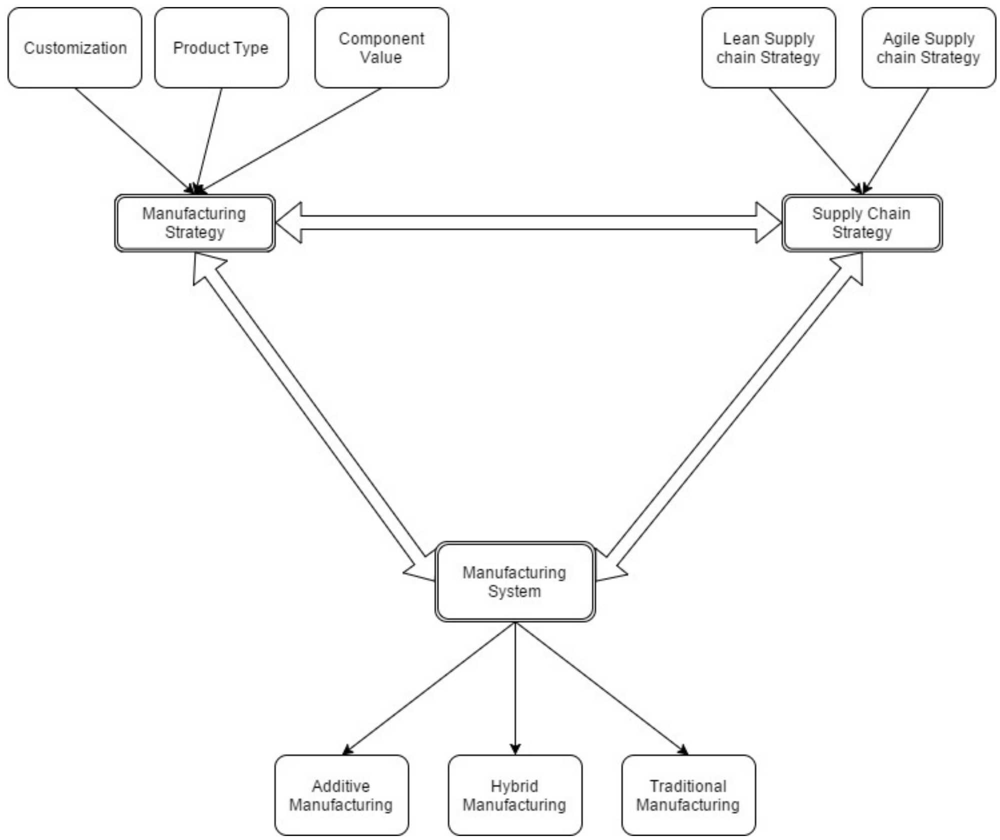

Figure 5.1: Conceptual Framework

5.2.1 Conceptual Framework Basis

The developed conceptual framework is based on the following theories that are discussed in the literature:

Walter et al. (2004) discussed the effect of additive manufacturing on the supply chain. The authors suggest new solutions for supply chain based on both the centralized and decentralized applications of additive manufacturing. In other words, they suggest either implementing additive manufacturing technologies on location or to stick with traditional manufacturing method and outsource the production of some parts through additive manufacturing in locations close to customers. They explained the advantages, as well as, the disadvantages of both centralized and decentralized application of additive manufacturing. According to Walter et al. (2004) implementation of additive manufacturing on location have the advantage of cutting high inventory costs and cutting production lead-times and delivery lead-times, and overcome batch constraints. They addressed these advantages to the use of additive manufacturing since *"it takes too much time and costs too much to produce the required parts on demand using conventional production technologies"*. They also suggest decentralized application of additive manufacturing technologies can be used to eliminate these costs. However, the authors were concerned there will be the problem of having enough demand to warrant additive manufacturing machines on location which let the cost of outsourcing much higher in that case. The authors depended on a case study of an original equipment manufacturer operating in the aircraft industry. From their findings, the authors suggest that to maximize the benefit of additive manufacturing, a hybrid system must be applied but concede that centralized application of additive manufacturing will be the first to be used, due to the significant changes the decentralized manufacture will require. Based on Walter et al. (2004) theory, we proposed additive manufacturing technologies are not suitable in all cases. However, implementation of additive manufacturing will definitely reduce the inventory level in dramatic way.

Besides, we also built our framework on Tuck and Hague (2006) theory which focuses on the cost effective production of customized products. Tuck and Hague (2006) suggest that additive manufacturing increase the customization level, and thus transport costs are reduced and that the burden of part cost will move from skilled labor operating machinery to the technology and material. This conclusion is supported by Ruffo et al. (2006). Tuck and

Hague (2006) also present and explain that additive manufacturing influences supply chains in terms of lean, agile and leagile. The authors claim that additive manufacturing enhances lean supply chains as the only requirements for producing a product are the design CAD file and raw material. In addition, Tuck and Hague (2006) also suggest that because additive manufacturing can be used for economic low volume production, there is no need to hold stock in inventory. Therefore, a fully JIT system is applicable. They conclude: *"Additive manufacturing could offer the first truly leagile supply chain paradigm, providing goods at low cost through the benefits of lean principles with the fast re-configurability and response time required in volatile markets. The production of goods through additive manufacturing could lead to reductions in stock levels, logistics costs, component costs (through reduction in assembled components) and increase the flexibility of production, through the ability to produce products to order in a timely and cost effective fashion."* Based on Tuck and Hague (2006) conclusion we base our framework on the two supply chain strategies; lean and agile. Due to the fact that additive manufacturing technologies are being used for the production of personally customized products, our framework illustrates the necessity to understand the strategy employed by the companies, to integrate additive manufacturing and customization.

5.2.2 Conceptual Framework Factors and the Inter-relationship Between Them

The key elements of a successful supply chain strategy are underlying in understanding the three Vs; Visibility, Variability and Velocity [Walker (2005)]. No matter what the specific competitive priority for the organization is, the goal of the supply chain management is to increase the visibility and velocity while reducing the variability [Narasimhan et al. (2008)]. The three Vs are defined as follows:

- Visibility is the ability to view information in all parts through the supply chain [Narasimhan et al. (2008)]. Increasing visibility in the supply chain benefits not only the suppliers and/or the partners, but also, and most importantly, the customers. That is because when visibility is increased, managers in the supply chain can react to change or eliminate unnecessary activities that waste resources and thus focus on enhancing the performance of activities that add value to the product.
- Velocity is the relative speed of all transactions that have to be done along the supply chain [Narasimhan et al. (2008)]. The higher the speed of transactions, the better; it results in a higher asset turnover for stockholders and quick delivery and response for customers. Velocity is similar to visibility; both are enhanced by supply chain management.
- Variability is the natural tendency of the results of all business activities to fluctuate above and below an average value along supply chain. Variability measures the fluctuation of average values of time to completion, number of defects, daily sales and production yields [Walker (2005)]. In contrary of visibility and velocity, variability decreases with good supply chain management. Supply chain management aims to reduce variability as much as possible.

Supply chain should match the degree of demand uncertainty [Fisher (1997)]. Implemented strategies of supply chain can be either Pull or Push systems [Cachon (2004)]. The push strategy in the supply chain is typically the method used to save customers' waiting time. Ferguson et al. (2002) called this system an "Early-commitment". Adopting this method, companies try to manufacture and deliver products to the shelves before they get orders from customers, in a way to let the final customers find their needs on hand. Thus, customers get the product at the exact time when they need it and can immediately have it.

There are three main types of supply chain strategies within push strategy:

1. Stable strategy which is appropriate for a supply chain which focuses on execution, efficiency and cost performance. With this strategy, only simple connectivity technologies are needed, and real time information is not highly demanded either.

2. Reactive supply chain strategy works well when the supply chain acts to fulfill the demand from trade partner's sales and marketing strategies.

3. Efficient reactive supply chain strategy is the strategy that focuses on efficiency and cost management.

Companies add value to their products in their customers' perspective by saving customer's time of waiting to satisfy their needs. However, push strategy could not be perfect for all types of products and that is because one critical point is missing in this approach. Customization has not been taken into consideration. Innovative and, sometimes, functional products need to be customized according to customers' preferences. Push supply chain does not give the customers the opportunity to customize their goods. However, pull supply chain is the preferable strategy in such cases. Pull supply chain allows the customer to ask first in order to manufacture what he/she wants, and then the product is delivered to them

[Iyer and Bergen (1997)]. Applying this strategy, however, makes customers wait for some time to get what they ask for.

3D printing implementation in a supply chain provides the ability to enhance supply chain efficiency and effectiveness in terms of cost reduction, and time saving [Tuck and Hague (2006)].

Even "Efficiency" and "Productivity" terms are sometimes used interchangeably, as in Sengupta (1995) or in Cooper et al. (2000). However, in this research we differentiate the definition of efficiency from productivity. Based on our understanding of the literature, "Productivity" is defined as the ratio between outputs and inputs. While, "Efficiency" is defined as the proximity of a focal organization to its benchmark within its cluster or industry depending on:

1. The minimum cost of production in manufacturing and delivering a final product to a final individual consumer, and
2. The velocity of the supply chain when transforming inputs into outputs and delivering the final product to its final customer. The manufacturing velocity is defined as the ratio of the value added to the total throughout time.

In manufacturing, managers should think about the two main cost drivers: direct and indirect costs, which are summarized in material, labor and overhead. At the same time, they should think about producing goods that aim to satisfy customers' needs. In that sense, an ideal product is one that consumes the least direct and indirect costs of material, labor and manufacturing overhead and, at the same time, satisfies customers' needs and wants [Sun (2011)].

Sun (2011) argues that in order to create a firm that uses the minimum possible inputs to produce the maximum possible value for customers, efficiency tool is needed. In his opinion, lean production is that efficiency tool.

At the same time, when looking more in-depth at lean principles, we ratiocinate that efficiency is the main root of lean. The following are some examples of lean principles:

As in Value Specification, in order to be efficient in delivering the right product that satisfies customers' needs, all non-value adding activities have to be eliminated from the process [Gupta and Wilemon (1990)]. Eliminating these unnecessary steps will accelerate the speed of production process with using fewer resources, thus improving both effectiveness and efficiency [Iansiti (1995b)]. In addition, Value Stream helps to visualize the sequence of activities in the whole process, thus making it easier to identify and eliminate non-value adding activities. This ensures increased efficiency.

Moreover, many authors, such as Sun (2011); Iansiti (1995a,b); Cordero (1991); Gupta and Wilemon (1990); Rosenau Jr (1988) and Gold (1987), have agreed on the basic idea of increasing and improving efficiency through lean management, which refers to the elimination of non-value adding activities. Therefore, working on purely value adding activities in less possible time, and with less resources used, improves and increases efficiency.

Besides that, and based on what has been discussed earlier, we conclude that lean production is recognized as an efficiency tool, because it focuses on producing outputs with the minimal cost by using the minimum resources possible to deliver products that have the maximum possible value for customers. In consequence, lean production creates firms seeking to add value to their products in all possible ways [Sun (2011)]; which means lean must not be for indoor use only. It must be widespread through the entire process, starting from getting raw materials and continuing until the product is in customers' hands. That means lean should go beyond production to reach the entire organization, including the supply chain. In that sense, firms that go beyond production in implementing lean thinking can be termed Lean Corporations, which is more accurate concept to be used [Sun (2011)]. Moreover, their activities could be acknowledged as a lean value chain.

In a lean value chain, manufacturers identify each activity to check whether it adds value or it is unnecessary and can be removed. Through lean techniques, managers encounter dispensable activities that create costs and eliminate them. For instance, the JIT technique permits manufacturers to avoid superfluous costs of shipping, receiving, inspection and rework [Sun (2011)].

What is more, lean value chain elevates manufacturers' flexibility in pursuing the market's changes due to demand uncertainty and changing customers' tastes and preferences. JIT lean tool allows firms to change outputs more quickly in response to demand changes, compared to other manufacturing methods.

Lean management is the main bridge that links 3D printing with supply chain. Lean management serves as a great linkage that connects both topics by focusing on the efficiency of production. Companies' success or failure depends on getting the right product at the right time, and at the right price to customers [Nyman and Sarlin (2014)]. As was clearly visible when reviewing the literature about lean management and additive manufacturing, they share two main characteristics:

1. Eagerness to increase efficiency. Many authors, such as Sezen (2009), explained lean as a method used to reduce costs, as well as, to increase efficiency and quality. Moreover, Shah and Ward (2007) defined it as a management philosophy. Their definition was perfectly positioned on clear identification and elimination of wastes not only

within, but over and above the production process to reach the whole manufacture's product value chain. Nevertheless, from all the reviewed literature, we concluded that all researchers agreed upon one main opinion in defining the objective of lean concepts. This objective is summarized in cost reduction and production efficiency improvement. In addition, researchers and authors in the additive manufacturing field agreed that additive manufacturing methods are able to cut down manufacturing costs and save time. Based on literature review, Wong and Hernandez (2012) proved that 3D printing is able to depreciate costs and save time. This has been cited by many other researchers such as: Noorani (2006); Herbert et al. (2005); Cooper (2001) and Ashley (1991). Cost reduction and time saving form the basis of doing things right in terms of what is known as "efficiency."

2. Better responsiveness to market changes in both demand and supply. Globalization and openness to the entire world's markets create rapid changes in natural conditions, technological progress, transport improvements, customers' income, customers' tastes and preferences, and future expectations of both customers and suppliers. In this sense, lean management uses practices and techniques that make the manufacturing process very responsive to these changes [Mohanty et al. (2007); Nightingale (2005)]. "Right amount at the right time" practice, "Pull System" tool and "JIT" tool are methods that technically enhance responsiveness to changes in the market. These methods are based on having low amount of raw materials inventory, as well as, work-in-progress and finished goods. Low inventory levels facilitate adapting to new changes in the market easily with minimal inventory costs. Moreover, additive manufacturing is based on producing small production runs pulled from customers'

needs, in contrast with traditional manufacturing [Campbell et al. (2011)]. This feature in additive manufacturing gives it the advantage to be able to adapt the market changes quickly by not holding high levels of inventory on hand.

Based on our previous discussion, we concluded that additive manufacturing has features that make it being able to work well with lean strategy in the supply chain, where it fits perfectly under the following principles:

1. Value Specification: Specifying value, from the end customers' view, involves trying to find out what customers desire from the product [Womack and Jones (1996a)]. Thus, in order to specify the value, a lean practice of realizing customers' needs has to be applied. In that sense, a lean tool has to be put into action in order to translate customers' needs into tangible product. Here comes additive manufacturing to play a role in transforming the specified value of customers' needs into real products [Nyman and Sarlin (2014); Wong and Hernandez (2012)] because 3D printing is a very flexible production tool. Products can be produced to meet customer's exact requirements for the product. Materials used, shapes, sizes and any other features can be adjusted on the spot to meet what the customer requires, with minimal costs of production compared to the traditional methods.

2. Value Stream Identifying: Organizations must identify value stream of products through every step of the supply chain, in order to enhance the value added activities and eliminate the non-value adding ones from the process [Womack and Jones (1996b,a); Womack et al. (1991)]. When companies identify the value stream in

their supply chain, they will be able to reduce costs which are synonymous with waste [Shah and Ward (2007); Ohno (1988)]. Additionally, 3D printing has proven it effectiveness in reducing costs to the minimum by reducing waste from production [Berman (2012); Sealy (2012)]. On that account, 3D printing could serve as an effective lean tool to produce and deliver products that hold the maximum value to customers with the minimum wastes and costs.

3. Pull Principle: Womack and Jones (1996a) explained the pull principle as "production should be done only when customers demand the product." That consecutively explains the Right Amount at the Right Time practice in lean management that calls to produce the needed quantity only when it is needed [Shah and Ward (2007)] because excess in production leads to higher costs in inventory. Based on these principles and practices, we can presume that 3D printing perfectly performs the needed duties to be a proper tool in lean management. Depending on the fact that 3D printers can be adjusted to produce any product required by customers, at the time it is demanded, without the need to change production process or change or retrain personnel as is often required with traditional machinery. In addition, it allows for product differentiation and customization, because of its ability to flexibly produce any size or shape required [Sealy (2012)].

With 3D printing, both customers and businesses can benefit from designing and personally customizing their final products. This new technological manufacturing method makes it possible to modify the functionality of a product, from one side, and physically from the other, in order to fit the needs of the customer, in a way that was not available before. This, of course, has affected the supply chain. Businesses should keep pace with these changes and keep modifying their supply chain to fit the new requirements of the market.

Literature has showed that supply chain is not fixed for all types of products or all types of businesses. Supply chain differs from one production line to another to match the uncertainties in both demand and supply [Lee (2002)]. Some businesses are looking to shorten the supply chain by eliminating some activities, while others are interesting in having a responsive one and others like to hedge the risks stemming from either supply or demand uncertainties.

When additive manufacturing is applied, the supply chain takes a different shape. This is because traditional manufacturing methods (repetitive processes) depend mainly on mass production, where products are standardized and are made in batches and stocked in inventories and have to be distributed to wholesalers and retailers in order to arrive to final customers. With additive manufacturing, responsiveness and the flexibility of both customization and delivery is more easily achieved while eliminating all non-value adding activities such as inventory and distribution.

Lee (2002) argued that agile supply chain is a strategy that makes the supply chain capable of quickly responding to changes in the market and in customer preferences. Nevertheless, to diversify the product's functionality to perfectly match customers' needs . In the context of 3D printing, agile supply chain is the strategy that is qualified to deliver a perfectly customized product to customers, with the most efficient mode of delivery, at a minimized cost; this is achieved by cutting all unnecessary activities that add no value to the product. In addition, agile supply chain is capable of responding quickly to any changes in customers' preferences while risks are minimized.

Thus, agile supply chain is combining the characteristics of efficiency, responsiveness, risk- hedging and customization. Likewise, additive manufacturing is based on the same characteristics of responding to customers' requirements and perfectly customizing products to fit their needs, cutting costs by reducing waste and eliminating non-value adding activities. In this fashion, implementing 3D printing in focal organizations of the supply chain requires the supply chain to take the shape of an agile supply chain.

Previous studies found that technology has the ability to change and re-shape businesses as well as implemented strategies [de Jong and de Bruijn (2014)]. It is considered to be an internal strength point of the business SWOT analysis when businesses know how to properly employ these technologies to bring opportunities to their side. However, based on the held interviews, interviewees such as Asfour from ThreeAsfour and Gleekie from FERCO LTD, claim that 3D printing cannot be implemented in businesses to produce all types of products and/or all product components. They suggest that additive manufacturing is more feasible when it is used with high valued components or for complex products.

3D printing has been applied to low-volume production, and the output can be of higher rank than traditional manufactured output; that is 3D printed products (especially consumer goods and health aids) are characterized by being higher quality, lighter, more customizable, stronger, already assembled and having lower cost [Wong and Hernandez (2012); Ashley (1991)] than items produced by traditional manufacturing methods, due to the 3D printer's ability to precisely control the quantity of material used to make the product.

Nyman and Sarlin (2014) argued that additive manufacturing is powerful and makes manufacturing processes easier and customization less expensive for customers. In traditional manufacturing methods, managers forecast future demand. Based on that forecast, a sufficient amount of outputs, that is in accordance with management's forecast, is produced and stocked in inventory [Lee and Billington (1992)]. However, when 3D printing is implemented in a manufacturing method, real-time demand manufacturing is set in motion. This feature in additive manufacturing results in shorter lead time from order to delivery and it gives the supply chain more flexibility in responding to changes in product demand. 3D printing allows manufacturing to become more agile, more flexible, more able to respond rapidly to shifts in market demand, and more capable of introducing new products quickly and inexpensively. As a result, both manufacturing and consumer behavior are affected. It also affects the supply chain; it accelerates the shift from "Push Supply Chains" to "Pull Supply Chains." This is because 3D printing makes it possible to store products, parts and components on computer files, with no need to have them physically in warehouses. Each component can be pulled only at the time it is needed. Contrast this with the JIT lean management tool that let managers keep some inventory on hand in warehouses to avoid the risk of shortage [Conerly (2014)]. Thus, a very low volume of raw materials and work-in-progress will be in inventory, and no finished goods will be stored in inventory [Conerly (2014)]. As a result, overall supply chain management costs will be lower than those of traditional manufacturing supply chains, because of the reduced inventory costs and the reduced waste of outdated products. However, the production cost per one unit in traditional manufacturing methods, where production runs for huge batches, is much lower than in additive manufacturing [Conerly (2014)]. Conversely, the opposite is true for small production runs; cost per unit in additive manufacturing for small batches is relatively low compared to that in traditional manufacturing. Figure 5.2 is a hypothetical graph that explains the difference between production cost per unit when using a 3D printing method of manufacturing and a traditional manufacturing method, with reference to number of units produced in each method.

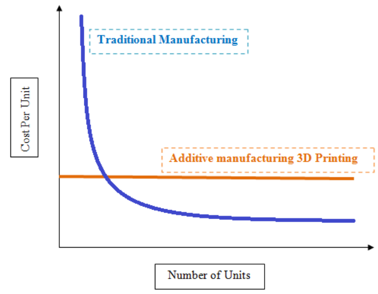

Figure 5.2: Hypothetical Cost per Unit in Both 3D Printing and Traditional Methods of Production. Source: Conerly (2014)

Additive manufacturing has the ability to personalize products to the customer's preferences. Additive manufacturing gives manufacturers the ability to be flexible in creating products based on each customer's requirements [Sealy (2012); Wong and Hernandez (2012); Gibson et al. (2010)]. Thus, in some industries, this manufacturing method delivers a perfectly customized product to customers, which, in turn, is reflected with higher customer satisfaction [Wong and Hernandez (2012); Noorani (2006)].

In that sense, with 3D printing, both, final customers and businesses can benefit from designing and perfectly customizing or even personalizing their final product; as the case in some companies such as Shapeways and XYZBags. This new technological manufacturing method makes it possible to modify the functionality of products, on one hand, and the physical appearance of products, on the other, in order to fit the needs of the customer in a way that was not available before. This, of course, has affected supply chain management. Businesses should keep pace with these changes and continue to modify their supply chain in a way that fits the new requirements in the market.

As a conclusion, cost reduction in manufacturing mixed with fast responsiveness, flexibility and customization make it easier for focal organizations to gain a competitive advantage in the market. That happens due to the ability to reduce prices for final customers, customizing the product to the final customer's preferences and expediting the delivery of products. As a result, customer satisfaction increases. Thus, as a result of increasing agility, flexibility, responsiveness, cost-efficiency, customization and customer satisfaction, and the overall profitability of the entity will be increased.

5.3 Final View of Theoretical Framework

Global competitiveness increases the complexity in all activities and processes in any business corporation. Business firms must clearly understand and know how to apply strategies in such a competitive market. Supply chain management is one the most effected approaches by this global competitiveness. Mabert and Venkataramanan (1998) argued that managing all the activities in the supply chain has become more challenging. That explains why practitioners and researchers paid more attention to this field. In the same manner, firms have to strategically manage their supply chain in harmony with the type of the products they produce in order to be effective and thus achieve higher financial and operational performance [Christopher and Towill (2000); Fisher (1997)].

Literature suggests two main strategies for the supply chain: efficiency in production strategy, which is also called lean strategy, and responsiveness to market which is also known as agile strategy [Bruce et al. (2004); Yusuf et al. (2004); Christopher (2000); Christopher and Towill (2000); Fisher (1997)]. Moreover, researchers in supply chain strategies are highly interested in studying the product's type. Based on Fisher (1997) framework that suggests having an alignment between supply chain strategy and the type of product manufactured, we proposed our theoretical framework. However, Fisher's framework proposes the two supply chain strategies and attached each of them to one type of products; in our framework, product's type depends on the complexity of the product. Product complexity is defined by the intricacy of producing one unit of the product. Novak and Eppinger (2001) explicate that product complexity depends on the production required knowledge, the difficulty to learn how to produce the product and the required time to produce one unit of the product. The authors depended in their definition on three main elements of product complexity. The first element is the number of the required product components to specify and produce. While the second element is the extent of interactions to manage between these components. Finally, the third element according to Novak and Eppinger (2001) is the degree of product novelty. Schoenherr et al. (2010) reinforce Novak and Eppinger (2001) central idea as they explain product complexity as it is characterized by the level of the product's customizability and novelty and by the variability of the product's components and the level of integration and interrelation of theses components.

Figure 5.3 presents the theoretical framework which is basically based on Fisher (1997) framework. It suggests two fundamental supply chain strategies as in Fisher's: 1) efficiency in production strategy, 2) and responsiveness to market strategy.

Efficiency in production strategy is characterized by end-to-end optimization, short-time to market and continuous production. Efficiency strategy is referred to lean production which means eliminating all kind of wastes to reduce the cost to the minimum [Womack et al. (1991)]. Lean production strategy requires a stable product demand which makes it easier to reduce wastes through optimizing end-to-end activities, such as the level of work-in-process and finished goods inventory. In addition, the optimization of the activities creates a stable and continuous production schedule which leads to shorten the lead time, as well. Thus, the main goal of lean production is to reduce cost and increase efficiency by eliminating wastes [Womack and Jones (1996b)]. Along these lines, in a stable product demand environment, push supply chain strategy best suits the efficiency in production strategy. On the other hand, responsiveness to market strategy is characterized by the agility, flexibility and customization. It provides the business firm with competitive advantage in a rapidly changing environment through offering unique customized features to customers. Rapid changes in customers' tastes and requirements have let the supply

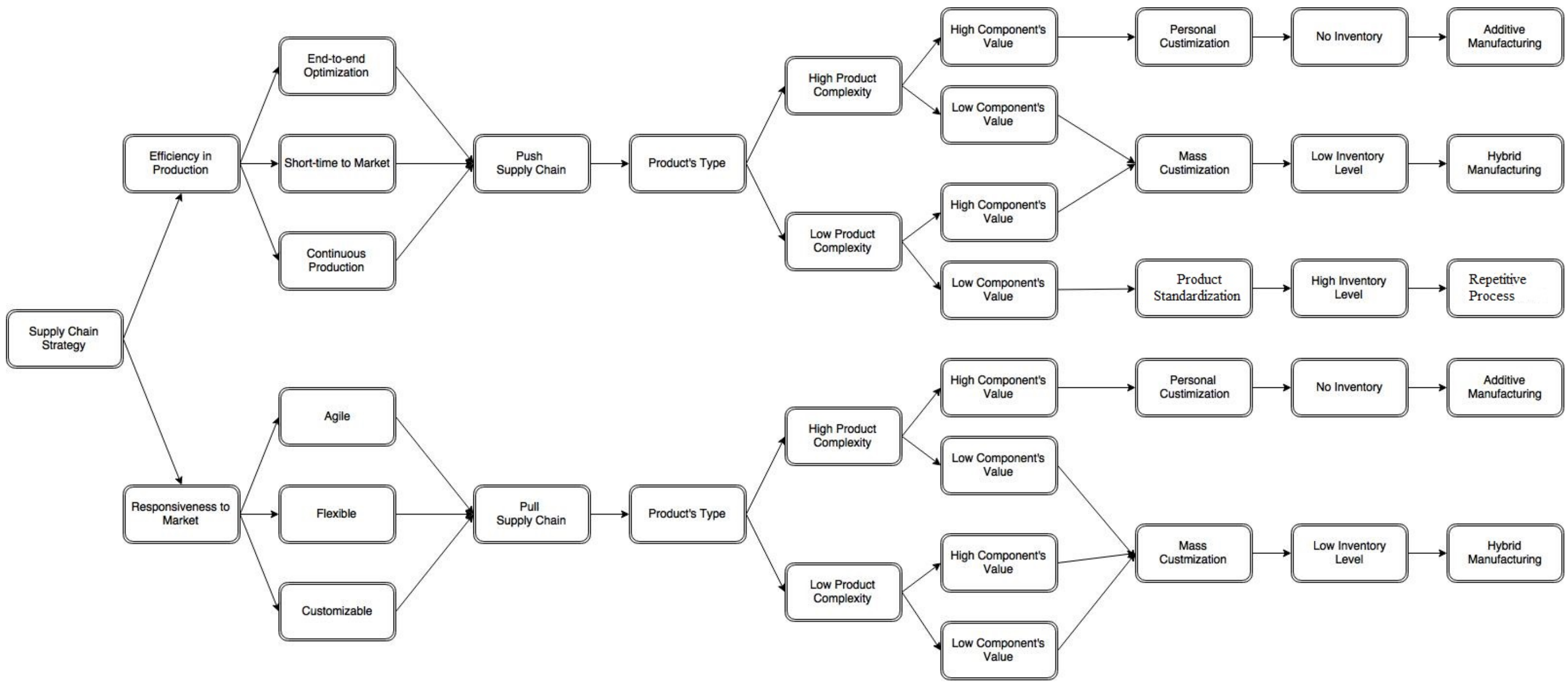

Figure 5.3: Theoretical Framework

chain to respond and act faster in providing the required goods. Agility has got much attention in the literature body. Researchers, such as Kidd (1995) have proposed agility as a tool to gain competitive advantage in a dynamic environment. Others have explained it as “the successful exploration of competitive base” [Yusuf et al. (1999)]. Agility means fast responsiveness and flexibility in responding to customers’ requirements. It requires innovation pro-activity and it offers better products’ quality. Thus, agility is not limited to a single business firm, but it is expanded to cover all the supply chain [Christopher (2000)]. While Christopher (2000) argues that agile supply chain reduces the lead time, Lee (2004) suggests that agile supply chain has the ability to respond faster and easily to changes in a very short time. Thus, this discussion leads business firms to adopt pull supply chain strategy when the market environment is changing rapidly. Due to the fact that pull strategy is able to respond faster to customers’ requirements, as well as, it is able to customize the commodity to their preferences. In general, researchers agreed that firms producing functional products better fit with efficiency in production strategy and thus need push supply chain, while companies produce innovative products need a responsiveness to market strategy and pull supply chain works better to them.

When the manufacturer decides which strategy to use, the first step is to check the product’s type. Products can be classified by their complexity; either high complexity products or products with low complexity. The main element that affects the selection of supply chain strategy is the product’s type [Huang et al. (2002)]. As mentioned before the product complexity, on one hand, depends on the required level of customization and the novelty of the product and on the other hand, it depends on the variability of the product’s components and the level of integration and interrelation of theses components [Novak and

Eppinger (2001); Schoenherr et al. (2010)]. After clarifying the product's type, the components value should be recognized. The value of the product's components can be either with high value or low value, as well. Products that are combined by high valued components are the ones that better to be customized. In this case, when the components' value is high and the product's type is characterized by high product complexity, personal customization better suits the production method. Thus, dramatically low or even no inventory is required for final goods. However, customization rises the production cost in the tradition manufacturing method. So, additive manufacturing method would be the appropriate method to be used in such cases. In contrary, when the product is characterized by low product complexity and it is produced by low components' value, mass production and/or mass customization are the best production strategies that can be used in this case. As a result, high inventory levels of finished goods will be on hand. Moreover, it is more feasible to use the traditional manufacturing method with low investment in additive manufacturing for prototyping purposes or for the production of some components, only.

Chapter 6

Empirical Analysis "Evaluating the Framework"

6.1 Survey Analysis

6.1.1 Introduction

The evaluation process of the framework is presented in this chapter. The first step in evaluating the framework is a survey questionnaire that is focused on additive manufacturing firms in different geographical areas and in different industries with different manufacture sizes. The reason of having participants from different backgrounds is to generalize the theoretical framework to different types of industries. Appendix G illustrates how the survey questions reconcile with the developed theoretical framework. A detailed description on how we designed the survey and the process we followed to run this survey is mentioned in the methodology chapter (see Chapter 2).

Participants were formally invited to take part in the survey questionnaire by e-mail, which also include relevant information regarding its purpose and general guidelines. A copy of the invitation email is presented in Appendix D.

It is worth mentioning that emails were sent to supply chain managers in the invited firms and in some cases they were sent to manufacturing managers when the supply chain managers' contact information were not available.

It is also worth mentioning that the data collection was done over a period of one month, starting from March 10^{th}, 2017 until April 10^{th}, 2017. During this period, 72 participants filled the survey. By this number of respondents we achieved 72% response rate. Nine participants do not use additive manufacturing in manufacturing process, but they use it in prototyping and/or in producing only some parts of the final product.

The following section presents the survey analysis which is mainly based on qualitative data analysis.

6.1.2 Participants' Profile

Participants in this survey are varying in many aspects, such as industrial background, company's size, geographical location and annual sales, among others. This variety in participants' profiles helps in generalizing the outcome of the survey. Next, detailed information is provided regarding participants' profiles.

Industries

Participants in the survey questionnaire have different industrial backgrounds. The first question of the survey helped us in identifying the participants' industry background. Table 6.1 shows that there are 17 different industries participated in this survey questionnaire.

This variety in industries helps in generalizing the final outcome and not keeping it limited to specific number of industries.

Company's size

The survey questionnaire was not specified to one company's size. The survey was intentionally sent to different firms sizes. Figure 6.1 shows the different sizes of companies based number of employees in the company. 43% of the participants have less than 50 employees and are considered as small companies. While almost 29% are large companies since they have more than 100 employees. The rest are medium sized companies.

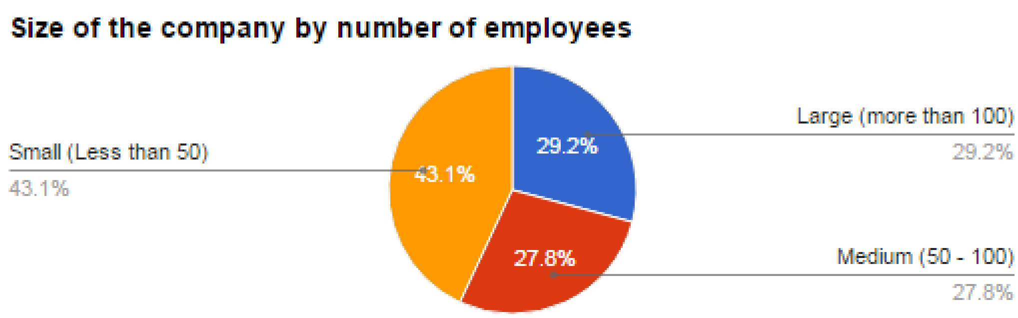

Figure 6.1: Size of the Company by Number of Employees

Industry in Which the Company’s Operates	Number of Responses
Fashion Industry	13
Machine Industry	11
Technology Industry	8
Manufacturing Industry	7
Accessories / Jewelry	5
Consumable Goods / Personalized 3D Printed Products	5
Food Industry	5
Aerospace Industry	4
Chemical Industry	4
Automotive Industry	2
Construction Industry	2
3D Printing Products	1
Biomedical Device Industry	1
Consulting / Systems Integration	1
Health Care Production Equipment	1
Mechanical or Industrial Engineering	1
Telecommunication Industry	1
Total:	72

Table 6.1: Participant’s Industrial Background

Years of operating

It is worth mentioning that participants in this survey questionnaire have a wide range of experience in operations, as it is shown in Figure 6.2. Years of experience range from less than a year to over 20 years. However, the majority of the respondents have a very good experience in the market that exceeds one year time period. This experience in the market gives validity to the outcome of this analysis.

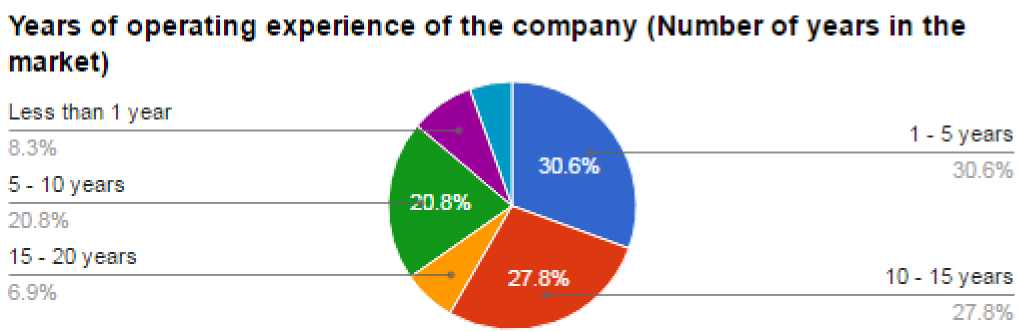

Figure 6.2: Years of Operating Experience of the Company

Annual sales

Participants are not only diverse in their size and years of operating, but also in their annual sales. From Figure 6.3 it is noticeable that participants vary in their annual sales from less than a million US Dollars to over 100 US Dollars.

This variety in annual sales helps in generalizing the outcome of this analysis to all firms in the additive manufacturing market.

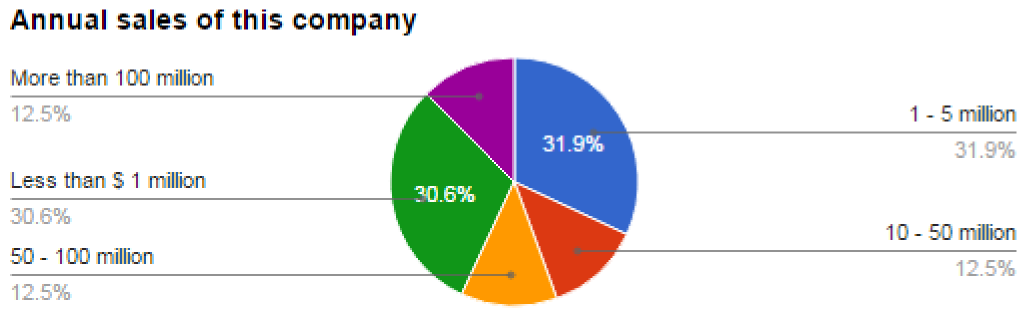

Figure 6.3: Annual Sales of the Company

Geographical scope of operating

In this survey we tried to reach companies from all over the world. Since additive manufacturing is applicable in almost all the world (even though it is applied with some constraints in some countries). Answers from participants show that this technology is widely used all over the world except in Africa, where only just one participant is operating in Africa. Figure 6.4 shows that most of the participants are located in USA, Europe and internationally.

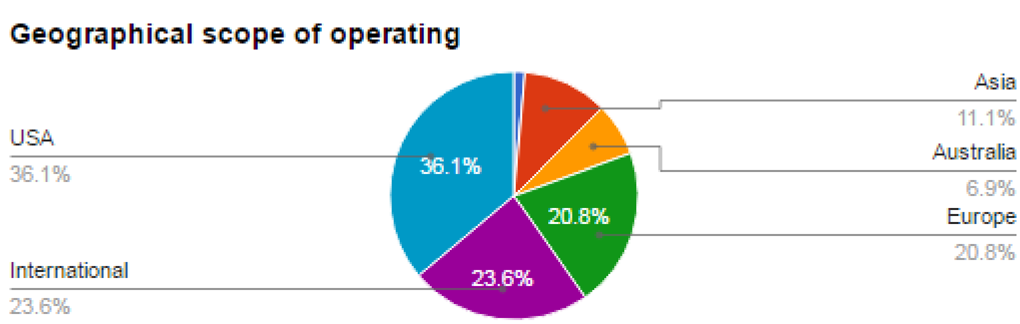

Figure 6.4: Geographical Scope of Operating

Customers

It is very important to notice here that even though manufacturers are located in different countries but as to Figure 6.5 two third of them are dealing with global markets. While, only one third of the participants are selling their products to local customers.

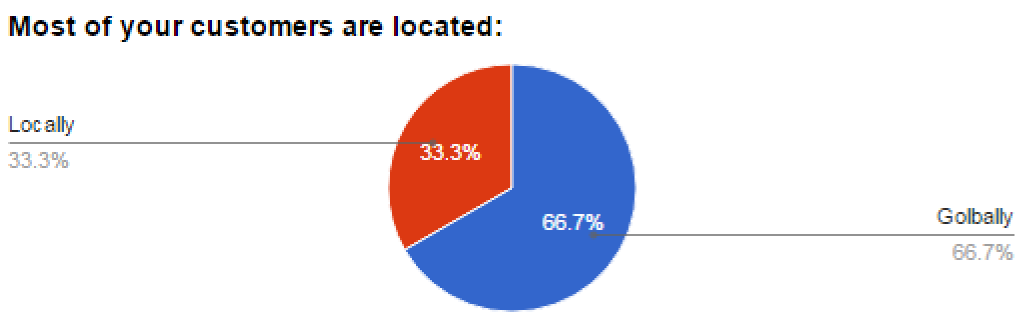

Figure 6.5: Customers Locations

6.1.3 Major Findings

The overall objective of this survey questionnaire is to evaluate the framework. Thus, the survey was created on the basis that each question in the survey is employed to evaluate the solution. On the other hand, the solution was the final product out of the research questions.

Thus, in order to evaluate the framework, we first checked the ability of survey questions to evaluate the research questions.

The following discussion is based on evaluating the following research sub-questions:

Research sub-question #1: "Does additive manufacturing fits both efficiency in production and responsiveness to market supply chain strategies?"

Research sub-question #2: "How can additive manufacturing change or re-shape supply chain management?"

In our proposed theoretical framework, we agreed that additive manufacturing fits both strategies of the supply chain management. It was remarkable that almost 97% of the participants agreed with the idea that additive manufacturing increase the efficiency in production. In addition, over 98% of them also agreed that additive manufacturing increase the agility of production. These large percentages give positive evaluation that our theoretical framework is on the right path when proposing that additive manufacturing fits supply chain strategies of efficiency in production and responsiveness to market.

Also, it is notable when checking the time to market; even though companies that apply additive manufacturing are located in almost all over the world, as well as, their customers; it was found that total lead time for almost 56% of the participants is less than 7 days and over 58% of the total respondents have manufacturing lead time less than a day; with an average of 4.42 on 5-point Likert scale on time delivery. In a comparison with literature, these ratios reflect normal lead time when additive manufacturing is applied. For example, Nyman and Sarlin (2014); Manners-Bell and Lyon (2012); Campbell et al. (2011) and Walter et al. (2004) assured that additive manufacturing dramatically reduce the lead time and they explained that by its ability to enhance the time-to-market, responsiveness, and the degree of agility in the supply chain. In addition, Berman (2012) states that 3D printers are able to produce the final product in just few hours which, in contrast, it needs days to be produced and assembled in traditional manufacturing system. Moreover, in a study that was held by Mohr and Khan (2015) and presented in Hamburg International Conference of Logistics, exemplify a case of a manufacturer that was able to reduce total lead time to as low as five days when additive manufacturing was applied. Due the globalized market, 85.5% of the participants store the final product in close distribution points to their customers in order to shorten the lead time and increase their on-time delivery. Moreover, almost 85% of the participants have the ability to reduce their supply chain length because of their ability to sell the final product directly to final consumers. Even though, those who depend on suppliers to sell their final product, it is noticeable that almost 55% of them deal with less than 20 retailers. Furthermore, 93% agreed that the implementation of additive manufacturing reduces the needed number of suppliers. That was approved by respondents since 61% of them deal with less than 20 suppliers. This also shows that supply chain has been re-shaped due to the use of additive manufacturing.

Likewise, respondents agreed that additive manufacturing does increase the cost efficiency. 97% of respondents totally agreed that it increases the efficiency (lowers the cost) of production while only 3% answered "maybe", but no one disagreed with its efficiency. 100% agreement on additive manufacturing ability to reduce cost is not novel. Walter et al. (2004) present a case from the aerospace industry to show how additive manufacturing was able to reduce the manufacturing and logistics cost, as well its ability to increase total efficiency of the supply chain. Additionally, Hopkinson et al. (2006) emphasize that 3D printing is more cost efficient in comparison to traditional manufacturing system. On the other hand, 68% of participants showed that their total annual waste in production process does not exceed 1%. However, it was noticeable that 4% claimed that their annual waste is more that 5%. When checking the data it was found that these participants do not use additive manufacturing in their production process, but only in prototyping or only to produce some parts of their final product. This comparison shows the ability of additive manufacturing to increase the efficiency of the production process. Besides, it was clear that additive manufacturing lowers the total cost of manufacturing which includes labor, maintenance and re-work cost. The 5-point Likert scale shows the firms agree that their total cost is reduced by the use of additive manufacturing technologies. As well, they agree that additive manufacturing lowers the inventory cost, as it is shown in Figure 6.6; where "1" indicates a very low cost and "5" indicates a very high cost.

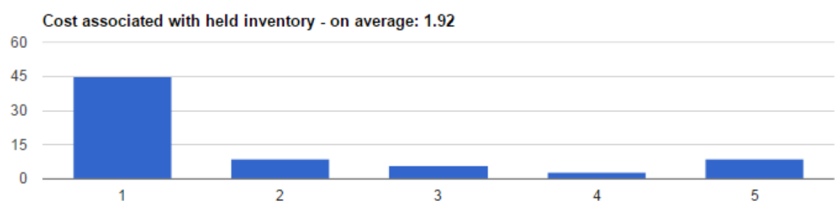

Figure 6.6: Cost Associated with Held Inventory

Additionally, responsiveness to market strategy in our theoretical framework is based on the flexibility of production to accommodate demand variations. The 5-point Likert scale, that asks if participants are able to respond to demand variations, shows that companies are able to accommodate demand variations on an average of 4.42. That means additive manufacturing helps in making firms more flexible to any changes in demand.

Moreover, customization becomes easier with the use of additive manufacturing technologies. Almost 60% of respondents use personal customization basis of manufacturing and more than 30% of them use both strategies of personal and mass customization, together. These large percentages are not easy to be reached in traditional manufacturing. Additionally, the rest of the respondents (10%) are producing based on the mass customization strategy, only. Customization in production helps companies to better forecast future customer expectations where almost 99% of them do follow-up future customer expectations. In addition, on average of 4.42 on 5-point Likert scale, firms are able to respond to demand variations. These factors facilitate the just-in-time (JIT) inventory system. We noticed that 75% of the participants are using the JIT inventory system which allows them to be more flexible to changes in future demand and to be more efficient in personalizing the final product to the customer's demand. Also, almost 54% of the participants do not keep more that 10% of needed raw material in inventory.

It is remarkable to the previous discussion that 73.6% of the respondents follow the pull production system. This system allows firms to be more efficient in personalizing the product and to be more capable in reducing the inventory's cost. This, on one hand, supports our proposed framework which states that additive manufacturing does work with the pull supply chain strategy. On the other hand, it shows that additive manufacturing is able to reshape supply chains due to the changes in demand.

Additionally, the use of additive manufacturing leads to more customer satisfaction. The previous discussion concludes that customers are more satisfied when purchase products that are personally customized to their demand. Moreover, it is clear that additive manufacturing companies can grab more customer satisfaction than traditional manufacturing ones. The 5-point Likert scale shows that customers rarely complain on additive manufactured products. Nevertheless, customers purchase additive manufactured products from these companies, more frequently. This is also a good indicator to more customers' satisfaction.

6.1.4 Conclusion

Our theoretical framework proposes that additive manufacturing fits both efficiency in production and responsiveness to market strategies. Then, it proposes that push supply chain best fits the efficiency in production strategy and pull supply chain fits the responsiveness to market strategy. Our evaluation concluded that companies which are based on additive manufacturing applies both pull and push supply chains. However, it was clear that most of the respondents, 73.6% of them, apply pull supply chain. But, at the same time, 18% of the respondents apply the hybrid strategy; they apply both pull and push strategies.

Survey participants were divided in their opinions about the possibility of applying additive manufacturing to all types of products. We noticed that 40% of them assured that additive manufacturing does not work with all types of products, but only with complex or high valued ones. While only 18% assured its possibility to fit the variety of product's types. But 42% were not sure if it works for all types of products or not. By considering only the definite answers and taking out the not assured ones, we end up that two third agree that it does not fit all types of products, but only the complex and/or high valued goods. This result conforms to our proposed theoretical framework. When analyzing more deeply this variety of responses, we can think about the wide range of industries that participated in this survey. That means, each respondent answered this question based on the type of product they produce. The data confirms that manufacturers that produce complex products (manufacturers in aerospace, chemical, construction, machine, and manufacturing industries) confirm that additive manufacturing is not applicable to all types of products. While manufacturers in fashion and accessory industries which produce less complex products agreed that additive manufacturing is applicable to all types of industries.

Analyzing the collected data through filtering processes on Microsoft Excel, we found the followings (Appendix G illustrates these findings):

1. 45.6% of the respondents agree that additive manufacturing technologies are not feasible to all types of products and components value, use JIT inventory method, and apply additive manufacturing to personalize products.

   (a) 35.6% of them apply pull supply chain, and

   (b) 10% apply push supply chain.

2. 54.4% of the respondents agree that additive manufacturing technologies is applicable to all types of products and/or components value, keep some inventory on hand, and apply additive manufacturing not only to personalize products but their production system is based on mass customization, too.

   (a) 16.4% of them apply pull supply chain, and

   (b) 38% apply push supply chain.

The outcome of the survey questionnaire gives a good insight of the validity of the proposed theoretical framework. On one hand, the collected data confirms that additive manufacturing is applicable to all industries. On the other hand, additive manufacturing guarantees efficiency in production, since it has the ability to shorten the time to market and increase the end-to-end optimization. That also can be translated in lowering the inventory level. In addition, it also guarantees the responsiveness to market because it increases the agility and the flexibility of the production process. Moreover, it enhances the customization level up to personalization with low level of costs.

6.2 Case Studies

6.2.1 Croft Filters LTD Case Study

Croft Filters Ltd is a family company established by two brothers (Neil and Mark Burns) in Warrington England in 1986 as Croft Engineering Services. But the name was changed in 2013 to better reflect the offering. The company's initial focus was retailing mesh and finding practical uses for it. As the company began to establish itself, it became well-known for high quality craftsmanship. Croft Filters has been supplying critical components to industry sectors across Europe and beyond including Pharmaceutical, Marine, Automotive, Space, Bespoke Manufacturers: Shoe, Safety: Showers, Oil & Gas, and Medical Instruments. Working closely with its customers, the company has accumulated vast knowledge and experience in delivering effective and practical filtration solutions at speed.

Croft employs 25 people and has annual revenue of 2 million US Dollars. As Croft Filters decided to invest in metal 3D printed meshes, they established a separate company called Croft Additive Manufacturing Ltd (Croft AM) in 2013. Croft AM's yearly revenue is around 260 thousand US Dollars and it employs 7 people.

Industrial filters that Croft Filters makes are custom products and manufacturing them requires a lot of manual work, like cutting and welding. Automating the filter production has been impossible because of one-off products. Croft believes that delivering quality product, being innovative, and being cost control, among others, are their competitive advantages. Croft has adopted the efficiency in production strategy to lower the costs. This strategy helped Croft filters to shorten their supply chain and so cutting down their overall lead time. However, to be innovative Croft Filters wanted to grab the opportunity of being the first to produce "eco-filter" for industrial use in UK. Croft Filters tried producing the eco-filter with traditional manufacturing methods, like drilling and milling, but that was impossible to be done. Neil Burns introduced the idea of producing the eco-filter through 3D printers, and they had a plastic prototype of the filter made. The prototype filter showed clear performance gains in the production size, shape, and production accuracy. However, they still needed a way to manufacture the filter out of metal so that it would be strong enough. Metal 3D printing seemed to offer the perfect solution for producing the eco-filter and it could probably be used to improve also other filters and to develop the production processes. Metal 3D printers can make filters in any shape or size and popular styles include cones, cylinders, baskets and screens. Filters can be manufactured in wire mesh, perforated plate and expanded metal with production varying from "one offs" to repeat orders for large international customers.

The decision to buy the metal 3D printer was made as a part of a big investment program at Croft Filters. They also decided to set up the new business as a separate company, to better support growing the business and minimize risks. Croft Additive Manufacturing Limited was structured on the bases of increasing the production efficiency. Thus, they invested in ReaLizer SLM 250 printer which is a large printer that is able to produce larger parts compared to most metal 3D printers and lowers the production cost per part as more parts can be built during a single production run.

Additive manufacturing offers a lot of benefits over conventional subtractive manufacturing methods, like milling. Most importantly the parts can be very complex without lengthening their production times, they can be lighter without sacrificing strength and in some cases several parts can be combined to a single part, leaving out assembly work. In addition, traditional mesh filters are very hard to clean to a high standard, because of the recesses between the mesh and the rim. When the filter is 3D printed, there are not any recesses as the mesh and the rim are a single part, which makes the cleaning process a lot easier and thus cost is reduced because less of work is needed (Figure 6.7).

Figure 6.7: Conventional vs Additive Manufactured Filter

Even though Croft's supply chain is based on push supply chain strategy, the use of additive manufacturing has shortened the time to market, even more. Delivering wedge wire filters to customers used to be slow, as the wedge wire producer has a lead time of 4-6 weeks. Now there is no need to wait for the wedge wire delivery. In one customer case, a wedge wire filter was designed, manufactured and delivered to the customer in total of 2 days. More efficient production and better quality have been produced by the additive manufacturing. The amount of manual work in filter production has been cut down significantly and the production process simplifies from 6 steps to a single step. Also there is no need for tooling and many filters can be printed as a single part, thus eliminating assembly work.

In addition, Croft filters have to have some semi-finished products in inventory in order not to start the customization process from the scratch. Croft Additive Manufacturing reduced its inventory to zero level.

Even the ReaLizer SLM machine that Croft AM has, in principle supports changing the build material, Croft Ltd directors agreed that using additive manufacturing is not worthy for all types of materials. Thus, they decided to use only one material which is stainless steel that is characterized by being with high value compared to other materials they use. On that basis, Croft AM produces only stainless steel mesh as a fully personalized mesh. However, when it comes to other material types, and the meshes are standardized, like the perforated plates, Croft filters produces them using the traditional manufacturing processes in large batches and stocks them in warehouses. In contrary, as the 3D printer that Croft AM uses has a big build volume compared to most other metal 3D printers, and it is possible to produce bigger parts or larger batches of parts on one run. The technology has made it possible to improve the product offering, cut down manual production work and achieve faster turn-around times for some traditionally manufactured products from Croft filters when customization is required.

Croft filters and Croft AM give practical evidence on the first part of our model as is illustrated in Figure 6.8 and Figure 6.9. And thus, we can assure the validity of the theoretical framework. The next case study evaluates and presents empirical evidences of the second part of the model.

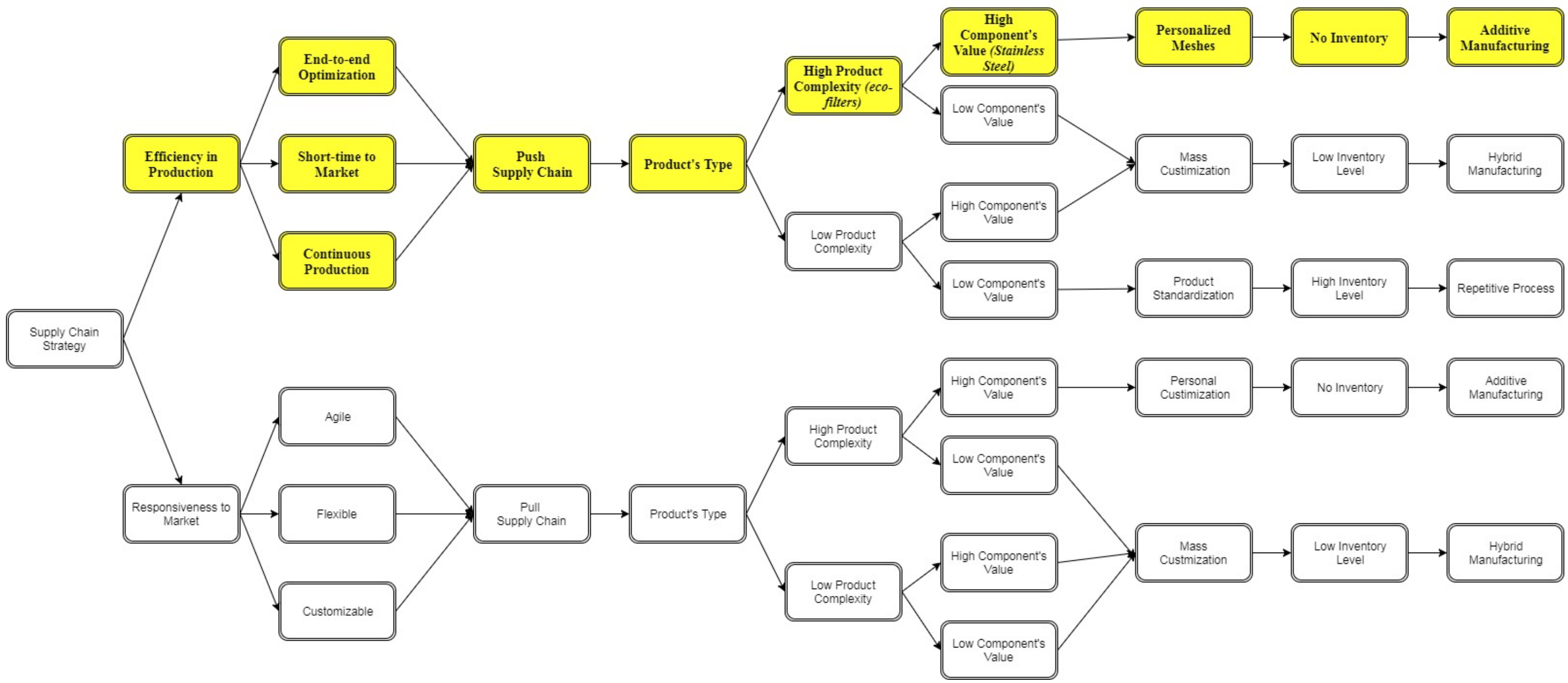

Figure 6.8: Croft AM Empirical Evidence on Theoretical Framework

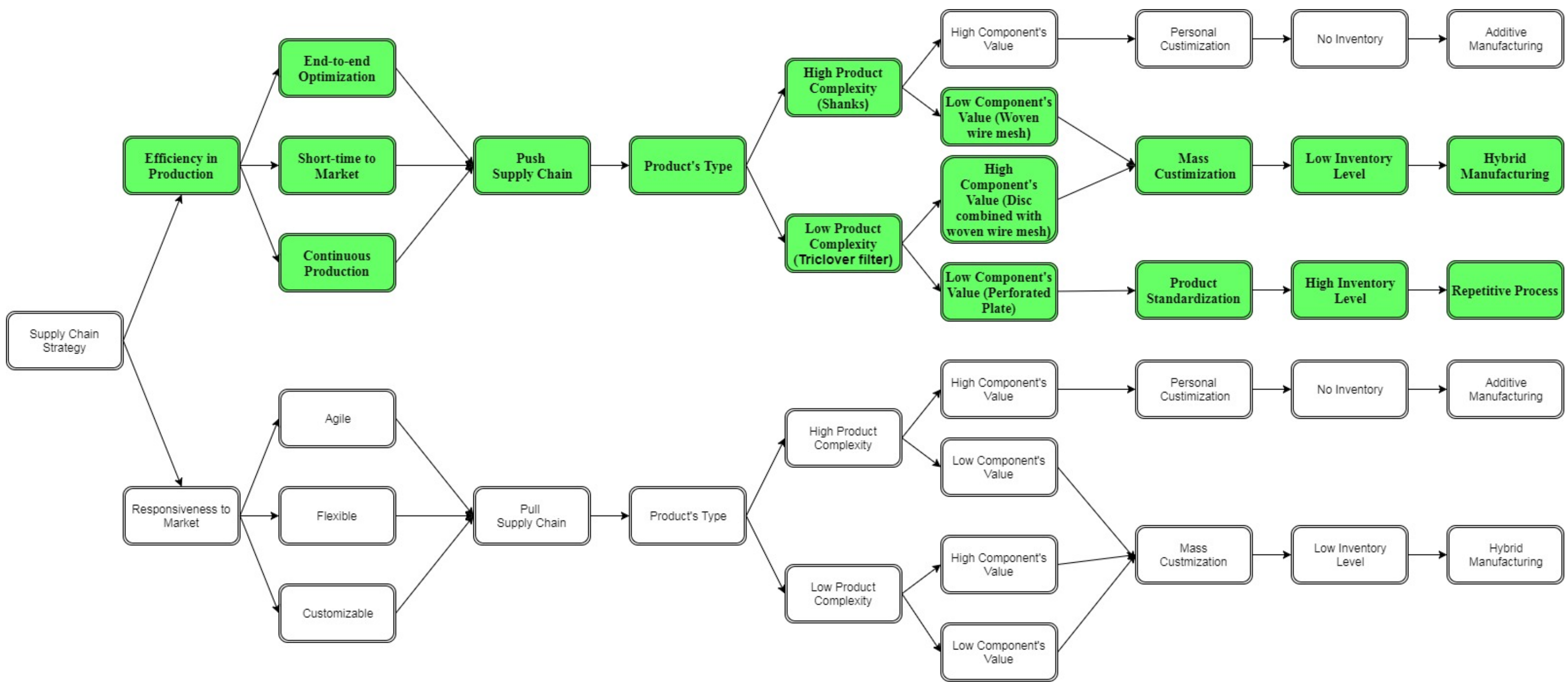

Figure 6.9: Croft Ltd Empirical Evidence on Theoretical Framework

6.2.2 MakieLab Case Study

MakieLab is a business specialized in producing personalized dolls. It was established in 2011 in London, United Kingdom by Alice Taylor. The basic idea that Taylor has is to let customers fully design their dolls by allowing them choosing their hair, eye color, clothes and everything else in the doll. The idea became feasible due to the online platform they developed and the use of 3D printers; where each customer creates the doll and then prints it using powdered nylon in 3D printers (Figure 6.10).

Figure 6.10: Makie Dolls

MakieLab has created a product and production process which is extensively based on the involvement of the customer. Thus, MakieLab makes it possible to change the role of customers in their production process to let them being the starting point of the production process. Doing so makes MakieLab to base their supply chain on pull strategy and to adopt the responsiveness to market strategy. Taylor said: *“the changing nature of consumer demand has been marked for some time and continues to put forth pressures on making. A growing number of consumers who are demanding products tailored to their individual*

preferences. Therefore, personalization has become available to and required by a wider range of consumers. The reason that makes it possible is the wide spread of the internet."
MakieLab controls all processes along the supply chain, from the online platform that customers use to design their doll, to printing the dolls on 3D printers, to the sales and delivery. Allowing customers to design 100% of the doll they are purchasing, on one hand, challenges the traditional role of a customer as a consumer, and gives them an active role in the making process. On the other hand, cost that is assigned to the design process is reduced dramatically and lead time is shortened to 2 - 3 business days. Once the doll is designed and ordered, MakieLab manufactures the doll using a non-toxic, nylon plastic material then dresses it and ships it to the customer. Nevertheless, since dolls are personalized to each customer, there is no doll stays on shelves in the warehouse. MakieLab enforces cost reduction per doll, and thus total cost when eliminating these steps from their supply chain. Today, the Makie dolls represent a fundamental principle of production, which is that new technologies can be applied in ways which they have never been used before, and thus it was able to change traditional methodology of production. In this case, 3D printing has been applied to a range of sectors and used for prototyping to production of component parts, but never had it been used to produce a children's toy. MakieLab makes it possible to produce complex product in one single step by using 3D printers to personalize the doll. MakieLab provides positive empirical evidence on adopting additive manufacturing to personalize complex products is valid with the adaptation of responsiveness to market strategy and pull strategy as is shown in Figure 6.11. Thus, we can conclude that another part of our theoretical framework is valid and applicable.

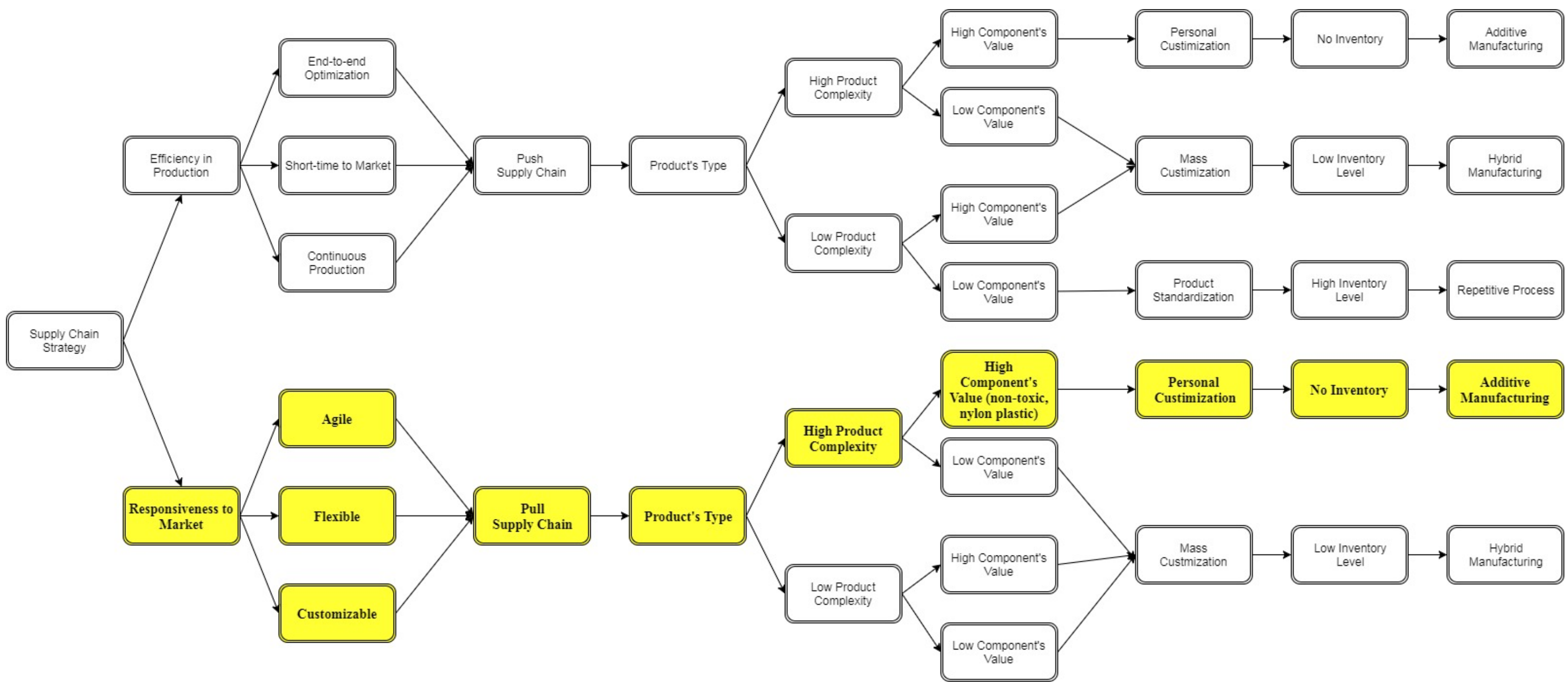

Figure 6.11: MakieLab Empirical Evidence on Theoretical Framework

6.3 Conclusion

Using a triangulation method validates the data through cross verification from survey questionnaire and case studies sources. In addition, the use of the two methods increased the confidence in the collected data [Thurmond (2001)].

The data collected for creating the case studies, as shown in Table 6.2, validate the collected data through the survey questionnaire. For example, while the collected data from the survey questionnaire show that additive manufacturing is able to increase the efficiency and reduce the cost of production; both case studies emphasize and validate this result. Croft Filters case study gives a great example of decreasing lead time from 4 – 6 weeks to only 2 days which harmonize with the 56% of the survey respondents who assure that additive manufacturing decreased their supply chain lead time to less than seven days and their manufacturing lead time to less than a day.

In addition, as it was found from the survey questionnaire, the case studies demonstrate that the use of additive manufacturing is not applicable to all types of products and/or product's components. When it comes to produce stainless steel meshes as a fully personalized mesh, Croft Filters LTD leaves the task to Croft AM. However, for other types of metals (less value than stainless steel) Croft Filters produces the mesh through traditional methods of manufacturing.

To conclude, collected data from the survey questionnaire are validated by the data collected for the case studies. Both gave the same results in terms of increasing efficiency, cost reduction, increasing agility and lead time reduction. In addition, the collected data validate our theoretical model and gave real examples of the applicability of this model.

	Case Study No. 1		Case Study No. 2
	Croft LTD	Croft AM	MakieLab
Product	Industrial Filters	Personalized Meshes	Personalized Dolls
Product's Type	High Product Complexity & Low Product Complexity	High Product Complexity	High Product Complexity
Component's Value	High Component's Value & Low Component's Value	High Component's Value	High Component's Value
Supply Chain Strategy	Push Supply Chain	Push Supply Chain	Pull Supply Chain
Level of Customization	Mass Customization and Product Standardization	Personalization	Personalization
Inventory Level	Low to High Level	No Inventory	No Inventory
Manufacturing System	Traditional (Repetitive Process)/ Hybrid Manufacturing	Additive Manufacturing	Additive Manufacturing

Table 6.2: Summary of the Data Collected From the Case Studies

Chapter 7

Conclusion

Companies are forced to rapidly switch towards low volume production of more innovative, customized and sustainable products with high value-added. Additive manufacturing is an innovative method of production that has to be utilized in an effective and efficient way to let companies gain competitive advantage and increase their market share. However, additive manufacturing is not applicable to all types of products. This research focused on additive manufacturing technology and studied its impact on supply chain management. This chapter reviews the research objective and gives brief answers to the research questions. Then, the major contributions of this research are presented. Finally, the research limitations are outlined and directions for future researches are provided.

7.1 A Review of the Research Objective and Research Questions

The objective, as defined for this research, is to develop a framework for using additive manufacturing as an appropriate production method for addressing the management of the supply chain strategy. In order to realize this objective, a solution was developed through design science research. The development of the solution was based on findings from the literature and from exploratory interviews. Next, this solution was evaluated through a triangulation method consists of survey questionnaire that was distributed to additive manufacturing firms, and two case studies for three firms, each apply different supply chain strategy, but both use additive manufacturing technologies.

The research question initially proposed in this research is now reviewed. A brief answer is provided in order to demonstrate how the research question and sub-questions were addressed as the research process evolved.

Under which conditions, in the supply chain, additive manufacturing technology replace traditional manufacturing system?

We answered this research question through proposing a theoretical framework. The proposed framework facilitates the understanding of the conditions that additive manufacturing technologies can replace the traditional manufacturing system.

Based on our theoretical framework, additive manufacturing can replace traditional manufacturing system in both supply chain strategies; efficiency in production and responsiveness to market. However, it depends on the product's type and on the components value of the product. This means, additive manufacturing is better to be implemented and fully utilized when the product is characterized with high complexity of production and it is compound of high components value. Otherwise, traditional manufacturing should take place in the production system either with some help of additive manufacturing, a hybrid manufacturing system, or traditional manufacturing should be the only method of production, as when the efficiency of production strategy is implemented and the product is with low complexity and its components are with low value.

Research sub-question:

1. **Does additive manufacturing fits both efficiency in production and responsiveness to market supply chain strategies?**

   The theoretical framework is proposed to particularly answer this research sub question. This research agrees with the strategic management literature which emphasizes that manufacturers must have a clear strategic thinking. This agreement is illustrated in a theoretical framework that directs to the preferable manufacturing method in accordance with the product types and the value of its components. This theoretical framework studies the supply chain strategies and links them to the product types. Then it examined the harmony between the characteristics of each strategy and the types of the manufactured product. Based on that correspondence, level of customization is determined. Finally, the best production method is suggested. The conclusion of this framework, the results of the survey questionnaire, and the case studies approve that additive manufacturing fits both efficiency in production and responsiveness to market supply chain strategies only when the product is categorized with high product complexity and contained high component's value. Otherwise, hybrid manufacturing system or traditional manufacturing systems should be used.

2. **How can additive manufacturing change or re-shape supply chain in terms of customization?**

   Both the conceptual and theoretical framework that were proposed in this research were able to answer this research sub-question by giving evidences on additive manufacturing ability to change and reshape the supply chain due to the fact that additive manufacturing leveraged the customization level and decreased its cost. This enables supply chains to be shorter by eliminating the retailer's roles and let manufacturers become closer to customers. That means supply chains are more agile in manufacturing process and more cost efficient in reducing the inventory levels and reducing the lead time. Data collected from the survey questionnaire, as well as the case studies, were able to answer this research sub-question.

7.2 Contribution of the Research

In this research, we focused on operative characteristics of supply chain strategies to grab the opportunity of implementing 3D printing as an appropriate production method. This study contributes to the field of additive manufacturing research by offering a framework explains the conditions that make the implementation of additive manufacturing feasible in supply chains. The framework describes two possible supply chain strategies and links each of them to the product types and the value of the product's components to end up with the feasible manufacturing system.

Our theoretical framework suggests that additive manufacturing can be implemented if the firm is adopting efficiency in production or responsiveness to market supply chain strategies. However, additive manufacturing technology is not always the best manufacturing system to be used when it comes to the product type and the value of its components. Thus, our framework recommends implementing additive manufacturing when the product is complex and it is compound of high value components.

At the time of writing this PhD thesis, there has been very few studies focusing on the study of additive manufacturing implementation, and no one focused on supply chain strategies or product types to describe the feasibility of additive manufacturing implementation. In the identification of the research problem in adopting additive manufacturing technologies, the research problem highlights the lack of additive manufacturing implementation studies in the literature, specifically highlighting that top managers face the difficulties and the fear of taking the decision of implementing new technologies in the manufacturing process. As was highlighted in the introduction, literature review, and understanding the problem chapters of this study, additive manufacturing technologies does not success to all manufacturing businesses. Thus, this study has provided some insight into when firms should implement additive manufacturing as the only production method and when it should be a complementary method to the traditional one based on some characteristics in the product itself and in the management of the supply chain.

7.3 Limitations

7.3.1 Methodological Limitations

The lack of scholarly researches in this area of study conducted the selection of qualitative approach of research. Thus, this research is exploratory in nature to gain an understanding of underlying opinions of how or to what extent using additive manufacturing affect supply chain management. Whilst the appropriateness and application of qualitative research has been discussed in full in Chapter 2, it is acknowledged that qualitative research is harder than others to generalize from. However, it is important to recognize that this research was not design with intention of widespread generalization of results, and it is acknowledged that further research would help to extend the generalizability of this study's findings.

Qualitative data collection methods vary using unstructured or semi-structured techniques. Thus, we adopted three techniques in collecting data in this research. To better understand the problem, individual interviews were held. Four interviews were enough for the researcher to get the essential elements for understanding the problem and get out with the conceptual framework. However, this sample size is small to generalize the results. Thus, to override this limitation in the sample size, a questionnaire technique and case studies also were adopted in this research. However, due to huge population of firms, since this study is not limited to one type of industry or to one geographical area, the sample size is considered small, as well.

7.3.2 Execution Limitations

The preparation of this doctoral thesis must, by definition, be solely the work of a single student author. Thus, finite constraints bound the time and financial resources that are available. In social sciences, doctoral research tends to be more individual pursuit that is unable to leverage some of the benefits arising from research centers and research team. This is the case in this research.

The nature of the research participants must also be acknowledged as a potential limitation of this study. Since the implementation of additive manufacturing is still brand new in most firms, participants were very sensitive to declare information regarding the manufacturing operations, in use strategies, as well as, financial information. Thus, a number of interviews and surveys were discarded due to lack of needed information. In addition, large number of potential participants refused to be interviewed or to answer the questionnaire for fear of leaking information to competitors, or as to their organization guidelines. A sample of emails we received that declare participants refusal to fill-out the survey is presented in Appendix E.

7.4 Future Research Directions

The work in this thesis has covered and explored the connections between and among the supply chain strategies, products types and component's value, and additive manufacturing technologies. It ended up with proposing a framework that helps manufacturers in taking decisions on which production method is better for them to implement for their production. However, there are still several research directions for the future work as the extension of the current study.

First and foremost, future development of the work in this doctoral thesis could be the incorporation of uncertainty issues. Although a large number of models have been developed, more investigations are still needed to overcome the limitations of current models. In this research, environmental risks and governmental restrictions for using 3D printing have not been mentioned or addressed. However, it is well know that some countries have some political issues that make the adoption of 3D printing forbidden. Thus, some research can be directed to study the effect of these environmental and political risks of using additive manufacturing in some geographical regions.

Secondly, this research project did not address what could be the impact of using additive manufacturing on a macro-economic scale. A further research can study the situation of future factories and how 3D printer can affect them with easiness and possibility to have small units of factories in households. Would that affect the gross domestic product (GDP) for a country?

Another direction for the future work is the multi-scale modeling; the integration of factories through the supply chain for multi-product continuous plants. This can be studied by extending the proposed framework. The integration of global supply chain planning and production scheduling will incorporate the production systems for these manufacturers.

Finally, this research focused only on success stories in the marketplace. However, there are many failure ones. Thus, some research work can be dedicated to study these cases and know why and how they did not succeed in adopting additive manufacturing into their businesses.

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Appendices

Appendix A

Interview Questions

Interview Questions

Part I

This part focuses on gathering Company's General Info:

1) In which industry is your company operating (if available please provide industry classification, e.g. ATECO?
2) Which geographical markets are you operating into? (manufacturing and selling)
3) What is the size of your company? In terms of number of employees and annual revenue?
4) Who are your direct and indirect competitors?
5) What is your competitive advantage? What makes customers prefer your product over other competitors?
6) How can you describe your customers? Which segments are you serving?
7) What is your distribution strategy? How much is managed online and how much in store?
8) What are your strategic values? (the degree to which a particular action or planned action is important or useful in relation to something that it wants to achieve)
9) What are your key performance indicators?

Part II

This part focuses on gathering Company's Supply Chain Info:

1) How many suppliers are you dealing with?
2) How you deal with your suppliers? Do you have long term contracts with them? Do you consider them as partners?
3) What is your suppliers' management strategy? E.g. how many suppliers per item, localization decision, local vs global procurement, etc.
4) How many retailers are you dealing with?
5) How you deliver the final product to the customer? Do you depend on outsourcing or do you have your own delivery system?
6) To what level do you integrate among your supply chain partners? Do you share critical or confidential information with them?
7) How do you link together purchasing, manufacturing and logistics?
8) How long does the production process take between the placement of an order and delivering the product to the customer?

<u>Part III</u>

This part focuses on gathering <u>Company's Costs Info</u>:

1) How can you describe the current inventory level compared to a similar company in size and industry but applying traditional manufacturing system?
2) What processes do you apply in order to reduce wastes and costs?
3) Compared to the TM, do you agree that AM reduced the wastes that could be in terms of material, defects, etc?
4) Do you think AM increase or decrease the productivity? And how?
5) Do you consider 3D printers a good way to reduce the final product's cost? Cost per unit higher or lower when AM is used?
6) How can you comment on AM machinery cost compared to traditional manufacturing ones? And what about employees training cost for using 3d printers?
7) Do you believe that investing in 3D printing generates more returns than traditional machinery?
8) Compared to TM do you think the gross profit margin increased when AM is in use?

<u>Part IV</u>

This part focuses on gathering <u>Company's Manufacturing System (AM) Info</u>:

1) Does AM affect your supply Chain? and how?
2) Does AM add value to the final product? How?
3) Does AM provide a value directly perceived by the customer? Does it increase the customer satisfaction of the final product? How does it increase their satisfaction?
4) Are there boundaries that limit AM production process, such as material type, quality, product's size or shape, etc…?
5) What are the main risks you perceive in using AM?
6) What are the pros and cons of using AM?

Appendix B

Invitation Letter

Greetings,

My name is Raed Handal; I am PhD Candidate in the Economics and Information Technology Management Doctorate program at the University of Pavia, (Italy). I am working on a doctoral research project about Additive Manufacturing in Supply Chain Management.

The main objective of the doctoral research project is to find out the impact of Additive Manufacturing (3D printing) on Supply Chain Management performance, in different industries; in a way to discover a better and new way to improve Supply Chain Management performance through the use of 3D Printing and check if the last could be considered as a Lean Management Tool.

I am contacting you to check your interest and your availability to participate in this research.

Your participation would constitute in an interview (by phone or skype) lasting 30 -40 minutes.

All information provided will remain confidential. No data or information about your company will be shared with anyone or publicly published. Only aggregate results will be used and the name of the company will be disclosed.

At the end of the study, we will share with you the results of our work and these will allow you also to have a glance of what other companies are experiencing and doing.

Your participation will definitely increase the validity of the research results and the knowledge obtained from this study will be of great value in guiding professionals to be more effective in supply chain management. Furthermore, your time and help will be greatly appreciated.

We would be grateful if you could let me know whether you are available for participation and in case the date and time that suits you for the interview.

Thanks in advance,

Raed Handal, PhD candidate
Economics and Management Technology
“DREAMT” 29th cycle
Department of Economics and Management
Università di Pavia
Via S.Felice 5, 27100 Pavia
http://phdemd.unipv.eu/site/en/home/phd-students/scheda760005005.html
Email address: **raed.handal01@universitadipavia.it**
LinkedIn: https://www.linkedin.com/in/raed-handal-b942243b
Skype address: Raedshandal
Telephone #: +39-324-907-5993

Appendix C

Supply Chain Management Survey

Supply Chain Management

This survey examines various aspects of supply chain management practices in an organization. You will be asked questions concerning the company's current business practice. If you are unable to complete the survey yourself, please entrust the task to another person who is knowledgeable about supply chain management practices.
Your participation in the survey is critical to the success of the study and all of your responses will be kept confidential. No personally identifiable information will be associated with your responses to any reports of these data. All responses will be used for educational purposes only. There is no right or wrong answer to the following questions. We are only interested in your assessment of your organization's activities. Completion of this survey questionnaire will indicate your willingness to participate in this study.

* Required

1. **Industry in which the company ('s main business unit) operates:** *

   Mark only one oval.

   - Machine Industry
   - Chemical Industry
   - Fashion Industry
   - Technology Industry
   - Manufacturing Industry
   - Food Industry
   - Telecommunication Industry
   - Construction Industry
   - Automotive Industry
   - Aerospace Industry
   - Other: ____________________

2. **Size of the company by number of employees** *

   Mark only one oval.

   - Small (Less than 50)
   - Medium (50 - 100)
   - Large (more than 100)

3. **Years of operating experience of the company (Number of years in the market)** *

   Mark only one oval.

   - Less than 1 year
   - 1 - 5 years
   - 5 - 10 years
   - 10 - 15 years
   - 15 - 20 years
   - More than 20 years

4. **Annual sales of this company**
Mark only one oval.

- ◯ Less than $ 1 million
- ◯ 1 - 5 million
- ◯ 10 - 50 million
- ◯ 50 - 100 million
- ◯ More than 100 million

5. **Geographical scope of operating** *
Mark only one oval.

- ◯ Africa
- ◯ Asia
- ◯ Australia
- ◯ Europe
- ◯ USA
- ◯ International

6. **Most of your customers are located:** *
Mark only one oval.

- ◯ Golbally
- ◯ Locally

7. **Does the company use additive manufacturing in the production system** *
Mark only one oval.

- ◯ Yes
- ◯ No (Skip next question)

8. **Years of additive manufacturing experience of the company**
Mark only one oval.

- ◯ Less than 1 year
- ◯ 1 - 5 years
- ◯ 5 - 10 years
- ◯ More than 15 years

9. **Number of suppliers the company deals with** *
Mark only one oval.

- ◯ Less than 20
- ◯ 20 - 50
- ◯ More than 50

10. **Final products are directly sold to final consumer:** *

Mark only one oval.

- Yes totally to final consumers (skip the next question)
- No, totally to retailers
- For both customers and retailers

11. **Number of retailers the company deals with**

Mark only one oval.

- Less than 10
- 10 - 20
- 20 - 50
- 50 - 100
- More than 100

12. **What is the average number of times your typical customer is likely to purchase your product per month?** *

Mark only one oval.

- Less than 5 times per month
- 5 - 10
- 10 - 15
- More than 15

13. **Total annual cost of raw material used** *

Mark only one oval.

- Less than 20% of annual sales
- 20% - 50% of annual sales
- More than 50% of annual sales

14. **What type of inventory system the company use?** *

Mark only one oval.

- Just in Time
- Tradition warehousing inventory

15. **On monthly average how much raw material inventory you keep on hand?**

Mark only one oval.

- Less than 10% of next month's production
- 10% - 20%
- 20% - 50%
- More than 50%

16. **In your opinion, do you think that additive manufacturing can increase the efficiency (lower cost) of the production system?** *

Mark only one oval.

- Yes
- No
- Maybe

17. **In your opinion, do you think that additive manufacturing can increase the speed of the production system?** *

Mark only one oval.

- Yes
- No
- Maybe

18. **In your opinion, does additive manufacturing improve supply chain management?** *

Mark only one oval.

- Yes
- No
- Maybe

19. **In your opinion, do you think additive manufacturing applies to all types of products?** *

Mark only one oval.

- Yes, regardless its value or its complexity
- No, only to complex or high valued product
- Maybe

20. **Do you believe that the implementation of additive manufacturing system reduces the needed number of suppliers?** *

Mark only one oval.

- Yes
- No
- Maybe

21. **Does the company follow-up/ forecast future customer expectations?** *

Mark only one oval.

- Yes
- No

22. **Total Lead time (the time between the initiation and completion of a production process)** *
Mark only one oval.

- Less than 1 day
- 1- 3 days
- 3 - 7 days
- 7 - 14 days
- More than 14 days

23. **Manufacturing lead time** *
Mark only one oval.

- Less than 1 day
- 1 - 3 days
- 3 - 7 days
- More than 7 days

24. **Total annual waste in production process** *
Mark only one oval.

- Less than 1% of annual sales
- 2% - 3%
- 3% - 5%
- More than 5%

25. **Does the company follow the pull production system (produces only what has been ordered by customers) or Push production systems (produces quantities based on market expectations and forecasting future quantity demanded)** *
Mark only one oval.

- Pull (Skip the next question)
- Push
- Use both pull and push production systems

26. **On average how much final product inventory you keep on hand?**
Mark only one oval.

- Less than 10% of next months sales
- 10% - 20%
- 20% - 50%
- More than 50%

27. **Production system in the company is based on personal customization or mass customization?** *
Mark only one oval.

- Personal customization
- Mass customization
- Both are used

28. **Products are stored at appropriate distribution points close to customers in the supply chain**
Mark only one oval.

- Yes
- No
- Sometimes

29. **Ability to respond to and accommodate demand variations** *
Mark only one oval.

	1	2	3	4	5	
Extremely Worse						Extremely Good

30. **Your ability to deal with the periods of poor supplier performance without affecting lead time**
Mark only one oval.

	1	2	3	4	5	
Extremely Worse						Extremely Good

31. **Total cost of manufacturing, including labor, maintenance and re-work cost**
Mark only one oval.

	1	2	3	4	5	
Very low						Very high

32. **Cost associated with held inventory** *
Mark only one oval.

	1	2	3	4	5	
Very low						Very high

33. **On time delivery**
Mark only one oval.

	1	2	3	4	5	
Rarely						Always

34. **Customer complaints** *

Mark only one oval.

	1	2	3	4	5	
Rarely	⬭	⬭	⬭	⬭	⬭	Very often

Powered by Google Forms

Appendix D

Informed Consent E-mail

Dear Sir/Madam,

My name is Raed Handal; I am PhD Candidate in the school of Economics and Management at the University of Pavia, (Italy). I am working on a doctoral research project comparing the supply chain management performance when using traditional manufacturing system vs. additive manufacturing (3D printing) system to study the impact of additive manufacturing on supply chain management performance, in different industries.

Thus, I am writing to you inviting you to participate in this research by completing a brief survey. In order to ensure that all information will remain confidential, please do not include your name or your company's name.

This survey examines various aspects of supply chain management practices in an organization. You will be asked questions concerning the company's current business practice. If you are unable to complete the survey yourself, please entrust the task to another person who is knowledgeable about supply chain management practices.

The survey will not take more than 10 - 15 minutes to complete. Kindly spare a few minutes from your busy schedule to complete the survey as your participation is of value to this study.

To fill the survey, please use the following link: **https://goo.gl/onGmEE**

Your participation in the survey is critical to the success of the study and all of your responses will be kept confidential. No personally identifiable information will be associated with your responses to any reports of these data. All responses will be used for educational purposes only. There is no right or wrong answer to the following questions. We are only interested in your assessment of your organization's activities. Completion of this survey questionnaire will indicate your willingness to participate in this study. If you require additional information or have questions, please contact me by email mentioned below.

Thanks in advance for your time and cooperation.

Sincerely,

Raed Handal
PhD Candidate
Department of Economics and Management
Università Di Pavia
Via S. Felice 5, 27100 Pavia
Email: raed.handal01@universitadipavia.it
PhD website: https://goo.gl/VdXGg7
University of Pavia website: http://www.unipv.eu/site/home.html

Appendix E

A sample of E-mails that Declare Participants Refusal to Fill-out the Survey

Re: Invitation to participate in a research

psoares@photolitec.org via eigbox.net
to me

Gratcia,

No interest !

Pascal

Simplify3D Education <education@simplify3d.com>
to me

As part of corporate guidelines, we decline participation in this survey.

~Simplify3D Support

No Thank you

NeuWave Info
to me

From: Raed Handal [mailto:raed.handal01@universitadipavia.it]
Sent: Monday, March 13, 2017 2:51 AM
To: Raed Handal <raed.handal01@universitadipavia.it>
Subject: Invitation to participate in a research

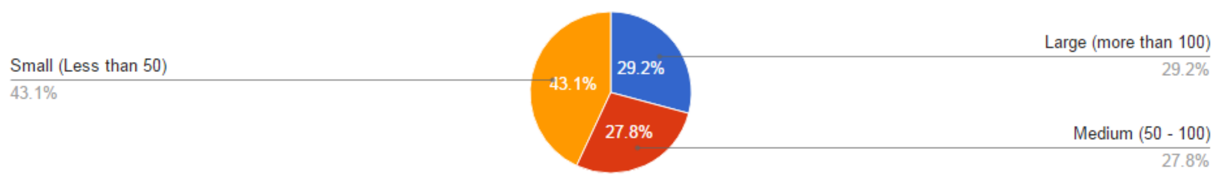
Dear Sir/Madam,

Appendix F

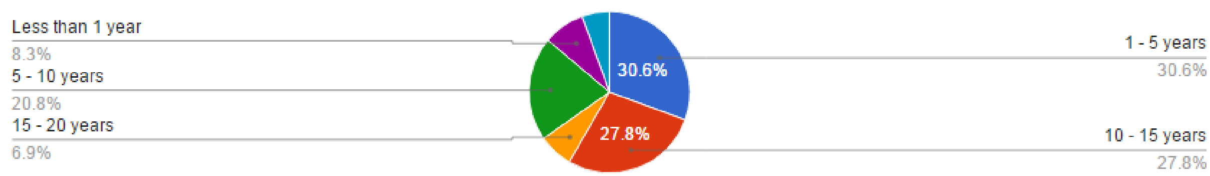
Survey Analysis

Industry in which the company ('s main business unit) operates:	Top results
Fashion Industry	13
Machine Industry	11
Technology Industry	8
Manufacturing Industry	7
Food Industry	5
Aerospace Industry	4
Chemical Industry	4
Automotive Industry	2
Construction Industry	2
3d printing products	1
Accessories	1
Biomedical Device Industry	1
Consulting / Systems Integration	1
Consumable Goods	1
Consumable goods	1

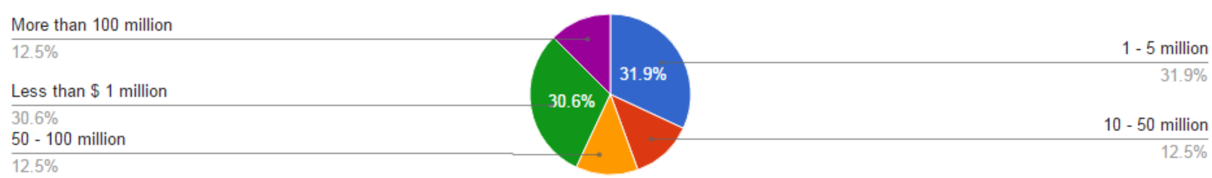
Size of the company by number of employees



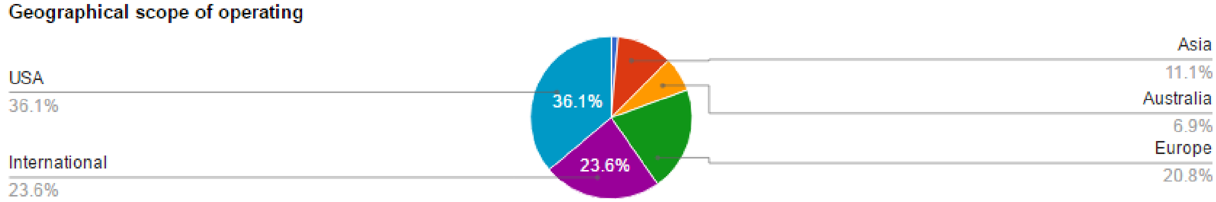
Years of operating experience of the company (Number of years in the market)



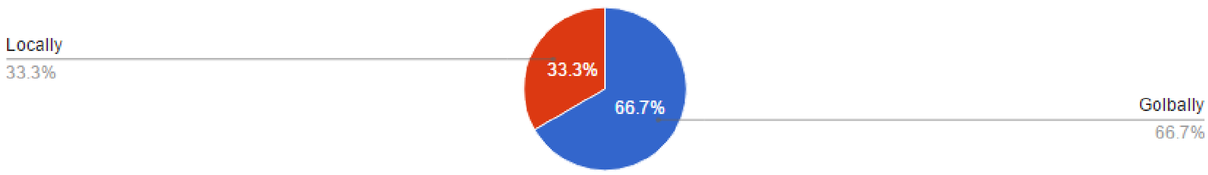
Annual sales of this company



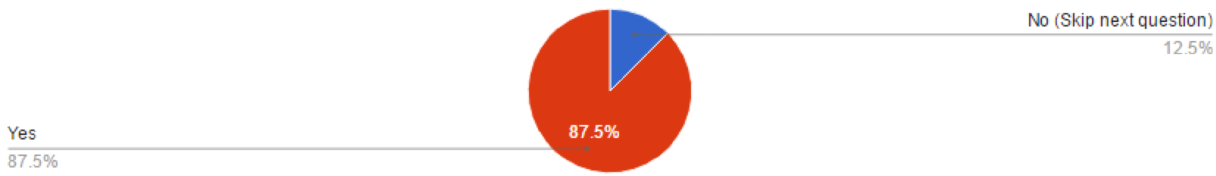
Geographical scope of operating



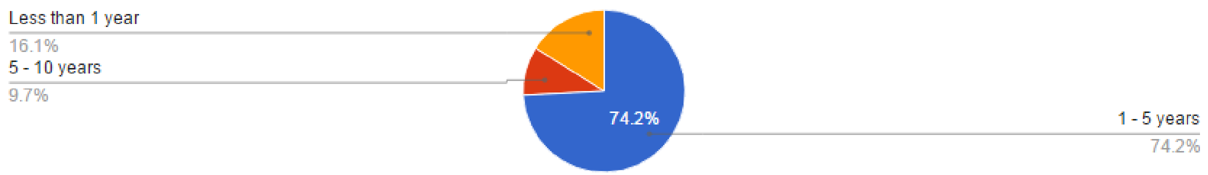
Most of your customers are located:



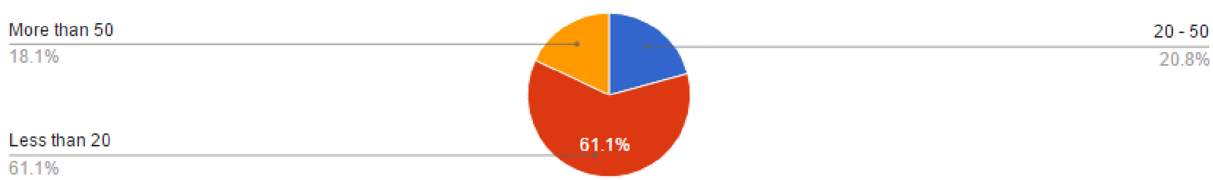
Does the company use additive manufacturing in the production system



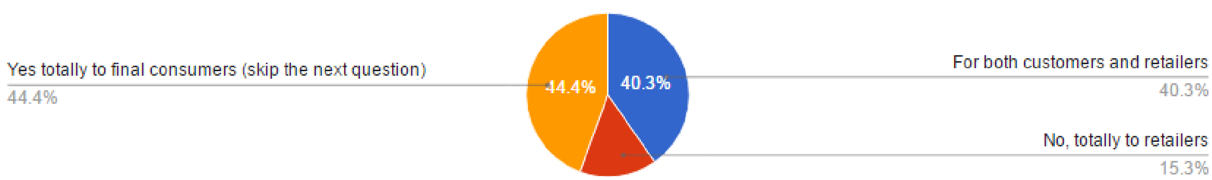
Years of additive manufacturing experience of the company



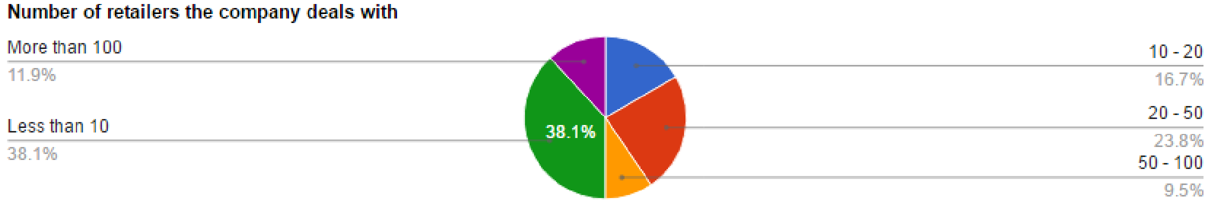
Number of suppliers the company deals with



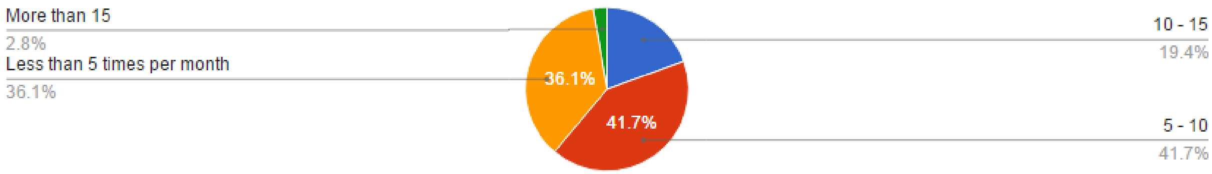
Final products are directly sold to final consumer:



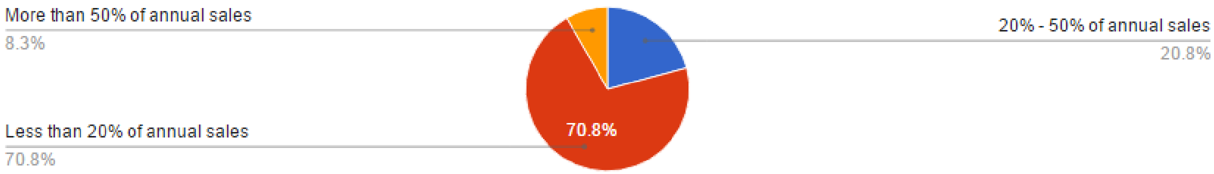
Number of retailers the company deals with



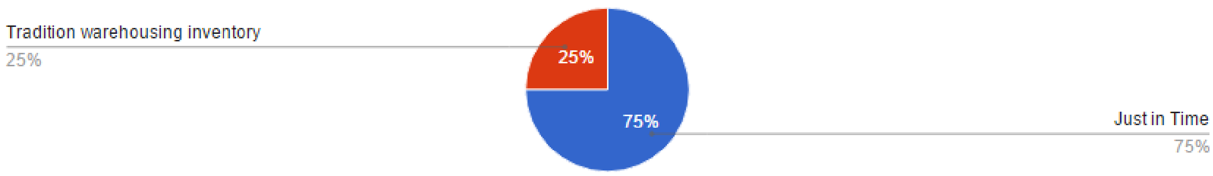
What is the average number of times your typical customer is likely to purchase your product per month?



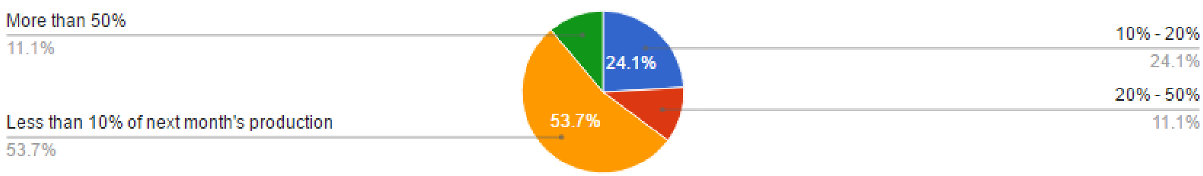
Total annual cost of raw material used



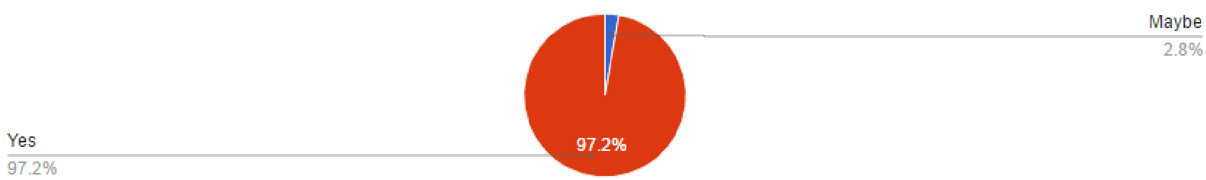
What type of inventory system the company use?



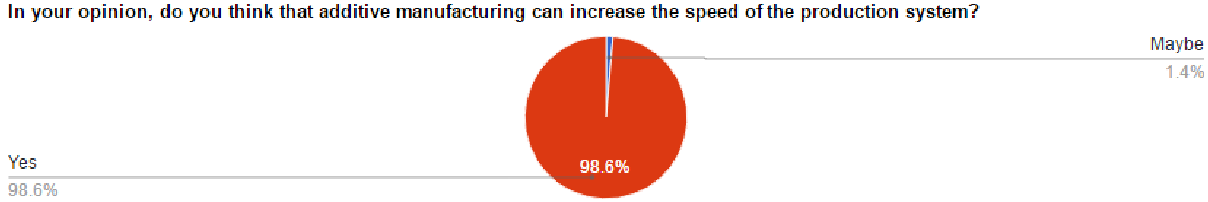
On monthly average how much raw material inventory you keep on hand?



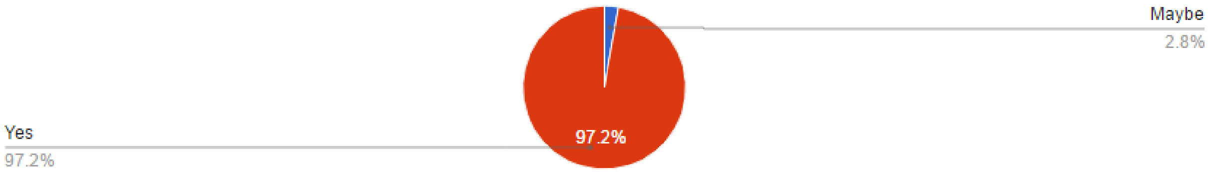
In your opinion, do you think that additive manufacturing can increase the efficiency (lower cost) of the production system?



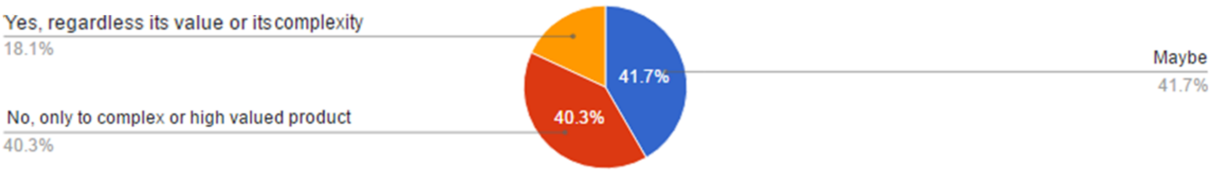
In your opinion, do you think that additive manufacturing can increase the speed of the production system?



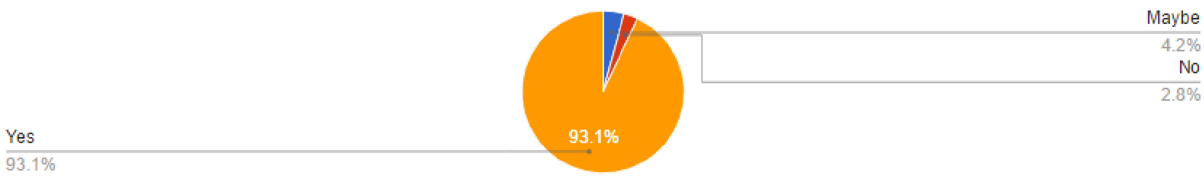
In your opinion, does additive manufacturing improve supply chain management?



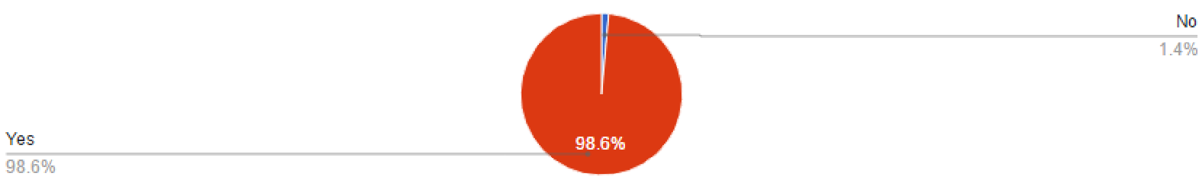
In your opinion, do you think additive manufacturing applies to all types of products?



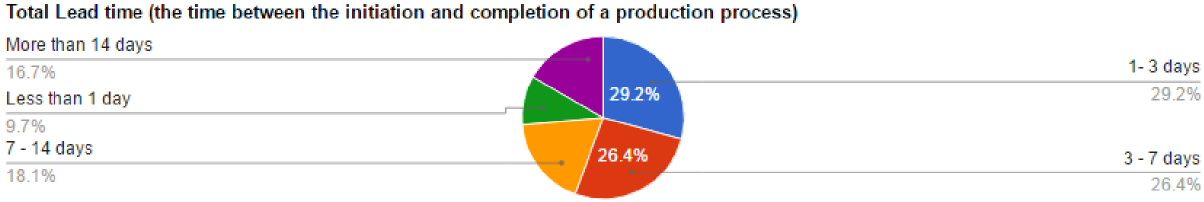
Do you believe that the implementation of additive manufacturing system reduces the needed number of suppliers?



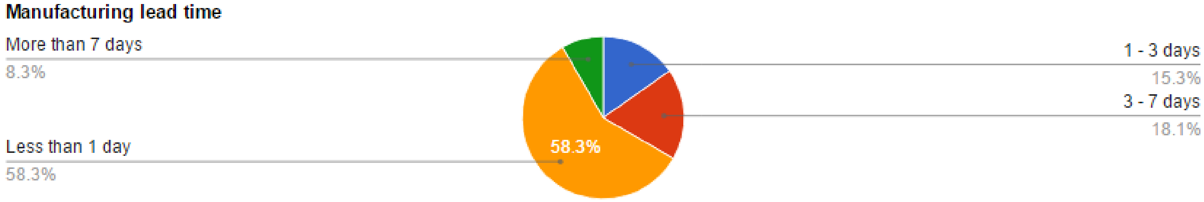
Does the company follow-up/ forecast future customer expectations?



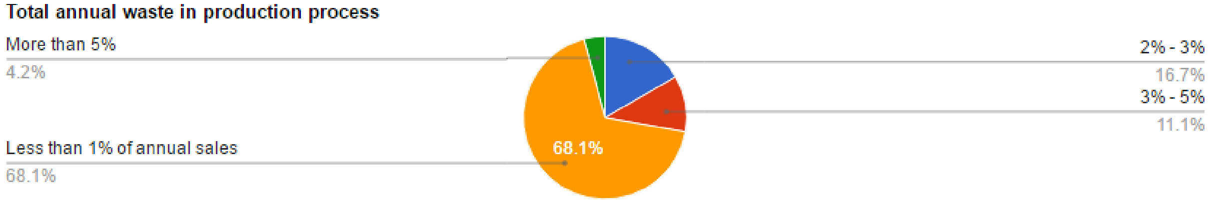
Total Lead time (the time between the initiation and completion of a production process)



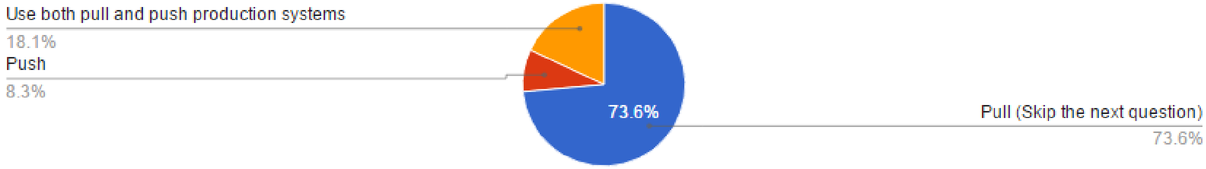
Manufacturing lead time



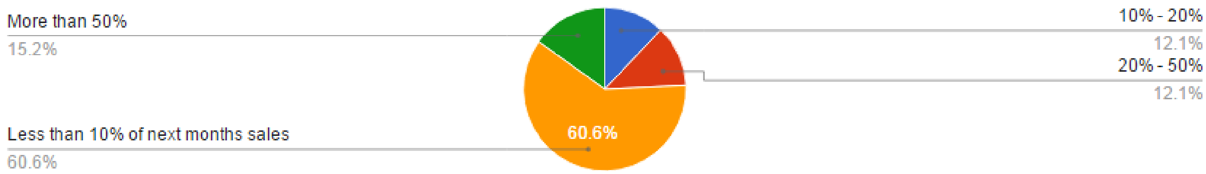
Total annual waste in production process



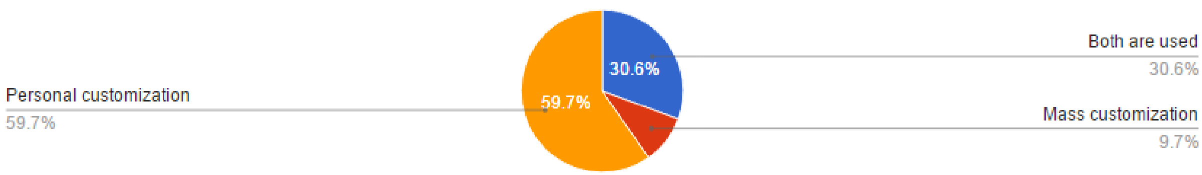
Does the company follow the pull production system (produces only what has been ordered by customers) or Push production systems (produces quantities based on market expectations and forecasting future quantity demanded)



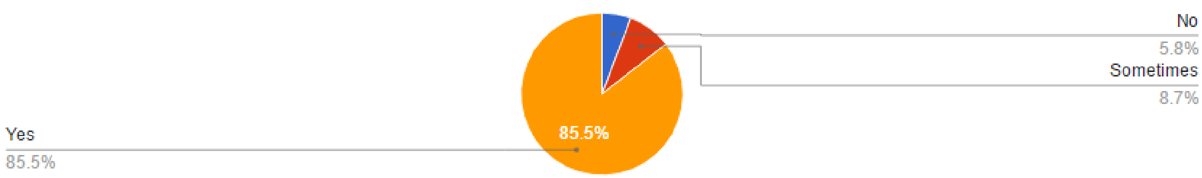
On average how much final product inventory you keep on hand?



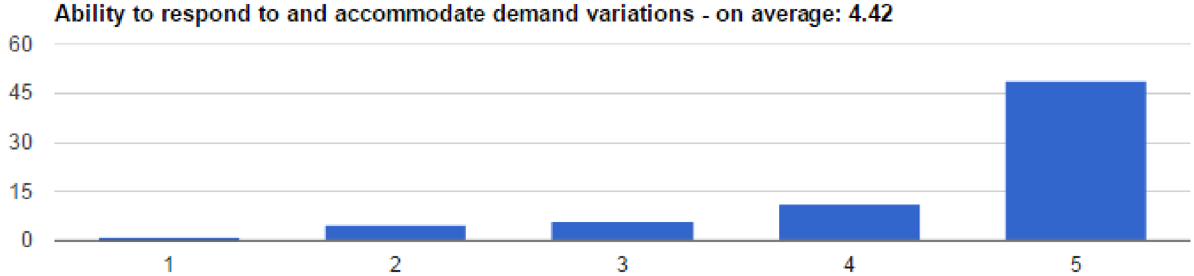
Production system in the company is based on personal customization or mass customization?



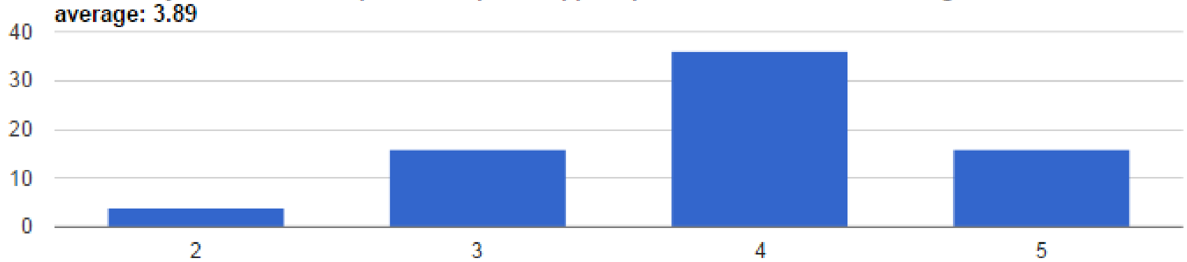
Products are stored at appropriate distribution points close to customers in the supply chain

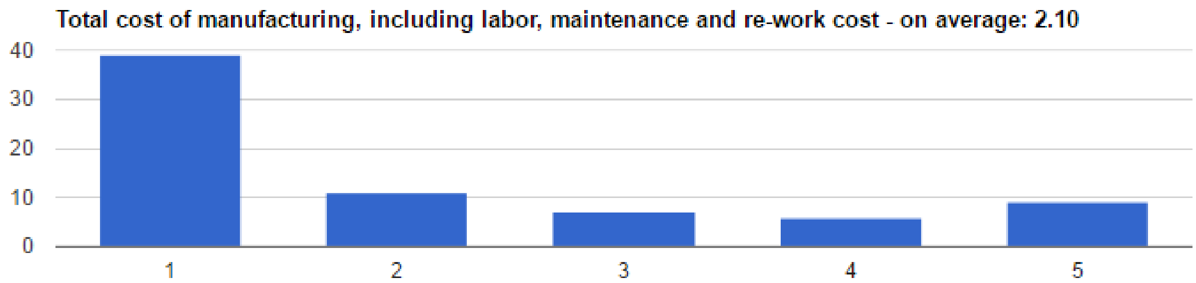


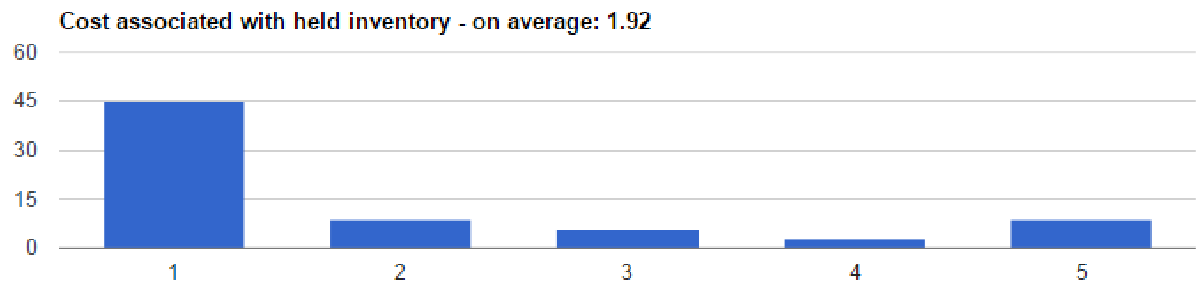
Ability to respond to and accommodate demand variations - on average: 4.42

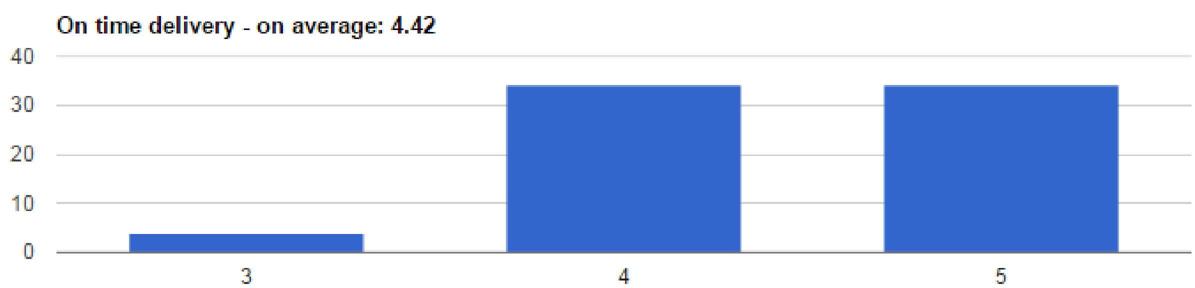


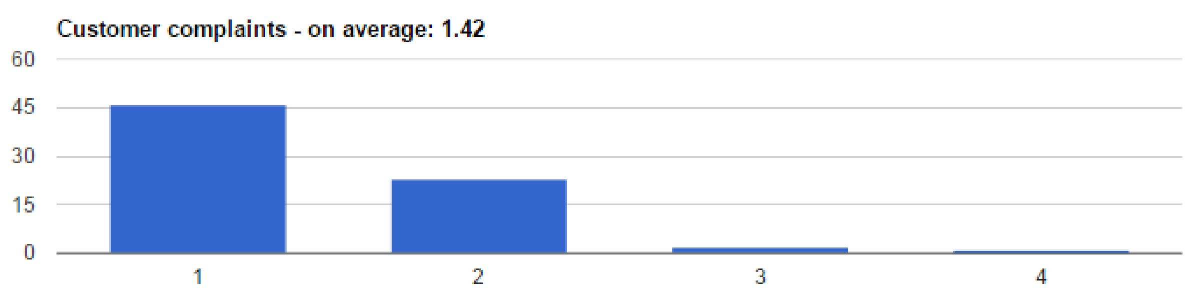
Your ability to deal with the periods of poor supplier performance without affecting lead time - on average: 3.89

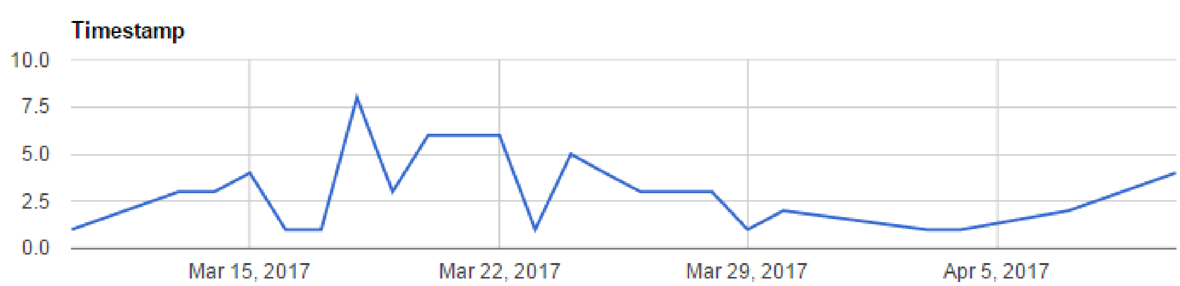



Total cost of manufacturing, including labor, maintenance and re-work cost - on average: 2.10
40
30
20
10
0
1
2
3
4
5


Cost associated with held inventory - on average: 1.92
60
45
30
15
0
1
2
3
4
5

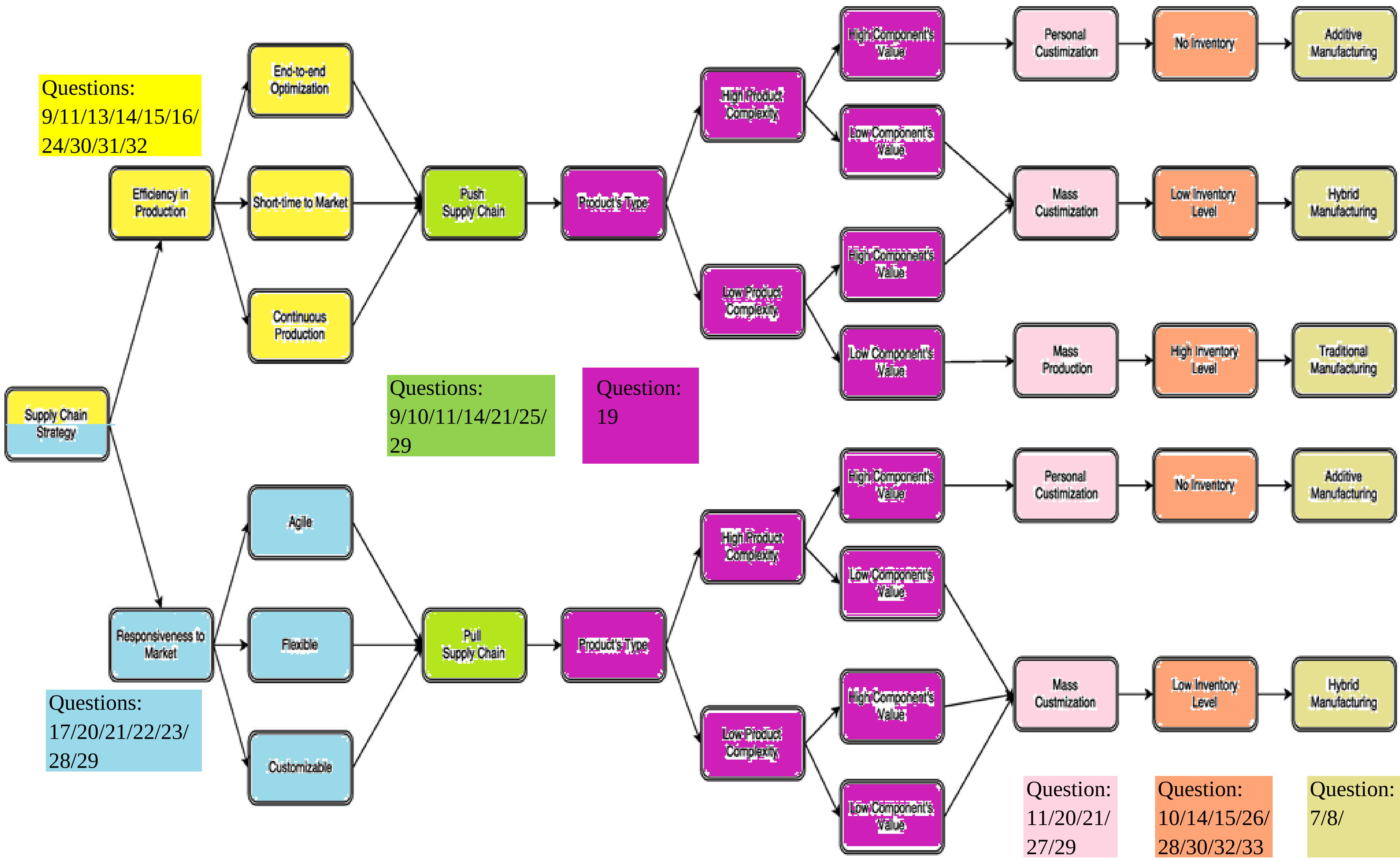

On time delivery - on average: 4.42
40
30
20
10
0
3
4
5


Customer complaints - on average: 1.42
60
45
30
15
0
1
2
3
4

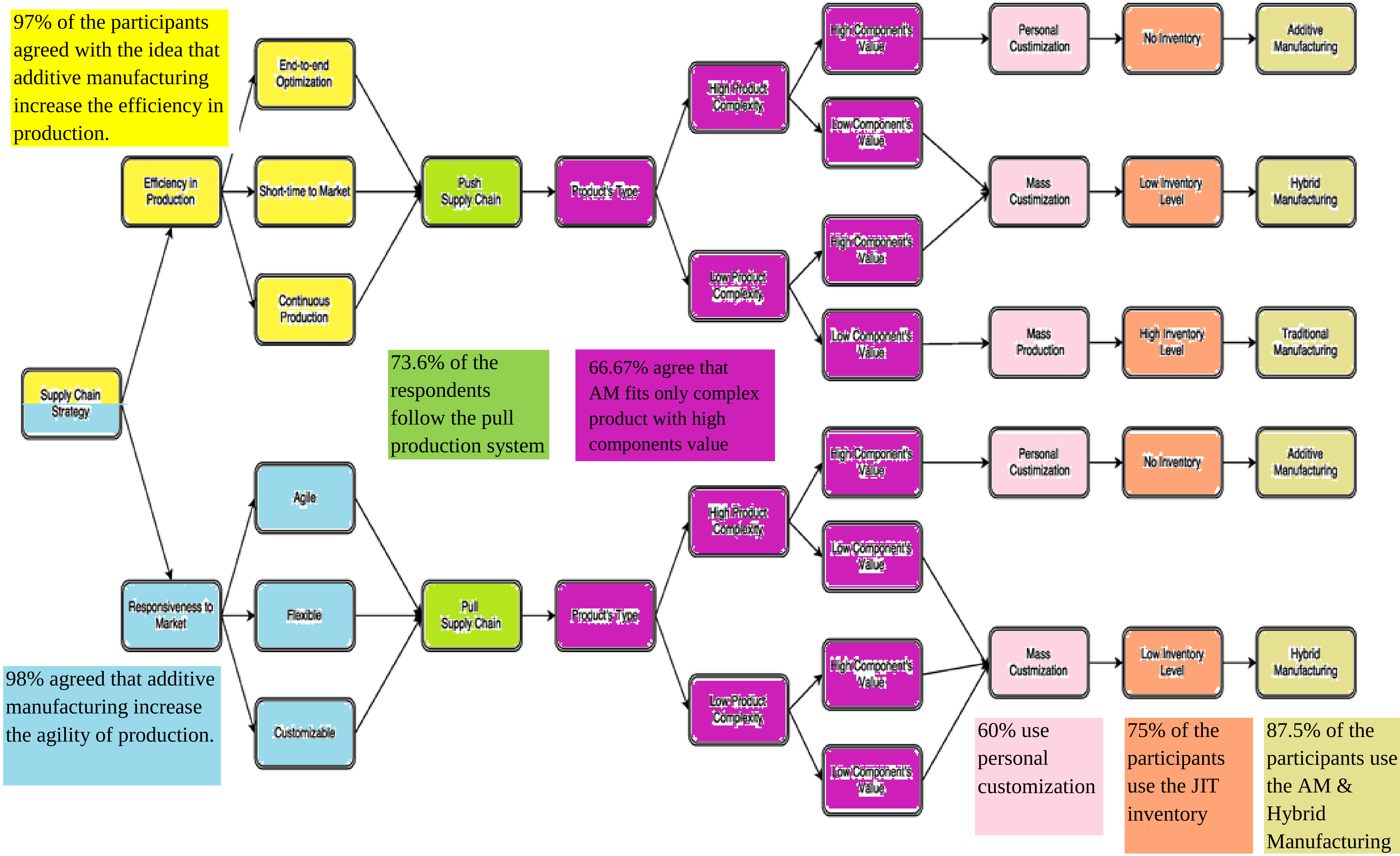

Timestamp
10.0
7.5
5.0
2.5
0.0
Mar 15, 2017
Mar 22, 2017
Mar 29, 2017
Apr 5, 2017

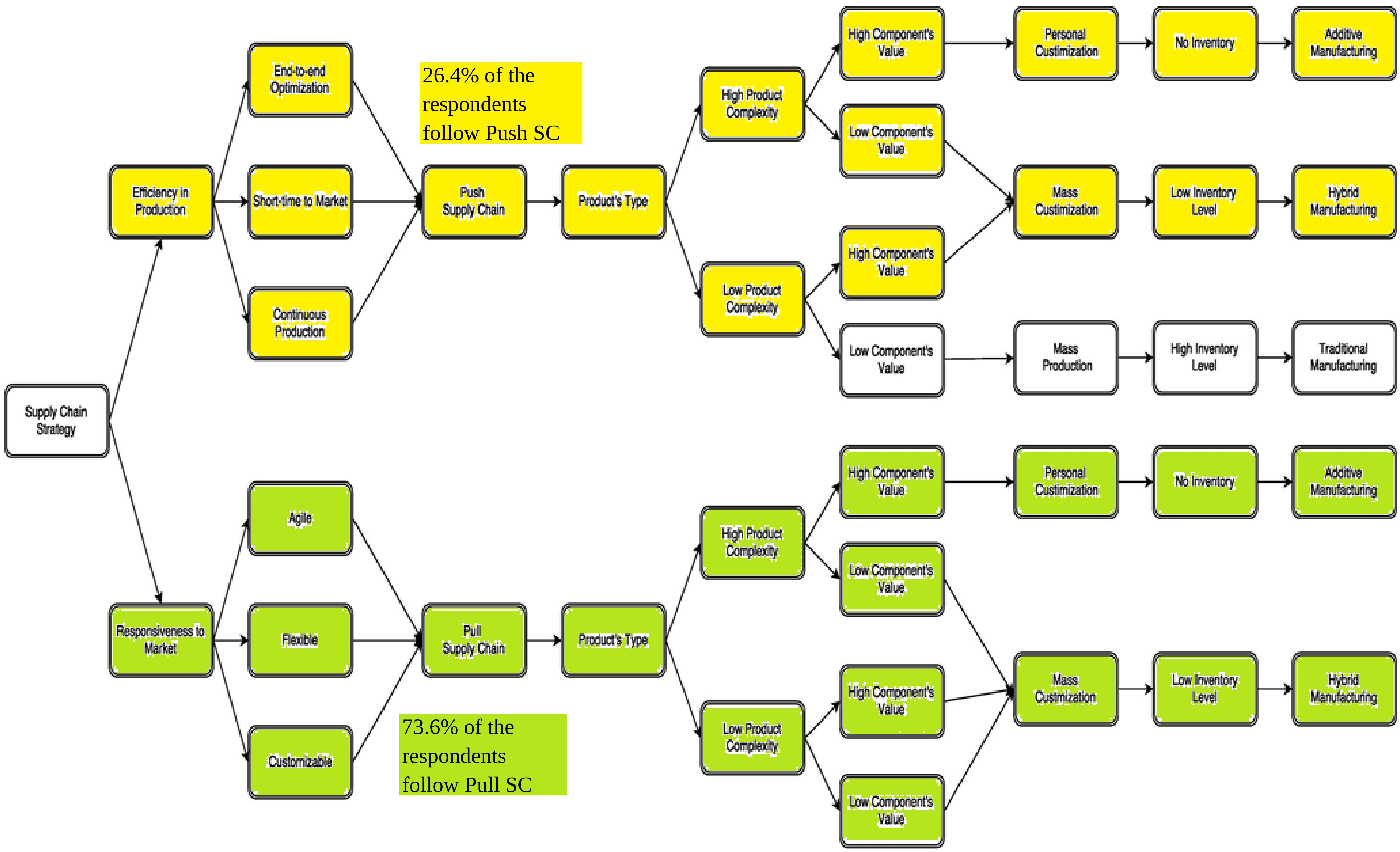
Appendix G

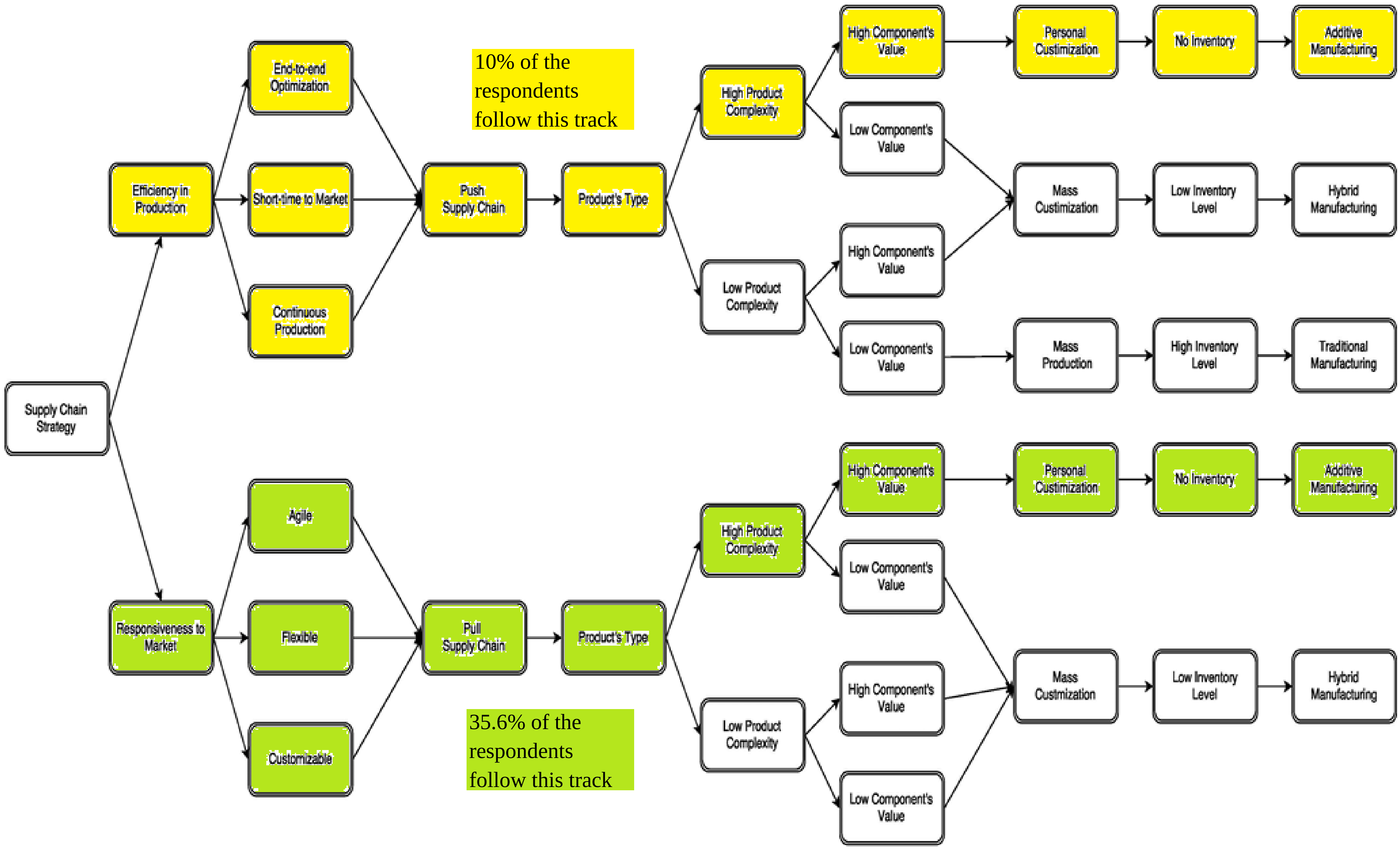
Reconciling Survey Questions with the Theoretical Framework



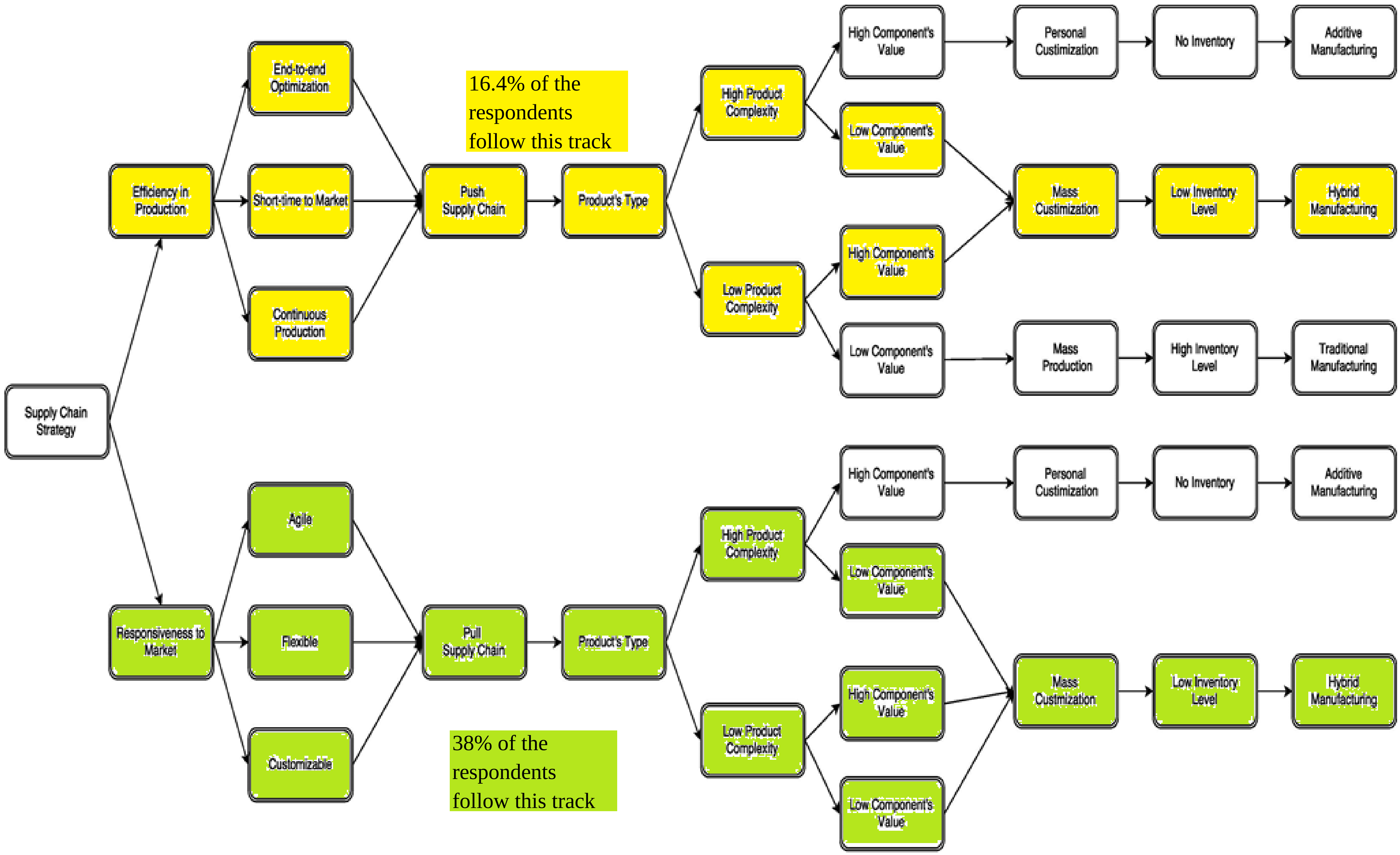
Questions:
9/11/13/14/15/16/
24/30/31/32
Supply Chain Strategy
Efficiency in Production
End-to-end Optimization
Short-time to Market
Continuous Production
Push Supply Chain
Product's Type
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
Mass Production
No Inventory
Low Inventory Level
High Inventory Level
Additive Manufacturing
Hybrid Manufacturing
Traditional Manufacturing
Questions:
9/10/11/14/21/25/
29
Question:
19
Responsiveness to Market
Agile
Flexible
Customizable
Pull Supply Chain
Product's Type
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
No Inventory
Low Inventory Level
Additive Manufacturing
Hybrid Manufacturing
Questions:
17/20/21/22/23/
28/29
Question:
11/20/21/
27/29
Question:
10/14/15/26/
28/30/32/33
Question:
7/8/


97% of the participants agreed with the idea that additive manufacturing increase the efficiency in production.
Supply Chain Strategy
Efficiency in Production
Responsiveness to Market
End-to-end Optimization
Short-time to Market
Continuous Production
Agile
Flexible
Customizable
Push Supply Chain
Pull Supply Chain
Product's Type
Product's Type
High Product Complexity
Low Product Complexity
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
Mass Production
Personal Custimization
Mass Custimization
No Inventory
Low Inventory Level
High Inventory Level
No Inventory
Low Inventory Level
Additive Manufacturing
Hybrid Manufacturing
Traditional Manufacturing
Additive Manufacturing
Hybrid Manufacturing
73.6% of the respondents follow the pull production system
66.67% agree that AM fits only complex product with high components value
98% agreed that additive manufacturing increase the agility of production.
60% use personal customization
75% of the participants use the JIT inventory
87.5% of the participants use the AM & Hybrid Manufacturing


Supply Chain Strategy
Efficiency in Production
End-to-end Optimization
Short-time to Market
Continuous Production
Push Supply Chain
26.4% of the respondents follow Push SC
Product's Type
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
Mass Production
No Inventory
Low Inventory Level
High Inventory Level
Additive Manufacturing
Hybrid Manufacturing
Traditional Manufacturing
Responsiveness to Market
Agile
Flexible
Customizable
Pull Supply Chain
73.6% of the respondents follow Pull SC
Product's Type
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
No Inventory
Low Inventory Level
Additive Manufacturing
Hybrid Manufacturing



Supply Chain Strategy
Efficiency in Production
End-to-end Optimization
Short-time to Market
Continuous Production
Push Supply Chain
Product's Type
10% of the respondents follow this track
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
No Inventory
Additive Manufacturing
Mass Custimization
Low Inventory Level
Hybrid Manufacturing
Mass Production
High Inventory Level
Traditional Manufacturing
Responsiveness to Market
Agile
Flexible
Customizable
Pull Supply Chain
Product's Type
35.6% of the respondents follow this track
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
No Inventory
Additive Manufacturing
Mass Custimization
Low Inventory Level
Hybrid Manufacturing


Supply Chain Strategy
Efficiency in Production
End-to-end Optimization
Short-time to Market
Continuous Production
Push Supply Chain
Product's Type
16.4% of the respondents follow this track
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
Mass Production
No Inventory
Low Inventory Level
High Inventory Level
Additive Manufacturing
Hybrid Manufacturing
Traditional Manufacturing
Responsiveness to Market
Agile
Flexible
Customizable
Pull Supply Chain
Product's Type
38% of the respondents follow this track
High Product Complexity
Low Product Complexity
High Component's Value
Low Component's Value
High Component's Value
Low Component's Value
Personal Custimization
Mass Custimization
No Inventory
Low Inventory Level
Additive Manufacturing
Hybrid Manufacturing