ADDITIVE MANUFACTURING IMPLEMENTATION
IN
HEALTHCARE SYSTEMS:
A SUPPLY CHAIN PERSPECTIVE

KONSTANTINOS CHALDOUPIS

Salford Business School

University of Salford, Salford UK

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Abstract

Additive Manufacturing (AM), or “3D Printing”, also called the ‘Third Industrial Revolution’, allows companies and individuals to “print-out” solid objects layer-by-layer based on access to 3-dimensional computer data. Several authors have pointed out that AM has the potential to reduce the number of stages in the traditional supply chain and to fundamentally revolutionize manufacturing operations and supply chains. Evidence suggests that AM technology as a driver of supply chain transformation it can achieve precision, speed, affordability, and materials range. Therefore, it has the potential to redesign products with fewer components and to manufacture products near the customers. Production applications of AM technologies can be found mainly in aerospace, automotive, medical, and consumer goods. Although a number of companies are already using AM technologies they face particular difficulties in the implementation process. In particular, studies on AM implementation are disappointingly absent, especially in relation to supply chain. Most studies on supply chain focus mainly on the potential disruptions of AM in distribution/logistics and therefore on location of manufacturing. Hence, an investigation on the key AM implementation factors within the various stages of a supply chain from the selection of raw material-equipment suppliers towards the customers needs to be examined.

This study proposes an AM implementation framework on supply chain. It focuses on the healthcare sector and medical device manufacturers. Healthcare organisations must constantly monitor supply chain performance to add value across entire supply chain. AM presents an effective and promising commercial proposition to respond to the increasing healthcare demands in the developing world by providing customized products, which can improve medical care, reduce healthcare costs by decreasing time spent under direct care and improve success rates. It is carried out through a case study research approach combined with background theory on advanced manufacturing systems. Three case studies were conducted to examine the AM implementation process on supply chain.

The most significant contribution of the research is the proposed AM implementation framework from a supply chain perspective. At the time of writing this is the first study which examines the AM implementation process on the supply chain of medical device manufacturers. Hence, AM medical device manufacturers can use it as a guide to develop their own implementation plans.

CHAPTER 1

INTRODUCTION

1.0 Introduction to Additive Manufacturing

Additive Manufacturing (AM) also called 3D printing has attracted increasing attention in recent years. The Economist (2012) has called 3D printing 'the third Industrial Revolution' due to rapid technical development in the area. Deloitte (2014) reports that AM can be used for both product and supply chain innovations. In relation to product characteristics, Holmstrom et al. (2010) has presented the special benefits of this technology which can be found in economical custom products, design customization, waste reduction and potential for simpler supply chains. In particular, from a supply chain perspective it has been suggested (Walter et al. 2004; Khajavi et al. 2014; Durach et al. 2017) that AM can be a disruptive force and completely alter manufacturers' perceptions on conventional supply chain and operations. AM technology has the potential of simplifying supply chains as it is capable of reducing the number of parts in a product and thus the number of links in a supply chain. This is because the technology compared with traditional techniques can deliver new products, which require highly specialized structures, with less material in various locations. As a result, AM can reduce the need for warehousing, transportation, and packaging and therefore bring out the potential of achieving rapid production close to the end users. Hence, AM can enable companies to achieve distributed manufacturing (Walter et al. 2004; Khajavi et al. 2014; Durach et al. 2017).

1.1 Overview of Additive Manufacturing

Gibson et al. (2015) state that the terms 3D Printing and AM are often used interchangeably, as both refer to the layer-by-layer creation of physical objects based on digital files that represent their design. Furthermore, 3D Printing has been used for more than two decades, primarily for rapid part prototyping and small- run production in a variety of industries (Gibson et al. 2015).

Reeves (2014) defines the difference between 3D Printing and AM according to which, 3D Printing is typically associated with people printing at home or in the community compared with AM which is associated more with production technologies and supply chains. However, the author underlines that both produce parts by the digital addition of layers (Reeves 2014).

The American Society for Testing and Materials International (ASTM committee F42) decided that the standard terminology to describe the entire field will be Additive Manufacturing. The terms 3D Printing and AM can be considered synonymous umbrella terms for all 3D Printing techniques.

According to ASTM (2009) Additive Manufacturing (AM) is defined as the manufacturing process to build three dimensional objects by adding layer-upon-layer of material. The committee points out that the process starts with a computer-aided-design (CAD) file that includes information about how the finished product is supposed to look. Furthermore, the material can be plastic, metal, concrete or even human tissue (ASTM 2009).

Campbell et al. (2011) presents the unique characteristics of AM production over traditional manufacturing techniques, which leads to the following benefits:

Create complex structures: The authors first point out that AM has the ability to create complex shapes that cannot be produced by any other conventional manufacturing methods. This is because when designers use AM processes can selectively place material only where it is needed and therefore they can create strong and complex structures that are also lightweight.

Manufacturing based on digital design: Furthermore, the authors emphasise that AM allows for overnight builds, which results in decreased time to produce products and thus the time between design iterations is reduced. According to the authors the reason for this is that all AM processes are based on a three - dimensional solid model and therefore these computer-controlled processes require a low level of operator expertise, which leads to less human interaction needed to create an object. In addition, the produced part represents the precise designer's intent as it is generated directly from the computer model and thus any inaccuracies found in traditional manufacturing processes are now eliminated.

Single tool process: Moreover, in traditional machining several tool changes are needed to create the finished product. However, when using AM, the desired geometry can be achieved without changes in any aspect of the process and therefore AM can be considered as a “single tool” process. Thus, AM in effect, makes shape complexity free as there is no additional cost or lead time between making an object complex or simple. As a result, the authors noted that AM processes can be excellent for creating customized, complex geometries.

Potential for global production: Here, the authors underline that the technology has the potential to achieve product distribution. AM processes are based on a digital file which can be sent to any printer anywhere that can manufacture any product within the design parameters of the file.

Sustainability: Finally, AM processes are inherently “green.” The authors explain that there is virtually zero waste since only the material needed for the part is used in production (Campbell et al. 2011).

1.2 Research Scope: AM Supply Chain Implementation

Production applications of AM technologies can be found mainly in aerospace, automotive, medical, and consumer goods. However, although that a number of companies are already using AM technologies they face particular difficulties in the implementation process. In particular, studies on AM implementation are disappointingly absent, especially in relation to supply chain. As it can be seen from the next section (1.3 Overview of the literature review), most studies on supply chain focus mainly on the potential disruptions of AM in distribution/logistics and therefore on location of manufacturing (Mellor et al. 2014; Ruffo et al. 2006; Walter et al. 2004; Tuck and Hague 2006; Sirichakwal1 and Conner 2016; Durach et al. 2017). Hence, an investigation on the key AM implementation factors within the various stages of a supply chain from the selection of raw material-equipment suppliers towards the customers needs to be examined. This will be central to the form of the AM implementation framework on supply chain, which is the overall aim of the thesis. This study focuses on the healthcare sector and medical device manufacturers – the vast majority of those are SMEs. Healthcare organisations must constantly monitor supply chain performance to add value across entire supply chain. AM presents an effective and promising commercial proposition to respond to the increasing healthcare demands in the developing world by providing customized products, which can improve medical care, reduce healthcare costs by decreasing time spent under direct care and improve success rates.

1.2.1 Aim

Therefore, the overall aim of the proposed research study will be to develop an AM implementation framework from a supply chain perspective.

1.2.2 Main research Question:

How do organisations implement AM as an operational process from a supply chain perspective?

Research questions:

- How does AM technology impact the supply chain?
- What are the key factors affecting implementation of AM on supply chain?
- How do those factors impact implementation of AM on supply chain?

The main objectives of this research are:

- To investigate the impact of AM process on supply chain.
- To develop a conceptual framework for implementation of AM on supply chain.
- To examine and enhance the proposed implementation factors on supply chain using real case studies.

1.3 Overview of the Literature Review

1.3.1 Additive Manufacturing Technology as a Driver of Supply Chain Transformation

Several authors (Walter et al. 2004; Tuck and Hague 2006; Holmström et al. 2010; Khajavi et al. 2014; Durach et al. 2017) have stated that AM can have a disruptive effect on conventional supply chains as it is capable of shortening them by reducing their number of stages with immediate impact on their operations. According to the authors AM technology, as a driver of supply chain transformation, has the potential when compared with traditional techniques to deliver new products, which require highly specialized structures, with less materials in various locations. As a result, the authors point out that AM can reduce the need for warehousing, transportation, and packaging and therefore it has the potential to deliver small production volumes for different market segments. Thus, it can be possible to achieve distributed manufacturing (Walter et al. 2004; Tuck and Hague 2006; Holmström et al. 2010;

Khajavi et al. 2014; Durach et al. 2017). Table 1.1 presents the differences between a traditional supply chain and an AM supply chain.

Table 1.1: Traditional supply chain versus Additive Manufacturing supply chain Source: The Author

Traditional supply chain	AM supply chain
Goods are sold based on a 'push' sales strategy	On demand production – Agility Faster deployment of changes
Long lead times of transportation	Less time to market for products
High transport cost	Low transport cost
Mass production – Economies of scale	Specialist production – No economies of scale
High inventory costs	Spare parts inventory management – Less spare parts in stock

In particular, Waller and Fawcett (2014) state that AM can be very useful for materials and spare parts inventory management as it uses only the material needed and therefore less material required in the production process. As a result, the technology can have potential implications throughout the stages of the supply chain from purchasing towards inventory management and transportation. Furthermore, AM allows for more agility and responsiveness to market changes as the technology is used for rapid prototyping and therefore the time required for product development is significantly less. Therefore, based on the above, the technology is more appropriate for low volume production and thus meets particular customer needs with high value/specialist production. Finally, as the technology is based on digital data which can be sent to any printer and thus is location independent it has the potential to 'push' goods into different markets close to the end users and hence to achieve distributed – decentralised manufacturing (Waller and Fawcett 2014). The following Figure 1.1 illustrates the potential of the technology to deliver goods straight to the end users and thus reduce the number of stages within a supply chain.

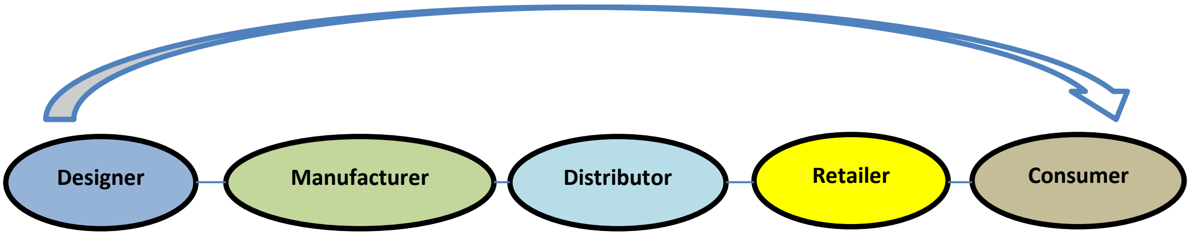


Figure 1.1: Additive Manufacturing Supply Chain. Source: The Author

There are several studies which examine the key aspects which need to be considered by managers when incorporating AM within their supply chain. Kieviet (2014) identified the need to develop a comprehensive tool to incorporate all aspects of supply chain performance (costs, service, quality, and lead time) within the field of complexity management. Sebastian and Omera (2015) suggested that for managers to eliminate the effects of disruption to their future supply chains they need to produce a flexible management strategy which will take advantage of the resulting opportunities. Rylands (2015) concluded that when managers consider deploying AM within production, they need to examine all key aspects categories which include technical, social, managerial and environmental.

Other studies focus on the potential disruptions of AM in global supply chains, transportation, inventory and logistics. Bhasin and Bodla (2014) suggested that AM will significantly reduce transportation and inventory costs as production in future supply chains will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer. Ye (2015) developed an AM Competitiveness Score Model to assess and quantify its competitiveness (or impact) in centralised as well as decentralised manufacturing setups. Mashhadi et al. (2015) utilised simulation tools such as Agent Based Simulation (ABS) and System Dynamics (SD) to evaluate AM supply chain. Durach et al. (2017) concluded that scenarios which involve an increase in decentralized manufacturing or the rise of AM printing services have a strong potential to become true rather than mass customization or a significant reduction of inventory.

Further studies investigate the social impact/sustainability of AM. Reeves (2009) addressed the Design-For-Manufacturing (DFM) rules associated with applications of AM to manufacture lighter weight, energy efficient products with fewer raw materials as a sustainable alternative to conventional machining. Huang et al. (2013) reviewed the societal impact of AM from a technical perspective. White and Lynskey (2013) compared aspects of traditional subtractive technologies and AM, such as cost of production, supply chain infrastructure, and sustainability to justify the potential economic benefit of using AM in application to end-useable parts. Kellens et al. (2017) concluded that from an environmental perspective, AM can be a good alternative for producing customized parts or small production runs as well as complex part designs creating substantial functional advantages during the part-use phase.

There are two extreme types of AM positioning models that companies can choose from. First the centralized model in which production facilities are concentrated in a particular location and serve the world market from that location. The other option is decentralizing production, where production facilities distribute in various regional or national locations close to the major markets (Holmström et al. 2010).

Walter et al. (2004) presents new supply chain solutions made possible by both the centralised and decentralised applications of AM. The authors demonstrate the benefits of AM technologies in the supply chain by focusing on the aircraft spare parts. According to their results, centralised has the potential advantage of cutting high inventory costs (of slow moving parts) and reducing the need to subsidise costs with profit of fast moving parts. In contrast the potential of distributed manufacturing can be found where demand is sufficient enough at a given location (Walter et al. 2004).

Hasan and Rennie (2008) following Walter's (2004) study on spare parts, presented a paper which investigates the applications of AM in the spare parts industry. Their findings reinforced the case that in order for AM technologies to be widely adopted fully functional supply chains are required. The authors in an attempt to enable such a supply chain, proposed a business model based on an e-business platform (Hasan and Rennie 2008).

Tuck and Hague (2006) in their approach in relation to centralised and decentralised applications of AM looked into the potential impact of AM on the supply chain infrastructure and logistics from a lean-agile supply chain perspective. According to their findings when lean principles are applied, AM has the possibility to provide goods at low cost and at fast response which is required in volatile markets. The authors also predict that local manufacturing is likely to lead to a reduction in transport costs and that the burden of part cost will move from skilled labour operating machinery to the technology and material (Tuck and Hague 2006).

Tuck et al. (2007) in another paper continued with the investigation of the flexibility of AM in a number of industrial sectors. The authors again here discuss the potential impact of AM on supply chain paradigms and reinforce their study with example cases from automotive production, motor sport and medical devices industries (Tuck et al. 2007).

Holmström et al. (2010) have also examined the potential disruptions of AM in the spare parts supply chain in the aircraft industry. According to their study, distributed deployment of AM can be very interesting for spare parts supply as it has the capability to improve service and reduce inventory. However, the authors believe that the distributed approach can become more feasible only if additive manufacturing develops into a widely-adopted process. The authors concluded that currently on demand centralized production of spare parts or deployment close to the point of use by generalist service providers of AM is the most likely approach to succeed considering the trade-offs affecting deployment (Holmström et al. 2010).

Khajavi et al. (2014) continued with the contribution on centralised and decentralised applications of AM on the configuration of spare parts supply chains. The authors developed a scenario modeling of a real-life spare parts supply chain in the aeronautics industry. The purpose of their study was to compare the operating cost of centralized additive manufacturing production and distributed production, where production is in close proximity to the consumer. According to their findings distributed production led to a reduction in inventory costs and spare parts transportation costs. However, their study also found that the initial investment in additive manufacturing machines and the significant increases in personnel costs make distributed manufacturing more expensive than centralized production. Therefore, in order for the distributed scenario to be more feasible AM machines must become less capital intensive, more autonomous and offer shorter production cycles (Khajavi et al. 2014).

Sirichakwall and Conner (2016) have utilised an approximate one-for-one inventory model for spare parts to analyse how inventory-related benefits can be derived from reductions in holding cost and production lead time. The authors concluded that (a) a reduction in holding cost has more impact on reducing the stock-out probability when the average demand rate for spare parts is low and (b) lead time reduction may negatively affect the stock-out probability.

1.4. Overview of the Research Design and Methodology

1.4.1 Philosophical basis of the study

According to Saunders et al. (2003) and his developed model for research methods known as 'onion', the research process can be defined in three 'layers': the outer layer is the research philosophy, followed by the research approach and finally the third layer the research strategy. Once the researcher has successfully completed the above stages then will be able to collect the data within a 'time horizon' (Saunders et al. 2003).

1.4.2 Interpretivism philosophy

Referring to the first stage the author identifies three philosophical paradigms: Positivism, Interpretivism and Realism. This study in relation to the first layer follows an Interpretivism philosophy as it involves implementation and therefore is an on-going process. The aim of the study is to investigate the implementation of AM on supply chain and the researcher is called to explore on the issues which emerge during this process. Therefore, the framework will be enhanced based on each organisations implementation process.

1.4.3 Inductive research approach

The researcher has followed an inductive research approach. Thomas (2006) states that this type of approach begins with the examination of specific information in relation to the research area, then an initial theory begins to emerge, which will be explored later with a view to develop a concept or a framework. The author states that the purpose of the framework is to incorporate the key themes in relation to the research area (Thomas 2006).

1.4.4 Research Strategy - Selection of Method

The researcher will follow a case study research associated with the qualitative research approach in order to be able to study in-depth the AM implementation factors within the supply chain. However, the case study on its own cannot provide an adequate methodology for the central research question taking also into consideration the exploratory nature of the research, which indicated by the lack of implementation studies in the field of AM. Therefore, the case study will be combined with background theory to enable the researcher to use existing knowledge on process technology implementation and develop an AM implementation framework on supply chain (Yin 2014). In addition, Voss et al. (2002)

emphasised that when this research approach is applied in operations management it can develop new theory and increase validity (Yin 2014; Voss 2002).

1.4.5 Evaluation of Research Method

According to Benbasat et al. (1987) the main strength of the case study approach is that it can be more applicable for studies which require further exploration, through a building process towards knowledge as it allows the researcher to collect in depth data for a particular phenomenon. Furthermore, the researcher through development stages can generate theory which has the potential to be tested. However, Flyvbjerg (2006) has argued that case study results through data collection are subjective and cannot be applicable to the broad population (Benbasat et al. 1987; Flyvbjerg 2006). The researcher in order to increase validity and develop general propositions uses a multi-case study approach with the aim to cover all the key AM implementation factors with particular impact on supply chain.

The researcher will focus on the healthcare sector. This particular sector has been chosen for two reasons: a) The medical sector in the UK is the largest adopter of AM. b) Applications in the medical sector have moved from prototyping to finished products (Rand 2013; PwC 2014).

1.4.6 Research Contribution

The most significant contribution of the research is the development of the AM implementation framework from a supply chain perspective with particular emphasis on the healthcare sector. At the time of writing this is the first study which examines the AM implementation process within the supply chain of medical device manufacturers. Hence, AM medical device manufacturers can use it as a guide in order to develop their own implementation plans.

1.5 Structure of Thesis

The thesis is structured as follows: The first chapter presents the background to research problem including an overview of the AM technology and some of the most influential studies on the impact of the AM technology on supply chain. This has led to the identification of the research gap and the lack of studies regarding the AM implementation from a supply chain perspective. Research questions and objectives are provided aiming to achieve the overall aim which is to develop an AM implementation framework from a supply chain perspective. Also, a summary of the chosen research method is presented based on a case study approach within the healthcare sector and medical device manufacturers. This chapter concludes with the main contributions of the research.

The second chapter presents the literature review used in accordance with the research questions. The chapter is structured as follows; The first section reviews AM technologies, the industry and applications. The second section provides a review of Advanced Manufacturing Technology implementation. The third section presents the latest studies on the impact of the AM technology on supply chain including AM implementation research in order to clearly define the lack of implementation studies from a supply chain perspective.

The third chapter describes the research methods employed in this study to answer the proposed research questions and achieve the research objectives. First it presents the philosophical underpinnings of the research in accordance with the qualitative research approach. Then the research design is explained including the case study approach and the data collection tools. Finally, the chapter concludes with the presentation of the methodology used for analysing the data collected.

The fourth chapter presents the pilot study, as the first stage of the data collection process, which was conducted to assist the researcher to gain an insight into the basic issues being investigated and at the same time to become familiar with the AM implementation process when examined from a supply chain perspective. The pilot study was utilised to examine and enhance the initial implementation framework based on literature review.

The fifth chapter describes the implementation framework. It first explains how the framework is developed and then presents the background of the development of the implementation factors within each construct. The proposed framework has included the results from the pilot case study, presented in the previous chapter, which were utilised to enhance the initial AM framework.

The sixth chapter in this thesis presents the multi case study. The implementation framework is examined on three medical device manufacturers, based on within-case analysis. The purpose is to identify and further enhance the proposed implementation factors and reach a comprehensive knowledge in relation to the implementation of technology when it is examined from a supply chain perspective.

The seventh chapter following the within case-analysis examines similarities and differences between the case studies in terms of their implementation process. For this purpose, the issues/activities, identified in the implementation process for each case study in relation to proposed factors are compared to provide a further insight to implementation of technology from a supply chain perspective.

Finally, the eighth chapter presents the conclusions of the study. This chapter provides the main contributions and limitations of study and explains the theoretical and practical implications of the research. Areas for future research are also included.

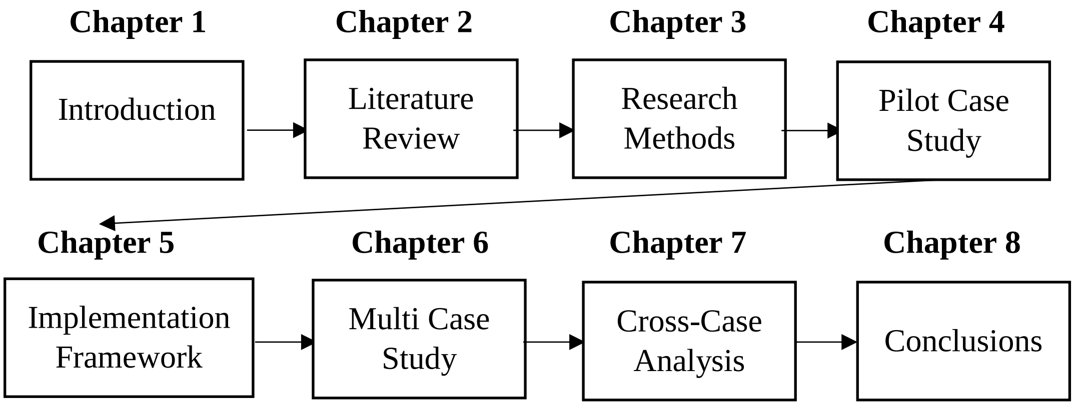


Figure 1.2: Thesis Structure, Source: The Author

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents the literature review performed in the research study. The aim of the literature review chapter is to provide answer for the first research question and identify the research gap. The research question - objective is the following:

Research question:

- How does AM technology impact the supply chain?

Research Objective:

- To investigate the impact of AM process on supply chain.

For this purpose, the chapter is structured as follows: the first section reviews AM technologies, the industry and applications. The second section examines Advanced Manufacturing Technology Implementation (AMT). The overall aim of the thesis is to develop an implementation framework for AM from a supply chain perspective and thus is necessary first to examine the existing literature on implementation of Advanced Manufacturing technologies (AMT). The third section provides an overview of Supply Chain Management (SCM) and presents the latest studies on the impact of the AM technology on supply chain including AM implementation research in order to clearly define the lack of implementation studies from the supply chain perspective.

2.1 Additive Manufacturing (AM)

Additive Manufacturing (AM) is based on the principal that the model, which is initially generated using digital 3D design data, does not require any tools, handwork and process planning to be fabricated. Although this may not be applicable for every case, AM technology can significantly simplify the process of producing complex 3D structures directly from CAD data. In conventional manufacturing methods, the selected tools, which will be used to fabricate different features of the model, are the result of careful planning and analysis of the part geometry. On the other hand, when AM is utilised, only some basic dimensional details and a small amount of understanding of the machine and materials is required in order for individuals to be part of the technology process (Gibson et al. 2015).

There is a number of stages involved within the AM process which will result to the final product. In the first stage a computerized 3D solid model is developed, which presents all the relevant geometric information regarding the final object. The 3D model is then converted into a standard AM file format such as the traditional standard tessellation language format or the recent AM file format. The STL file is transferred to the AM machine where it is manipulated, e.g., changing the position and orientation of the part or scaling the part. The AM machine is properly set up in relation to material constraints, layer thickness, energy source and so on for the building process to start. The part is built layer by layer within the AM machine and in most cases, does not require supervision as the process is automatic. Part removal takes place, once the AM machine has completed the build. After the part is built, some parts may require additional cleaning and removal of supporting structures. Experienced manual manipulation could be required within this stage. Once the previous stage has been completed the part is ready for use (Gibson et al. 2015). The following Figure 2.1 illustrates the generic AM process from CAD to physical part.

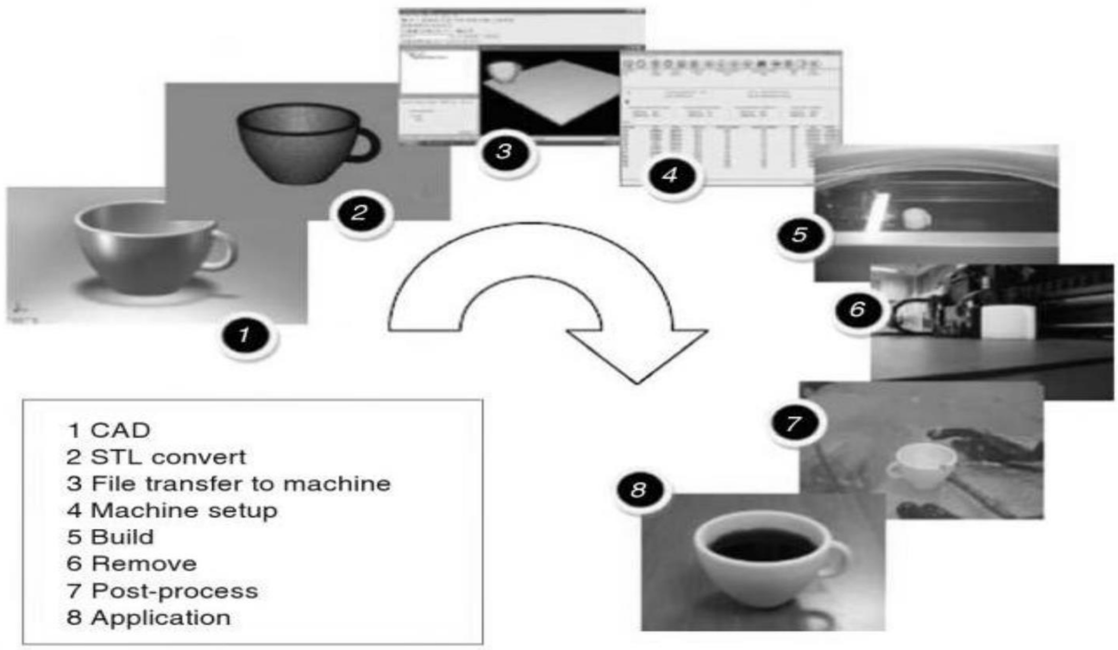


Figure 2.1: Generic AM process from CAD to physical part

Source: Gibson et al. (2015)

2.2 History of Additive Manufacturing

According to Sealy (2011) although that early AM experiments date back to the 60s, it was not until the in the 80s that AM could be commercialized with the use of associated technologies such as computer-aided design (CAD) software, lasers and controllers. Wirth (2014) points out that the history of AM started in the year 1986 with Charles Hull who patented a technology for printing physical 3D objects from digital data. He named this process 'Stereolithography' and founded the company 3D Systems, which later became one of the leading companies in the AM industry (Sealy 2011; Wirth 2014).

Furthermore, Wallenius and Decade (2014) underline that Stratasys was the second major player in the AM industry with very similar beginnings. Scott Crump with his invention of fused deposition modelling (FDM) founded the company in 1989. According to the authors the field of AM is dominated by the two industry leaders, Stratasys and 3D Systems. This is because they manufacture AM machines in all three technology categories, sell a wide range of AM materials guaranteed to be compatible with their machines, and offer support services for their customers (Wallenius and Decade 2014).

An overview of the developments in the following years and other important events in the history of AM are given in Table 2.1.

Table 2.1: Historical overview of the development of Additive Manufacturing. Source: Wirth (2014), adapted from Van West (2011); Wohler and Caffrey (2013)

Time	Event
1986	Charles Hull obtained a patent for Stereolithography.
1988	Scott Crump invented fused Deposition Modelling.
1991	The first Layer Laminate Manufacturing machine was sold.
1992	Selective Laser Sintering machines were released.
1993	MIT patented "3 dimensional printing techniques".
	The revenue for AM products and services worldwide is about $100 million.
2001	The average selling price for industrial additive manufacturing systems was about $118,000.
2006	RepRap, a self-replicating 3D printer, started as an open source project.
2007	The unit sales for personal 3D printers were about 65.
2010	Additive manufacturing had been used to bioprint blood vessels.
	The market for additive manufacturing grew up to $1.3 billion.

2012	About 7,800 industrial systems have been sold in 2012.
	The average selling price for industrial systems was about $79,500.
	Sales of personal 3D printers reach about 35,500 units, as fully assembled printers for home use are available from $1,500.
	The market for additive manufacturing, consisting of products and services grew up to $2.2 billion.

Examining the evolution of the technology, AM traditionally was used to build conceptual prototypes. This process was known as Rapid Prototyping (RP), which is often used as a synonym to AM. However, technological advancements towards the development of manufacturing functional prototypes has led to the evolution of Rapid Manufacturing (RM). Dimov et al. (2001) states that this concept is based on technologies that utilise layer manufacturing processes to produce parts. The authors explain that the main enabling technologies behind RM can be categorised in two groups: Rapid Prototyping (RP) and Rapid Tooling (RT). According to the authors RP includes processes for quickly fabricating physical models, functional prototypes and small batches of parts directly from cad models (Dimov et al. 2001).

On the other hand, Chua et al. (2003) underline that Rapid Tooling (RT) refers to the rapid production of parts that function as a tool which are used to serve traditional manufacturing methods. In particular, Levy et al. (2003) noted that tooling refers mainly to plastic injection moulds which are considered to be the most frequently used forming tools. The following Figure 2.2 shows the AM categories.

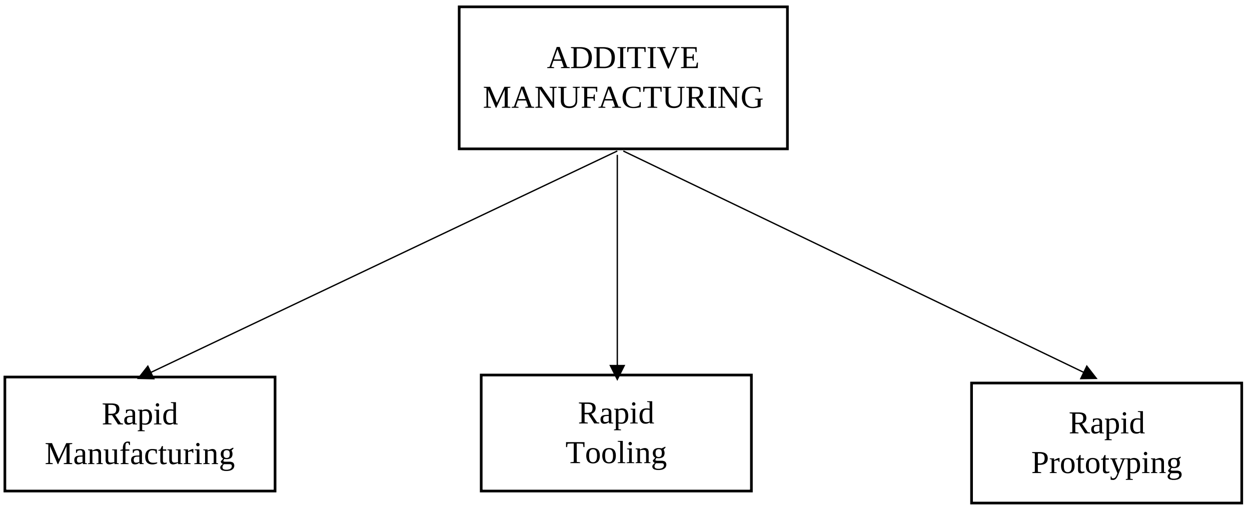


Figure 2.2: Additive Manufacturing categories, adapted from Levy et al. (2003)

2.3 Additive Manufacturing Technologies

According to Mellor (2014) the mechanisms and materials introduced along with the technological advancements have resulted in a number of different methods of categorising AM processes. The author adapted the Hopkinson et al. (2006) form of categorisation, which identified three basic materials states to categorise AM processes; liquid, powder and solid (Mellor 2014). This form of categorisation is presented in Table 2.2.

Table 2.2: AM processes categorised according to supply material state. Mellor (2014, p 12), adapted from Hopkinson et al. (2006)

Material State	Process	Materials
Liquid	Stereolithography (SL)	Polymers
	Fused Deposition Modelling (FDM)	Polymers
	Inkjet Printing (IJP)	Polymers
Powder	3D Printing (3DP)	Polymers, Metals, Ceramics
	Selective Laser Sintering (SLS)	Polymers, Metals, Ceramics
	Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS)	Polymers, Metals, Ceramics
	Electron Beam Melting (EBM)	Metals
	Direct Metal Deposition (DMD)	Metals
Solid	Laminated Object Modelling (LOM)	Polymers, Metals, Ceramics and Composites

2.3.1 Liquid-based processes

2.3.1.1 Stereolithography Apparatus (SLA)

The first of the liquid process for making models is known as Stereolithography Apparatus (SLA). Chua et al. (2003, p.42) described the SLA process as follows: “the process begins with the vat filled with the photo-curable liquid resin and the elevator table set just below the surface of the liquid resin. The operator loads a three-dimensional CAD solid model file into the system. Supports are designed to stabilise the part during building. The translator converts the CAD data into a STL file. The control unit slices the model and support into a series of cross sections from 0.025 to 0.5 mm (0.001 to 0.020 in) thick. The computer-controlled optical scanning system then directs and focuses the laser beam so that it solidifies a two-dimensional cross-section corresponding to the slice on the surface of the photo-curable liquid resin to a depth greater than one-layer thickness. The elevator table then drops enough to cover the solid polymer with another layer of the liquid resin. A levelling wiper or vacuum blade moves across the surfaces to recoat the next layer of resin on the surface. The laser then draws the next layer. This process continues building the part from bottom up, until the system completes the part. The part is then raised out of the vat and cleaned of excess polymer" (Chua et al. 2003, p.42).

Gibson et al. (2015) pointed out that the advantages of the technology can be found in part accuracy and surface finish. On the other hand, limitations are related mainly to the usage of photopolymers, since the chemistries are limited to acrylates and epoxies for commercial materials. Furthermore, the authors outlined that the current SL materials do not have the impact strength and durability of good quality injection molded thermoplastics. As a result of those limitations SL processes are not yet appropriate for production applications (Gibson et al. 2015).

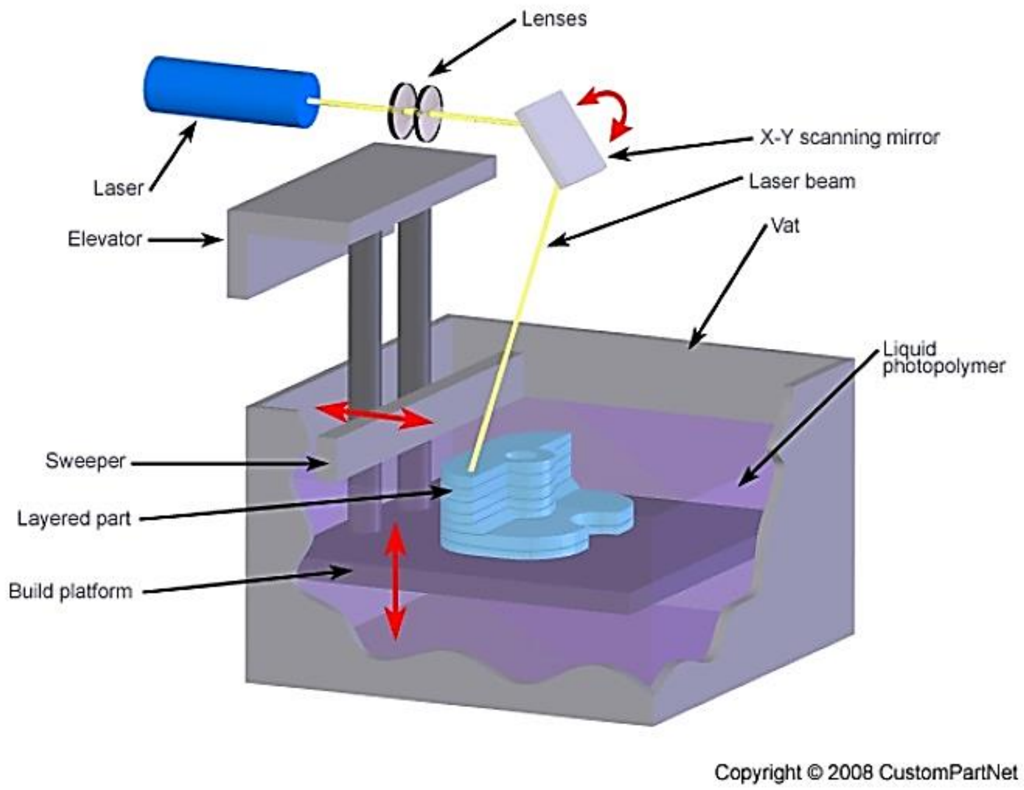


Figure 2.3: Stereolithography Apparatus (SLA)

Source: Custompartnet (2008)

2.3.1.2 Fused Deposition Modelling (FDM)

The second most commonly used AM technology after SLA is known as FDM and applications of the process can be found in prototyping, modelling and manufacture applications. Chua et al. (2003, p.114) described the FDM system as follows: “the CAD file is sliced into horizontal layers after the part is oriented for the optimum build position, and any necessary support structures are automatically detected and generated. The slice thickness can be set manually to anywhere between 0.172 to 0.356 mm (0.005 to 0.014 in) depending on the needs of the models. Tool paths of the build process are then generated which are downloaded to the FDM machine. The modelling material is in spools very much like a fishing line. The filament on the spools is fed into an extrusion head and heated to a semi-liquid state. The semiliquid material is extruded through the head and then deposited in ultra-thin layers from the FDM head, one layer at a time. Since the air surrounding the head is maintained at a temperature below the materials’ melting point, the exiting material quickly solidifies. Moving on the X–Y plane, the head follows the tool path generated by Quick Slice or Insight generating the desired layer. When the layer is completed, the head moves on to create the next layer. The horizontal width of the extruded material can vary between 0.250 to 0.965 mm depending on model. This feature, called ‘road width’, can vary from slice to slice. Two modeller materials are dispensed through a dual tip mechanism in the FDM machine. A primary modeller material is used to produce the model geometry and a secondary material, or release material, is used to produce the support structures. The release material forms a bond with the primary modeller material and can be washed away upon completion of the 3-D models” (Chua et al. 2003, p.114).

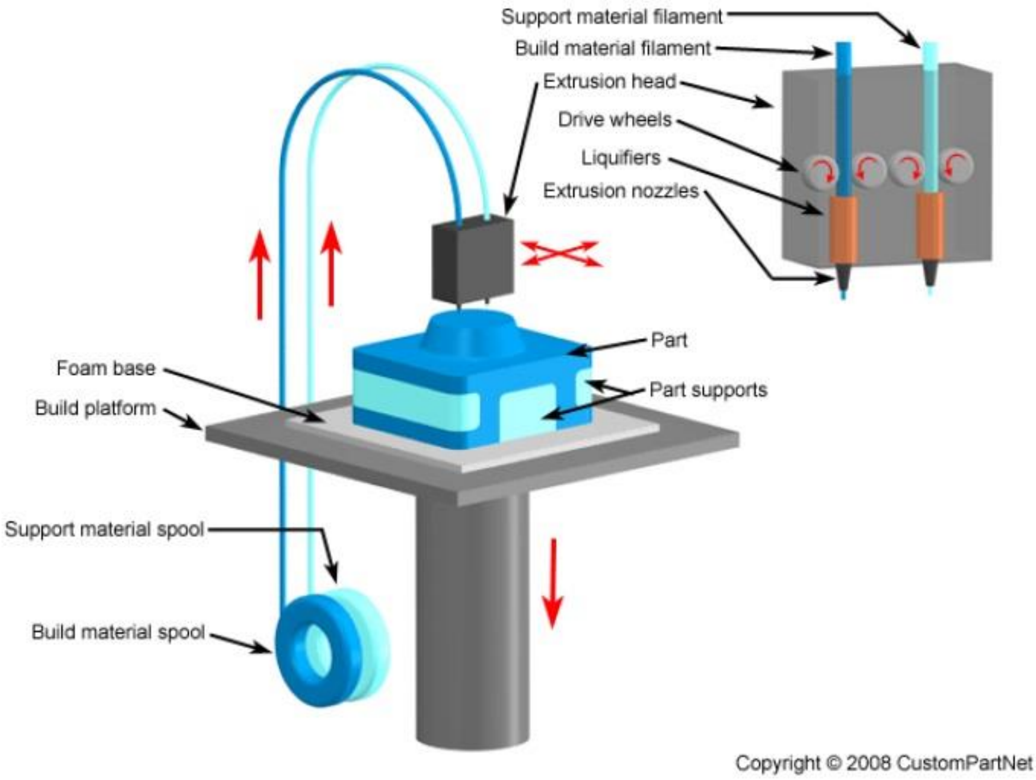


Figure 2.4: Fused Deposition Modelling (FDM)

Source: Custompartnet (2008)

2.3.1.3 Inkjet Printing (IJP)

Ink Jet Printing (IJP) is another popular process used for RP mostly, based on the two-dimensional printer technology storing liquid thermoplastic build and support material in headed reservoirs. The materials flow towards the inkjet head in which piezoelectric nozzles deposit droplets on demand to create layers down to 19 µm (Gatto et al. 1998). Singh et al. (2010, p.673) described the 3DP process as follows: "The process essentially involves the ejection of a fixed quantity of ink in a chamber, from a nozzle through a sudden, quasi-adiabatic reduction of the chamber volume via piezoelectric action. A chamber filled with liquid is contracted in response to application of an external voltage. This sudden reduction sets up a shockwave in the liquid, which causes a liquid drop to eject from the nozzle. The ejected drop falls under action of gravity and air resistance until it impinges on the substrate, spreads under momentum acquired in the motion, and surface tension aided flow along the surface. The drop then dries through solvent evaporation. Recent studies show that drop spreading and the final printed shape strongly depend on the viscosity, which in turn is a function of the molar mass of the polymer. More interestingly, the aforementioned group also found a printing height dependence of the final dried-drop diameter, which was a function of the polymer concentration" (Singh et al. 2010, p.673).

Kruth et al. (2007) noted that although, IJT offers accuracy and surface quality the slow build speed, the few material options and the fragile finished parts makes this technology almost solely suitable for prototyping and investment casting (Kruth et al. 2007).

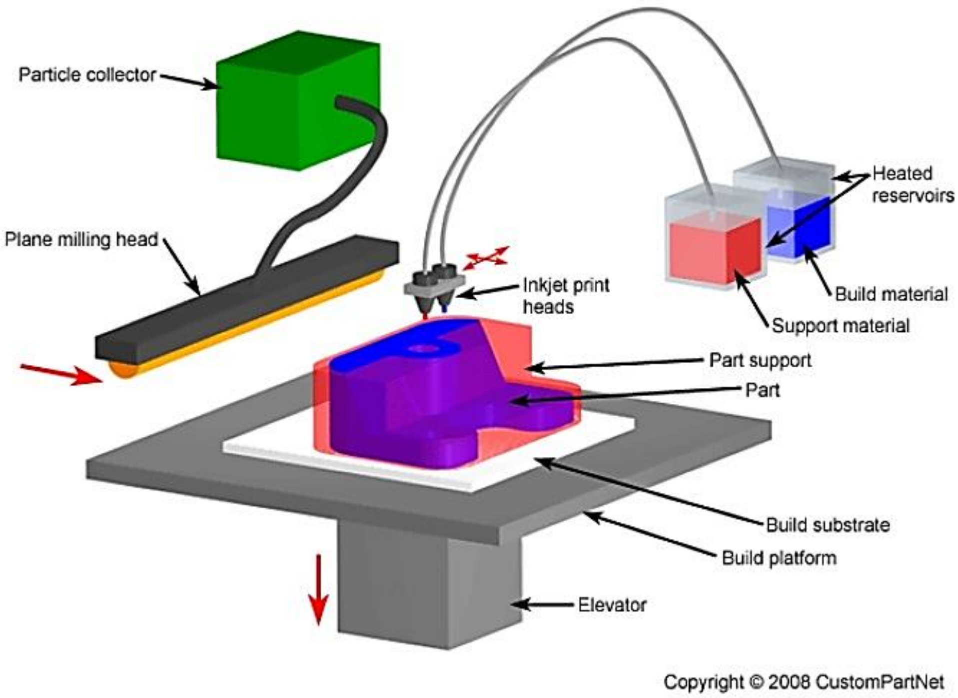


Figure 2.5: Inkjet Printing (IJP)

Source: Custompartnet (2008)

2.3.2 Powder-based processes

2.3.2.1 Selective Laser Sintering SLS

Selective Laser Sintering (SLS) is an AM powder based process that was originally developed by University of Texas at Austin in USA and commercialized by a company called DTM (later acquired by 3D systems Inc) (Hanemann et al.2006). Chua et al. (2003, p.175) described the SLS process as follows: "the STL file format are first transferred to the Vanguard™ system where they are sliced. From this point, the SLS process starts and operates as follows: (1) a thin layer of heat-fusible powder is deposited onto the part-building chamber; (2) The bottom-most cross-sectional slice of the CAD part under fabrication is selectively "drawn" (or scanned) on the layer of powder by a heat-generating CO2 laser. The interaction of the laser beam with the powder elevates the temperature to the point of melting, fusing the powder particles to form a solid mass. The intensity of the laser beam is modulated to melt the powder only in areas defined by the part's geometry. Surrounding powder remains a loose compact and serves as supports; (3) when the cross-section is completely drawn; an additional layer of powder is deposited via a roller mechanism on top of the previously scanned layer. This prepares the next layer for scanning; (4) Steps 2 and 3 are repeated, with each layer fusing to the layer below it. Successive layers of powder are deposited and the process is repeated until the part is completed. As SLS materials are in powdered form, the powder not melted or fused during processing serves as a customized, built-in support" (Chua et al. 2003, p.175).

According to Soe (2012) the advantages of the SLS process are: there is no need to have support structures when building parts, so parts can be built freely in the building chamber which increases productivity and lowers cost and also the parts produced are characterized by having good mechanical properties (Soe 2012).

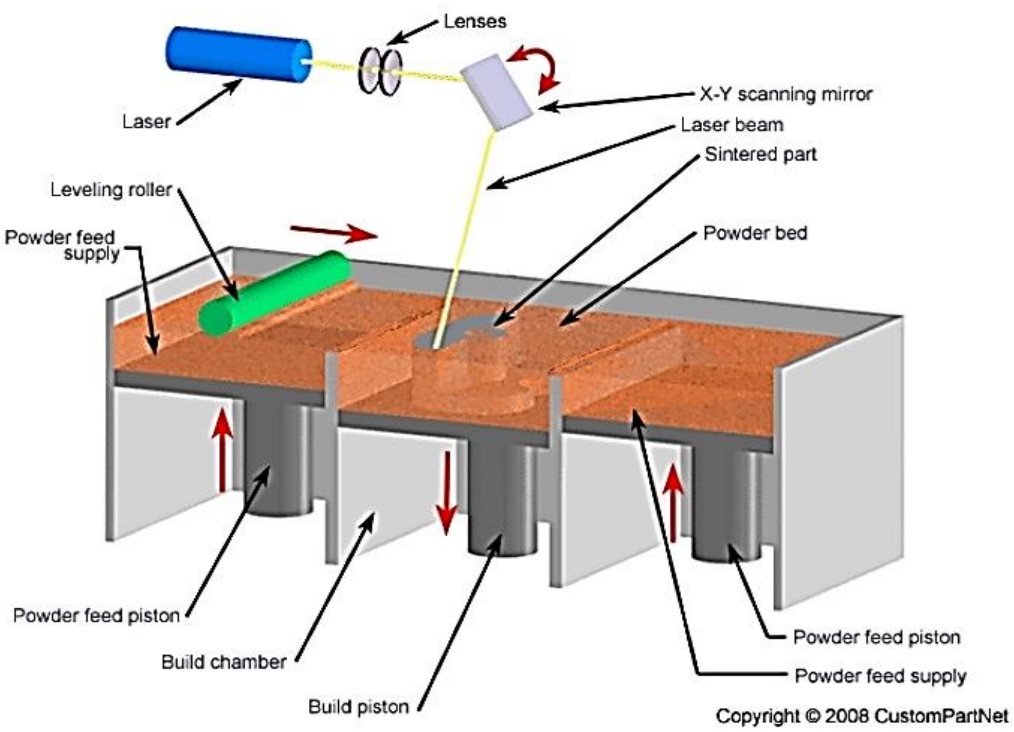


Figure 2.6: Selective Laser Sintering SLS

Source: Custompartnet (2008)

2.3.2.2 Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS)

Both SLM and DMLS are powder-bed AM melting processes and are grouped together in this sub-section due to their process similarities. Mellor (2014, p.17) based on Mumtaz and Hopkinson (2009) described the process as follows: ‘’Both are laser based powder-bed processes, capable of processing metallic, ceramics and polymers. Metal powders are most commonly used and are supplied in powder distribution size around 10 – 40 microns. The powder is dispersed over a build platform at 20 – 40 micron layers using a powder re-coater. A high-power laser (50W – 1kW) driven by the machine software then traces the contour and infill to melt the powder selectively. EOS, machine vendor for the DMLS process, suggest that metallic parts of 99.99% dense are achievable, with reports showing that properties can be comparable those of a cast or machined component. Support structures are required for overhanging features and anchors are required due to the high thermal stresses involve in the process. Similar to SL these support structures require more overall material and post processing. Some of the most commonly used metals include cobalt chromium, titanium alloys, steel alloys and tool steels’’ (Mellor, 2014, p.17).

Mumtaz and Hopkinson (2009) noted that the main advantage of SLM is the capability to build complex geometries that would otherwise be difficult or impossible to produce using conventional manufacturing processes. According to the authors this is due to the versatility, accuracy and small spot size of a laser beam. On the other hand, limitations of the technology can be found mainly on the surface roughness due to particle melting, melt pool stability and re-solidifying mechanisms (Mumtaz and Hopkinson 2009).

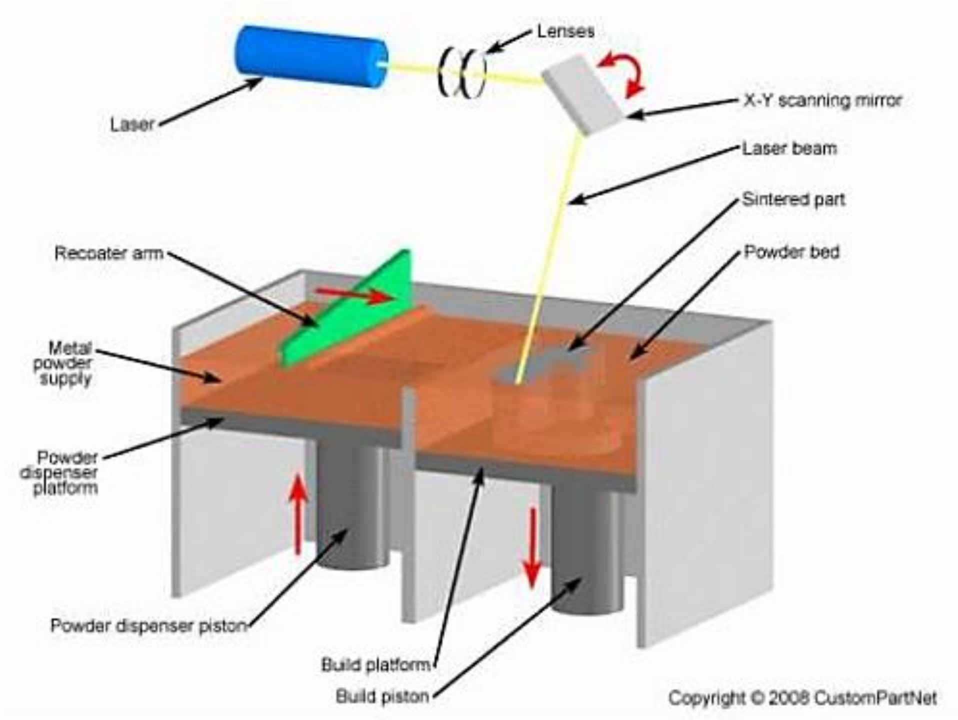


Figure 2.7: Direct Metal Laser Sintering (DMLS)
Source: Custompartnet (2008)

2.3.2.3 Electron Beam Melting (EBM)

Electron Beam Melting (EBM) technology builds fully dense parts from metal powder. Aliakbari (2012, p.22) based on Arcam (2009) described the process as follows**: ‘’**The metal powder is melted by an electron beam (power of up to 3kW) and so the technology uses high energy to provide high melting capacity and productivity. Parts are free from residual stresses and distortions. The required temperature is specific for different alloys, and the electron beam maintains that temperature. Then for each layer, the beam melts contours of the 2D shape of part and finally the balk; i.e. the surface area within the contours. Building parts at elevated temperatures results in stress-relieved products with good material properties. Also, the process occurs in a vacuum space to maintain the chemical specification of the powder material. Arcam, the owner of EBM patent, claims that their machines provide parts with excellent properties for strength, elasticity, fatigue, chemical composition, and microstructure’’ (Aliakbari 2012, p.22).

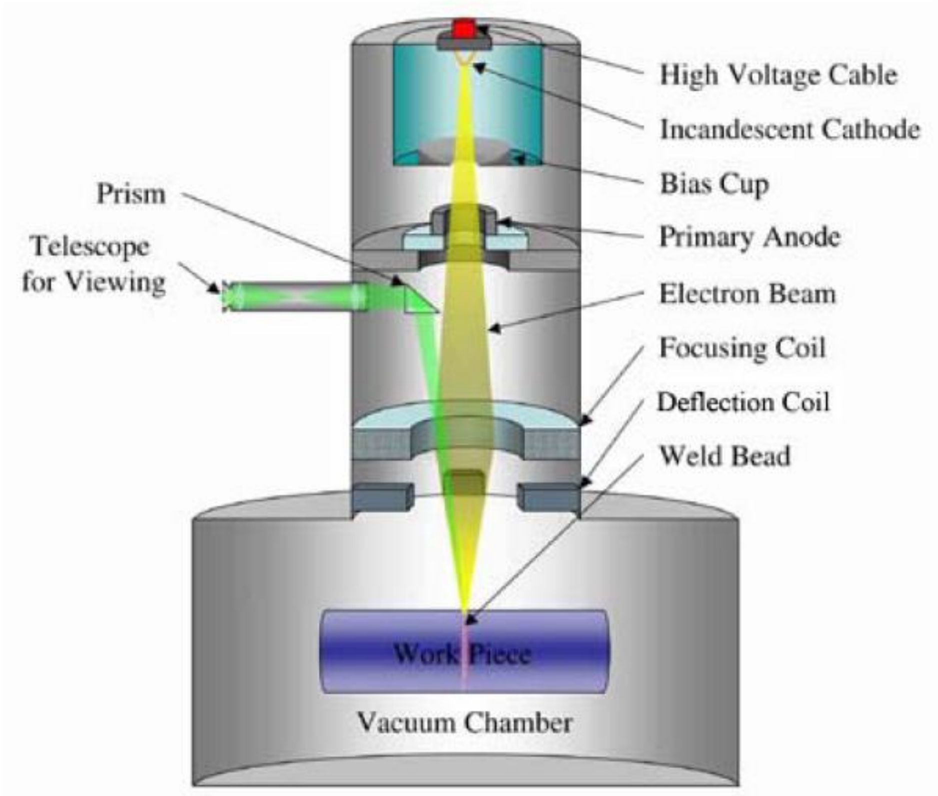


Figure 2.8: Electron Beam Melting (EBM)

Source: Custompartnet (2008)

2.3.3 Solid-based processes

2.3.3.1 Laminated Object Modelling (LOM)

In Laminated Object Manufacturing (LOM), sheets of paper, plastic, metal or composites are used. The sheets are formed layer by layer, using a laser and then a hot roller to bond the new layer to the previous one. On completion of the process the unwanted material is removed (Shames 2010). Chua et al. (2003, p.138) described the LOM process as follows: "in the building phase, thin layers of adhesive-coated material are sequentially bonded to each other and individually cut by a CO2 laser beam. The build cycle has the following steps: (1) LOMSlice™ creates a cross-section of the 3-D model measuring the exact height of the model and slices the horizontal plane accordingly. The software then images crosshatches which define the outer perimeter and convert these excess materials into a support structure. (2) The computer generates precise calculations, which guide the focused laser beam to cut the cross-sectional outline, the cross-hatches, and the model's perimeter. The laser beam power is designed to cut exactly the thickness of one layer of material at a time. After the perimeter is burned, everything within the model's boundary is "freed" from the remaining sheet. (3) The platform with the stack of previously formed layers descends and a new section of material advances. The platform ascends and the heated roller laminates the material to the stack with a single reciprocal motion, thereby bonding it to the previous layer. (4) The vertical encoder measures the height of the stack and relays the new height to LOMSlice™, which calculates the cross section for the next layer as the laser cuts the model's current layer. This sequence continues until all the layers are built. The product emerges from the LOM™ machine as a completely enclosed rectangular block containing the part" (Chua et al. 2003, p.138).

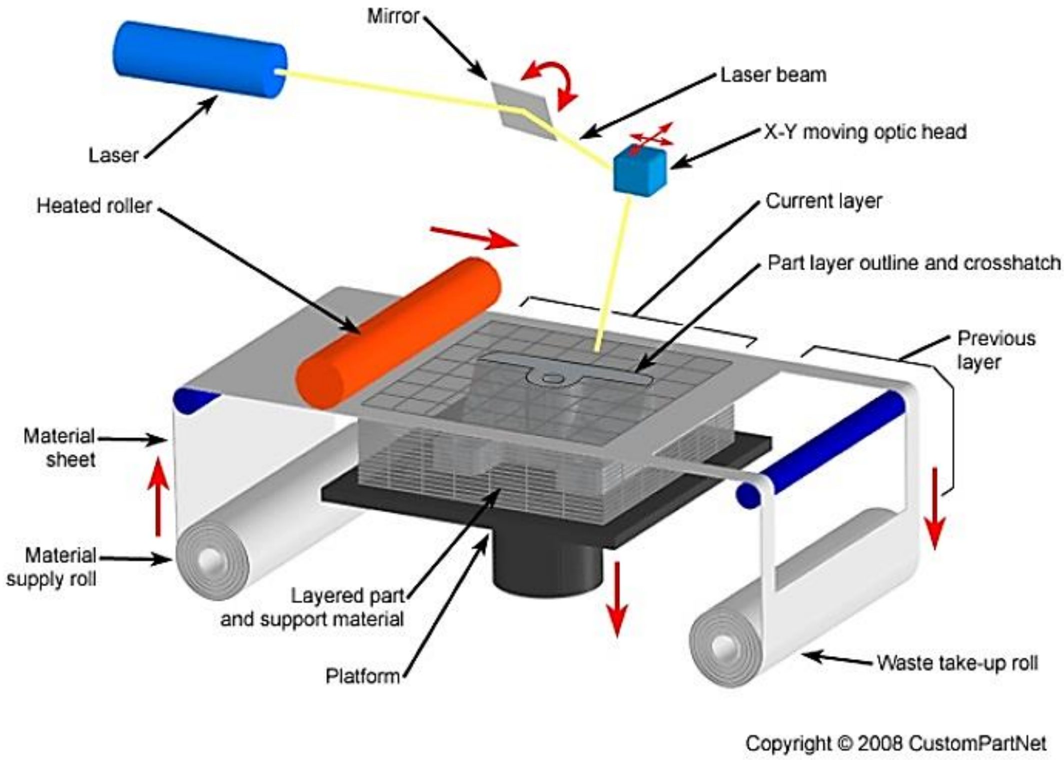


Figure 2.9: Laminated Object Modelling (LOM)

Source: Custompartnet (2008)

The following Table 2.3 provides information on each AM technology including advantages and drawbacks.

Table 2.3: Additive Manufacturing Processes: Advantages and Drawbacks

Source Ochi (2014, p 17)

AM Process	**Technology Summary**	**Material Type(s)**	**Strengths/Weaknesses**
SLA	Photosensitive liquid resin solidified by selective exposure to ultraviolet light. New layer of resin added once previous cross-section is complete	Acrylates Epoxies Resins (can be glass, ceramic, metal)	High-resolution, limited materials
SLS	Layers of powder are fused or sintered together by laser beam(s)	Metals Sand Ceramics Polymers (pure or filled)	No support structure, very high-temperature
3DP	Layer of powder is deposited and solidified by ink-jet printed binder. New layer of powder added once previous cross-section complete.	Ceramics Metals Polymers	Low-temperature, no support structure, low surface-quality
FDM	Stream(s) of heated viscous material deposited on build plate or previous layer, cools to solid state. New layer of material added once previous cross-section is complete.	Thermoplastics Wax Organics Polymers and binders containing glass, metals, ceramics	Inexpensive, can print multiple materials simultaneously
LOM	Thin sheets of material are laminated together only on desired cross-section of the layer, remaining material cut away by knife or laser, then new sheet applied or rolled on	Paper Polymers Composites Ceramics Metals	Full density, internal cavities easy, shrinkage after postprocessing

EMB	Surface layer of powder is melted together using a high-energy electron beam focused by magnetic coils. New layer of powder added once previous cross-section complete	Metals	High density, low energy consumption, must be in vacuum, expensive, small build volume

Munoz et al. (2013) provides a list with the main developers in any given AM technology area which is adapted from the ASTM International (2012). The following Table 2.4 summarizes the seven process classifications and technologies that comprise the AM market with selected market participants (Munoz et al. 2013; ASTM International (2012).

Table 2.4: Classification of additive manufacturing technologies including main developers. Munoz et al. (2013, p 6)
Source: ASTM International (ASTM International 2012)

Classification	Technology	Description	Materials	Developers (Country)
Binder Jetting	3D Printing Ink-jetting S-Print M-Print	Created objects by depositing a binding agent to join powdered material.	Metal, Polymer, Ceramic	ExOne (USA) VoxelJet (Germany) 3D Systems (USA)
Direct Energy Deposition	Direct Metal Deposition Laser Deposition Laser Consolidation Electron Beam Direct Melting	Builds parts by using focused thermal energy to fuse materials as they are deposited on a substrate.	Metal, Powder and Wire	DM3D (US) NRC-IMI (Canada) Irepa Laser (France) Trumpf (Germany) Sciaky (US)
Material Extrusion	Fused Deposition Modeling	Creates objects by dispensing material through a nozzle to build layers.	Polymer	Stratasys (US) Delta Micro Factory (China) 3D Systems (US)

Material Jetting	Polyjet Ink-jetting Thermojet	Builds parts by depositing small droplets or build material, which are then cured by exposure to light.	Photopolymer, Wax	Stratasys (US) LUXeXcel (Netherlands) 3D Systems (US)
Powder Bed Fusion	Direct Metal Laser Sintering Selective Laser Melting Electron Beam Melting Selective Laser Sintering	Creates objects by using thermal energy to fuse regions of a powder bed.	Metal, Polymer, Ceramic	EOS (Germany) Renishaw (UK) Phenix Systems (France) Matsuura Machinery (Japan) ARCAM (Sweden) 3D Systems (US)
Sheet Lamination	Ultrasonic Consolidation Laminated Object Manufacture	Builds parts by trimming sheets of material and binding them together in layers.	Hybrids, Metallic, Ceramic	Fabrisonic (US) CAM-LEM (US)
VAT Photopolymerisation	Stereolithography Digital Light Processing	Builds parts by using light to selectively cure layers of material in a vat of photopolymer.	Photopolymer, Ceramic	3D Systems (US) Envision TEC (Germany) DWS Srl (Italy) Litnoz (Austria)

2.4 Additive Manufacturing Industry and Applications

Cotteleer (2014) from Deloitte Services, adopts the Wohlers Associates report (2013) which predicts that the market for AM products and services will reach $10.8 billion worldwide by

2020. According to the report the global additive manufacturing market reached sales of $3.0 billion in 2013, a growth of 35 percent over sales of $2.3 billion in 2012. As a result, the AM industry over the last 25 years has grown by 25.4 percent, and 29 percent in the last three years (Cotteleer 2014; Wohlers Associates report 2013). The following Figure 2.10 shows AM industry by market size.

Figure 2.10: AM Industry Market size. Deloitte (2014, p6)

Source: Wohlers Data (2013)

According to Morgan Stanley (2013) which also adopts the Wohlers report (2013), consumer and auto are the current leaders. Furthermore, after consumer products at 22%, the next most important market is estimated to be motor vehicles at 19% always in accordance with the same report. Moreover, the report points out that the third-largest sector is medical/dental, at 16%. Finally, aerospace and military combined are the fourth largest market at 15% (Morgan Stanley 2013; Wohlers report 2013). The following Figure 2.11 shows the key industries today:

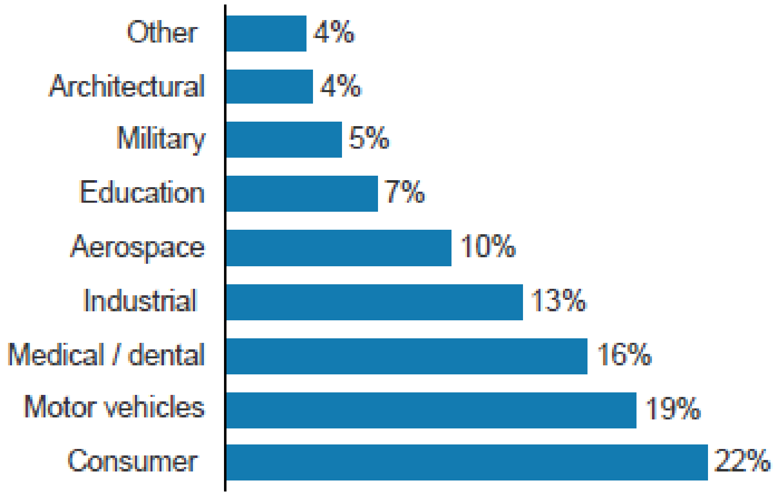


Figure 2.11: AM: Key Industries today. Morgan Stanley (2013, p10)

Source: Wohlers Report (2013)

Again here, Cotteleer (2014) from Deloitte Services with reference to Wohlers report (2013) state that in AM Industry, Prototyping (38%), tooling (27%) and functional parts (29%) lead among applications. The author noted that functional part production is growing faster than rest of market. Furthermore, the author emphasise that AM users and providers should move from prototyping and focus on end-parts production (Cotteleer 2014; Wohlers report 2013). The following Figure 2.12 shows AM systems deployments by applications:

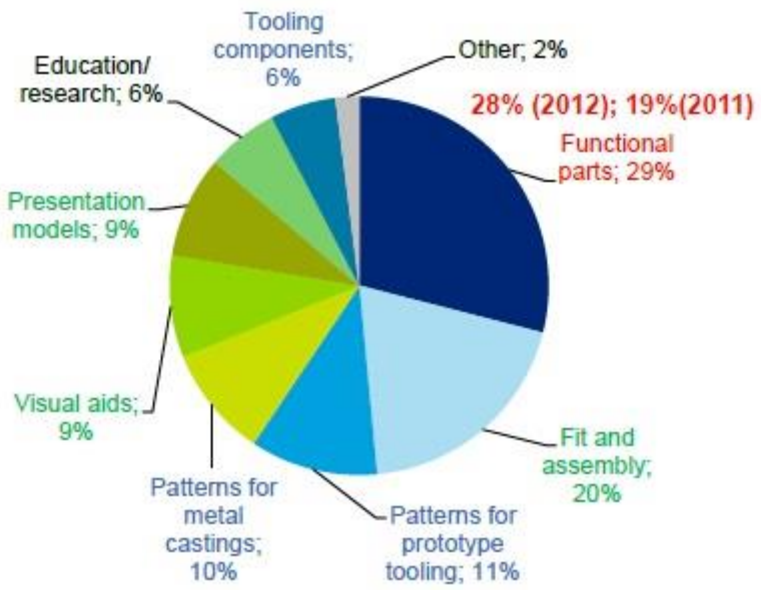


Figure 2.12: AM systems deployments by applications. Deloitte (2014, p7)

Source: Wohlers Data (2013)

Currently prototyping is still probably the largest application of AM followed by tooling and functional parts. However, according to PwC and the technology forecast (2014), although that prototyping will remain quite important, it will not be the main game changer in order for the AM technology to reach its potential benefits and move into high volume use cases. The report states that the AM industry should focus on opportunities which include production of final products or components (PwC 2014).

According to the latest report from Wohlers (2018), 135 companies around the world produced and sold industrial AM systems in 2017. In 2016, 97 manufacturers produced and sold AM systems, compared to 62 companies in 2015 and 49 in 2014. As a result, the industry is becoming highly competitive and it is marked by the entrance of new manufacturers who put pressure on the established producers of AM systems. An estimated 1,768 metal AM system were sold in 2017, compared to 983 systems in 2016, an increase of nearly 80%. This dramatic rise in metal AM system installations accompanies improved process monitoring and quality assurance measures in metal AM, although more work is ahead. Increasingly, global manufacturers are becoming aware of the benefits of producing metal parts by AM (Wohlers 2018).

Additive Manufacturing technology has experienced significant advances and today the technology is being used by a variety of industries.

2.4.1 Aerospace

Karagol (2014) based on Wohlers (2011) report, states that applications of AM technology can be found in the aerospace industry in a number of aircraft parts. In particular, according to the author AM machines produce aircraft parts with complex shapes or assembled from different parts and as a result the AM technology has contributed in tooling, inspection, maintenance, assembly and inventory (Karagol 2014; Wohlers 2011).

2.4.2 Automotive

AM in automotive industry has being wide - practiced by major manufactures in different geographic locations. In particular Mellor (2014) points out that in automotive AM applications have being confined to prototyping and tooling and provided an engineering solution to reduce lead times for economic low volume series production of a high value part (Mellor 2014).

2.4.3 Healthcare

Ventola (2014) describes the benefits of the technology in the medical sector where AM technologies are being used for a host of different applications. The author points out that AM produce a variety of accurately customized services, including implants and prosthetic devices, surgical instruments, tissue engineering, pharmaceuticals and dosage forms, medical and dental devices (Ventola 2014).

2.4.4 Consumer goods

Finally, the consumer market is expected to experience the biggest growth in AM. Here, Aliakbari (2012) also based on Wohlers (2011) report, points out that AM machines can make sculptural products, jewellery and fashion designs, home furnishings, textiles and even food. Consumers can also benefit from the technology as AM can offer them the potential of ordering their products online or even designing their own products (Aliakbari 2012; Wohlers 2011).

2.5 Additive Manufacturing Implementation

According to Ye (2015) governments and agencies use the Manufacturing Readiness Level (MRL), in order to assess the maturity of an evolving manufacturing method within selected industries. The author adopts the (MRL) from AM Platform (2014) and Roland Berger Strategy Consultants (2013), which shows how far a technology is from implementation, as a technology has to go through experimentation, refinement and realistic testing before it is released for adoption (Figure 2.13). In particular, the MRL is consisted of 10 levels with level 10 being the most mature and level 1 the least mature.

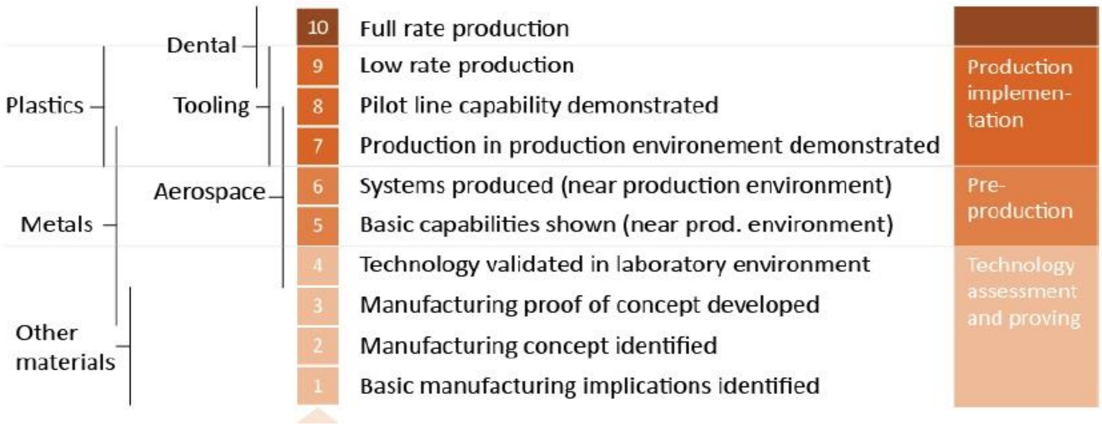


Figure 2.13: Mao Ye (2015, p10). Manufacturing Readiness Level

Source: AM Platform (2014) and Roland Berger Strategy Consultants (2013)

Therefore, the author states that it is clear from the above table that AM applications can be found at all levels on the MRL scale. In particular, AM plastic processes (they use plastics as a material) can be generally found at higher levels (MRL 7-9) in comparison with metal processes (MRL 3-7). Furthermore, the author points out that the dental industry in terms of using AM for production seems to be the furthest (MRL 9-10). In addition, the author underlines that the dental industry is followed by tool making with MRL between 7 and 9. Finally aerospace industry falls between MRL 4 and 8 (Ye 2015; AM Platform 2014; Roland Berger Strategy Consultants 2013).

However, according to PwC and the technology forecast (2014) there are many challenges for the AM industry despite its rapid growth. In particular, although that rapid prototyping is the main application of the AM industry, it will not be able to explore in the future the potential of the AM technology and deliver high volume productivity. The report states that the industry should aim for more fully functional and finished products or components in volumes that greatly outnumber the volumes of prototypes produced (PwC 2014).

The following Figure 2.14 from the PwC (2014) shows that prototyping has driven the adoption of AM so far and the lack of AM implementation within companies.

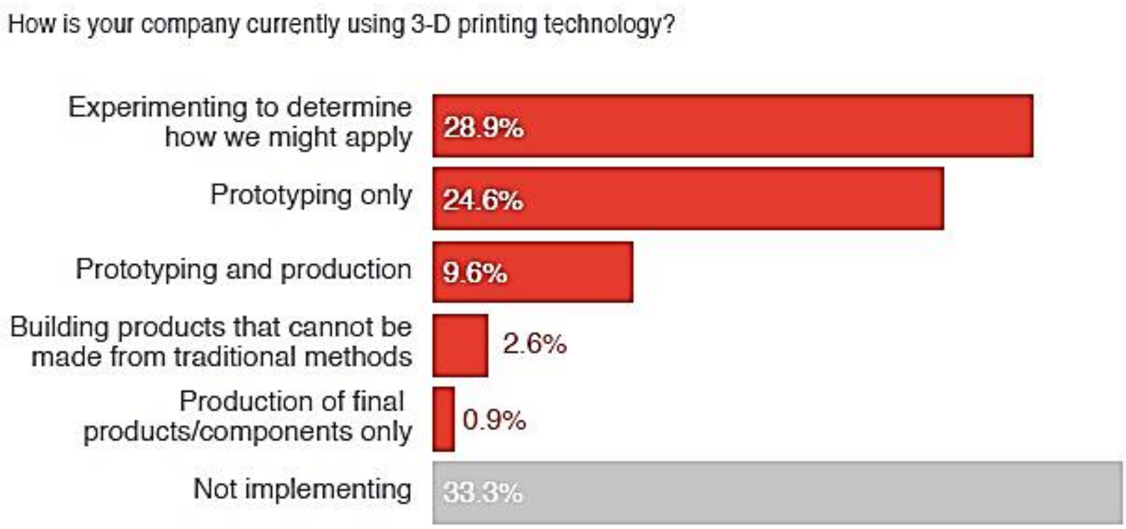


Figure 2.14: Prototyping has driven the adoption of AM technologies so far

Source: PwC (2014, p5)

The following Table 2.5 from Mohajeri, et al. (2014) adapted from Zäh and Hagemann (2006); Holmström et al. (2010) shows the benefits and limitations of AM Technology.

Table 2.5: Mohajeri et al. (2014, p1306). Benefits and shortcomings of AM, adapted from Zäh and Hagemann (2006); Holmström et al. (2010)

Benefits	Shortcomings
- More flexible development - Easier design and construction - Integration of functions - Less assembly - No production's tooling - Less spare parts in stock - Less complexity in business because of less parts to manage - No tools for productions need to hold in stock (only digital/CAD data) - Less time-to-market for products - Faster deployment of changes - Offer of individual products	- Available software is a limiting factor - High machine and material costs - High calibration effort - Quality of parts is in need of improvement - Rework of parts is often necessary (support structures) - Building time depends on the height of the part in the building chamber

2.6 Advanced Manufacturing Technology (AMT)

2.6.1 Advanced Manufacturing Technology Defined

Zairi (1992) defines advanced manufacturing technologies (AMT) as a social–technical system that requires continuous revisions, readjustments, and changes, in order to be able to adapt and respond to the changing demands of the competitive world, which is a very general goal but, at the same time, source of confusion (Zairi 1992p. 123).

Zammuto and O'Connor (1992) defines AMT as 'a family of technologies that include computer-assisted design and engineering systems, materials resource planning systems, automated materials handling systems, robotics, computer numerically controlled machines, flexible manufacturing systems, and computer-integrated manufacturing systems'. The common factor among these technologies is the use of computers to store and manipulate data (Zammuto and O'Connor 1992, p. 701).

Baldwin and Diverty (1995) defines AMT as 'the use of any integrated hardware-based and software-based technology from a functional group - design and engineering, fabrication and assembly, automated material handling, communications and inspection, manufacturing information systems, and integration and control'. The aim of these technologies is to improve efficiency and effectiveness of the firm in manufacturing a product or providing a service (Baldwin and Diverty 1995, p 5).

Beaumont et al. (2002) in his research categorises AMT into three categories: Direct, Indirect and Administrative. In relation to ‘Direct’ the technology can be found on the factory floor to cut, join, reshape and in general to modify materials. Examples of the technology within this category can be found in numerically controlled machinery and production line robots. Examining the ‘Indirect’ attributes the technology can be utilised to design products and schedule production. Examples here include computer – aided design and manufacturing resource planning (MRP) as well as production monitoring systems. Finally, ‘Administrative’ aspects of the technology are employed to provide administrative support to the factory in terms of integrating its operations with the rest of the organisation. Examples here can be found within cost control and communication systems which co-ordinate the electronic data within the various parts of the company (Beaumont et al. 2002).

Gunawardana (2006) states that the term AMT refers to computer-aided technologies and includes a number of variables in relation to design, manufacturing, transportation and testing, etc. According to the author AMT can be categorized into two principle ways: The classical continuum of basic manufacturing processes which extends from make-to-order manufacturing to continuous manufacturing; and the level of integration of the overall manufacturing system. The aim of AMT is to assist organisations in gaining a competitive advantage in terms of reducing operating costs and providing high levels of output by improving manufacturing flexibility and lead time to market (Gunawardana 2006).

Dangayach, and Deshmukh (2005) noted that in general the benefits of AMT, which have been widely reported in the literature, can be classified into two categories: tangible and intangible. The tangible benefits of the technology which can be quantifiable refer to inventory savings, less floor space, improved return on equity (ROE) and reduced unit cost of production. On the other hand, the intangible benefits cannot be easily quantified and include an enhanced competitive advantage, increased flexibility, improved product quality and quick response to customer demand. In general, the authors outlined that the advantages of the technology can be found in quality and flexibility and therefore can assist manufacturers to achieve technological competitiveness through quality, operational, organizational and financial improvements. (Dangayach, and Deshmukh 2005). In particular, Zhao and Co (1997) highlighted that the benefits of AMT can be found in reduced labour, improved product quality as well as increased product flexibility and reduced lead times (Zhao and Co 1997).

Zhou et al. (2008) in his definition of AMT used three measurement scales based to three categories of design, manufacturing, and administrative AMTs. The first category 'Design' refers to computer-aided design and computer aided engineering. Here, according to the authors the focus is on product and process design. The second category 'Manufacturing', includes computer – controlled processes applied in the fabrication/assembly industries. Measurements utilised in this category can be found in computerized numerical control, computer-aided manufacturing, robotics, real-time process control system, flexible manufacturing systems, automated material handling system, environment control system, and bar coding/automatic identification. The focus here is on actual production of the products. Finally, 'Administrative' AMTs refer to computerized shop-floor tracking systems. Measurements within this category can be found in manufacturing resource planning, activity-based accounting systems, electronic mail, electronic data exchange, and office automation (Zhou et al. 2008).

Chuu (2009) in his definition of AMT refers to manufacturing technology, which its attributes can be classified into two categories: Objective and Subjective. Objective attributes are related to numerical terms which are utilised to assess the quantitative effects of manufacturing technology by applying different numerical scales in relation to investment cost, setup time, work-in-process inventory, and throughput time, etc. On the other hand, Subjective attributes are related to qualitative definitions which are utilised to assess the qualitative effects of manufacturing technology in terms of flexibility, quality and learning. Therefore, AMT can be defined as any methodology based on the above which its application as part of the production system will improve performance in terms of cost, quality, and flexibility (Chuu 2009). The definitions of AMT are presented on the following Table 2.6.

Table 2.6: Definitions of Advanced Manufacturing Technologies

Source: The Author

Source/Reference	**Advanced Manufacturing Technology**
Zairi (1992)	A social–technical system
Zammuto and O'Connor (1992)	A family of technologies
Baldwin and Diverty (1995)	The use of any integrated hardware-based and software-based technology
Beaumont et al. (2002)	Direct, Indirect and Administrative
Gunawardana (2006)	The classical continuum of basic manufacturing processes and the level of

	integration of the overall manufacturing system.
Dangayach, et al. (2006)	Tangible and Intangible
Zhou et al. (2008)	Design, Manufacturing, and Administrative
Chuu (2009)	Objective and Subjective

In summary AMT involves the application of computers to various facets of the production process and according to Gunawardana (2006) can be grouped in to six categories as it is shown on Table 2.7.

Table 2.7: Type of Advanced Manufacturing Technologies
Source: Gunawardana (2006 p.121)

Functional group	**Technology**
Processing, fabrication, and assembly	FMC/FMS Programmable logic control machines or processes (CNC and NC) Lasers used in materials processing Robots with sensing capabilities Robots without sensing capabilities **Rapid prototyping systems** High-speed machining Near-net shape technologies
Automated material handling	Partial identification for manufacturing automation (bar coding) (AS/RS) Automated guided vehicle systems
Design and engineering	CAD/CAE CAD/CAM Modelling or simulation technologies Electronic exchange of CAD files Digital representation of CAD output
Inspection and communications	Automated vision-based systems for inspection/testing of inputs/final products Other automated sensor-based systems for inspection/testing of inputs
Manufacturing information systems	MRP MRP II
Integration and control	SCADA Artificial Intelligence/Expert Systems (ES) CIM

Thus, it can be seen from the above table that Rapid Prototyping systems belong to the functional group of ‘Processing, fabrication, and assembly’. As it was previously mentioned

Additive Manufacturing technology includes three main categories: Rapid Manufacturing, Rapid Tooling and Rapid Prototyping (Levy et al. 2003). AM traditionally was used to build conceptual prototypes. This process was known as Rapid Prototyping. However, technological advancements towards the development of manufacturing functional prototypes has led to the evolution of Rapid Manufacturing (Dimov et al. 2001). Additionally, the technology includes elements of the 'Design and Engineering' group as it is digital technology and it is based on the integration of software and hardware to produce the final product (Baldwin and Diverty 1995).

2.6.2 Advanced Manufacturing Technology Implementation

Gerwin and Tarondeau (1982) in their study explored on the strategies which need to be employed by organisations when dealing with uncertainty within the concept of implementing AMT technologies. The authors noted that cultural and other differences among the firms when pursuing coping strategies play a significant role during the innovation process. Their results indicate that common problems during the implementation process can be found mainly in the maintenance and control activities as part of the manufacturing process to manage uncertainty in terms of technical activities. Specific functions where most of the implementation problems occur include quality control, accounting, equipment maintenance and production scheduling. The authors agree that companies need to develop a better understanding of the applications of those coping strategies (Gerwin and Tarondeau 1982).

Voss (1985) has studied the implications of AMT and found that companies fail to capture the full benefits of the technology. In particular, the author outlined that success of technology is determined by two stages: technical success and business success which refers to the realization of the full benefits of the technology. His findings suggest that in order for companies to capture the full potential of the technology they need to achieve both stages. However, it appears that most companies achieve only the technical benefits of the technology which do not lead to the realization of business success. The author concluded that companies have the potential to achieve both stages but they need to work more towards the implementation of the technology (Voss 1985).

In another study and in accordance with the previous findings Voss (1988) concluded that the technical advantages of the technology do not necessarily capture the main benefits expected from the application of the technology. The author has based his propositions on

14 different advanced manufacturing technology innovations in the United Kingdom, United States, and Australia. The results indicated that a significant number of organisations which produced evidence of technical success has failed to demonstrate the business success of the technology on various levels within the outlined participants (Voss 1988).

Leonard-Barton (1988) in her paper examined the process of AMT initial implementation in order to gain a better understanding of the dynamics which evolve between technology and user environment. The author has approached the implementation process from an adaptive perspective according to which initial implementation of technical innovations is best viewed as a process of mutual adaptation of both the new technology to the organization and the organization to the technology. According to the author this adaptation process is necessary as it appears that there is no technology which perfectly fits an organisation. Therefore, organisations must alter the technology or change the environment or both. As a result, the mutual adaptation becomes an integral part of the implementation process (Leonard-Barton 1988).

Gerwin (1988) suggested a number of propositions which companies need to consider during the AMT implementation process in order to cope with the problems arising from uncertainty. The authors emphasised that companies should focus on strategies which support technical infrastructure development, participation and installation in stages **(**Gerwin 1988).

Park et al. (1990) underlined that in order for companies to fully implement AMT and other automation technologies they need to consider factors of demand which can be found in quality and quantity of demand as well as the breadth of the variety of products. The authors agree that any large initial investment on the above technologies includes a high level of risk as companies operate within a very competitive and uncertain environment. Therefore, they must be prepared to plan on the long-term in order to see return on their investment (Park et al. 1990 ; Parsaei et al. 1990).

Babbar and Rai (1990) stated that although companies have recognized the benefits of AMT they fail to implement it. The authors have introduced the concept of Computer Integrated Flexible Manufacturing (CIFM) which is based on flexibility and computer integration. In particular, taking into consideration that current technologies are characterized by increased automation, the authors believe that flexibility needs to be incorporated into the system design and should not be treated independently. Therefore, companies need to carefully plan and develop a strategy for implementation instead of rushing to invest in automation. The authors concluded that companies need to focus on the overall effectiveness of the process rather than the individual sub-components (Babbar and Rai 1990).

Boer et al. (1990) examined the benefits of Flexible Manufacturing Systems (FMS). The authors noted that although the technology has its origins in 1962 the number of companies which utilised the technology is significantly small. As a result, it is quite unclear under what circumstances the promises of FMS can be achieved. Their research has based on several case studies and found that when companies implementing the technology, the advantages of FMS maybe achieved although economic, technical and organisational problems and prerequisites may prevent or delay the full benefits. The authors stressed that the extent to which companies can exploit on the full benefits of FMS it will depend on the level of managerial involvement and innovation as well other organisational and technological adaptations. Therefore, business success and technology performance is interlinked with organisational innovation (Boer et al. 1990).

Cooper and Zmud (1990) have researched the implementation of a production and inventory control information system (material requirements planning: MRP). Their study has utilised literature based on the innovation and technological diffusion and empirically examined the synergy between managerial tasks and information technology within the concept of implementing new technologies. The authors have used a random sample of manufacturing firms across the United States and found that those synergies do not impact the overall application of MRP technologies and therefore further political and learning models need to be developed to examine infusion (Cooper and Zmud 1990).

Tyre and Hauptman (1992) investigated the extent to which organisations can cope with uncertainty when introducing technological changes. The authors in their research have first examined specific new features and functions as well as the development of new organisational relationships and operating concepts. The authors have suggested that organisations in order to cope with uncertainty and implement the new technology they need to follow three modes of action. First, they need to undertake preparatory research to initiate modification prior to implementation, then to collaborate with eternal technical experts during the first steps of the production process and finally to successfully integrate engineering and manufacturing functions engaged in start-up. The results indicate that the degree to which organisations manage the difficulties during the introduction of the new technology in terms of technical skills and support systems will play a predominant role in avoiding future disruptions in rems of operating functions and gains (Tyre and Hauptman 1992).

In a similar study, Tyre and Orlikowski (1993) based on the assumption that in order for managers to exploit the advantages of the new technologies they must adapt those technologies to fit with the overall strategy of the organisation, the authors investigate when and how to make those changes. According to the authors the process of implementing AMT technologies remains confusing. They argue, based on a data from European and US companies, that technological developments do not follow a steady pattern but occur between sort events of intensive change activity and periods characterised by routine use. Therefore, the process of successful implementation of those technologies depends on the extent to which those short episodes will be managed in terms of efficiency and change (Tyre and Orlikowski 1993).

Orlikowski (1993) have examined the implementation of AMT technologies, in relation to the application of CASE (Computer-aided software engineering) tools over time. Their findings are based on the empirical study into two organisations' experiences and they suggest that in order for organisations to better manage the application of CASE tools they need to understand that successful implementation involves a process of organisational change over time rather than the installation of a new technology. Here, researchers should also consider the broader social context of systems development as well as the intentions and actions of key players (Orlikowski 1993).

Afzulparkar and Kurpad (1993) in their study in relation to implementation of AMT have focused on the particular problems associated with implementing a cellular manufacturing (CM) project. The authors have noted that current research literature on Group Technology (GT) and CM have not covered all the factors which are critical for a successful implementation of a CM project. They provided guidelines and attempted to solve some of the problems occurred in relation to simulation modelling, cell design, cell operational logistics, and labour issues in CM (Afzulparkar and Kurpad 1993).

Ramamurthy (1995) noted that although it is generally agreed that the relationship between planning and implementation of AMT can assist companies to gain a competitive advantage, there is little evidence to empirically support the above assumption. The author has surveyed a sample of 222 manufacturing firms who have implemented the technology and examined the extent to which such planning systems can enable organizations achieve the potential of the technology in order to empirically verify the above issues. The results indicate that successful implementation and strategic change are interlinked with the quality of the planning system in terms of adaptiveness. In particular, according to the author efficient planning systems can contribute in exploiting the capabilities of the technology and therefore achieve superior performance (Ramamurthy 1995).

Small and Yasin (1997) in their article investigated the relationships between adoption of various AMT, how firms have planned and implemented them and their potential performance. The authors have collected data from 125 manufacturing firms in the U.S. Their results suggested that firms adopting integrated technologies had managed to achieve significantly higher levels of effort in terms of strategic planning and team-based project management. They have also found that when priority is given to developing human factors then the expected benefits from the AMT implementation can be achieved to a greater extend compared with their counterparts (Small and Yasin 1997).

Zhao and Co H C (1997) have examined a survey of 1000 firms in Singapore in order to draw conclusions on adoption and implementation of AMT. Their study focuses on identifying those 'successful factors', which play a significant part in the adoption and implementation of AMT. For this reason, the authors have employed statistical and factor analysis and their research has identified 27 'successful factors'. Their results indicated that the most important 'successful factors' contributing in the implementation of AMT can be found in project team integrity, strategic planning and project championship, and technical knowledge as well as training at all levels. Their research has also concluded that firm size and financial availability can determine successful from unsuccessful firms in terms of AMT adoption and implementation. In particular, although firms with large financial resources appear to be more successful, the number of employees in large firms does not necessary guarantee successful AMT implementation (Zhao and Co 1997).

Hamid (1997) in his research has studied the experience of a developing country in relation to AMT implementation. The author focused on three Malaysian manufacturing sectors and investigated the process of AMT utilisation from the initial steps regarding the adoption of the technology till its commercialization. The results indicate that in order for this process to be successful firms need to assess internal factors such as strategy and human organization combined with external factors like government support and relationships. It was also found that the level of external support can be significantly increased as the technology becomes more sophisticated and complex. The author underlined that a number of benefits have found to be associated with the AMT implementation including increased quality, reduced costs, faster turnaround and greater capacity (Hamid 1997).

Kakati (1997) in his study examined eight cases in relation to AMT justification. The author highlights that strategic myopia often restricts organisations from obtaining the benefits of new technology. He suggests that companies should first identify market forces, critical success factors, key competitive factors and opportunity gaps. Once those have been identified then AMT benefits should be measured through its contribution to the closing of competitive and opportunity gap (Kakati 1997).

Frohlich (1998) focused his study on how manufacturers, which are either early or late adopters of the AMT, can successfully apply appropriate strategies in order to exploit the full advantages of the technology. The authors argued that companies should employ different approaches of AMT implementation depending on the technological maturity. Their results indicate that early or late adopters of AMT should focus on different forms of learning in accordance with the requirements and the various issues associated with the new technology (Frohlich 1998).

Burcher et al. (1999) has contributed to the debate by examining three case studies of AMT implementation. Their results suggested that successful implementation needs to consider the integration across the systems and attention needs to be paid not only to those who actively participate in the technology process but also to people issues in general. The author noted that the above actions must take place within a broader perspective which is characterized by a market driven culture (Burcher et al. 1999).

Laosirihongthing et al. (2001) in their paper studied implementation issues of AMT in the Thai automotive industry. Their research examines the benefits of the new manufacturing technology (NMT) and the relationship between NMT used and organizational characteristics. Their research, based on descriptive statistical analysis, has concluded that principal ownership, size of company and labour union memberships can significantly impact the implementation of the technology. The authors also noted that NMT can lead to performance improvements which can be found in accuracy of product, work standardization, and company image (Laosirihongthing et al. 2001).

Buruncuk and Zarife (2001) in their work of implementing AMT examine the factors which contribute to the successful implementation of Information Systems (IS) projects. The authors pointed out that a large number of projects are unsuccessful, and their survey revealed that success factors can be found in system implementation, use of software package, quality of IT staff, software support, training of users, system testing, system planning, system design / analysis. They have also noted that although IT is an integral part of the companies' business process, the benefits of the technology are limited to reduction in cost and improvements in productivity. The authors concluded that the impacts of implementation and management of information technology is more important when compared with the tool or technology utilised within the company. This means that companies will gain competitive advantage when they have skilled management and proper implementation of Information Technologies' both tangible and intangible assets and not when they are entirely based on sophisticated and high-end IT implementation (Buruncuk and Zarife 2001).

Lewis and Boyer (2002) in their research investigated how performance can be impacted by the varied operations strategies, organizational cultures, and implementation practices. The authors based their study on the assumption that AMT implementation can offer to organisations a number of benefits and their research employed a survey of 110 plants which had all implemented AMT over the past 3 years. According to their results, a plant characterized by high performance employed a strategy focusing on quality, delivery, and flexibility over costs. Within those plants a balanced culture could also be found in terms of flexibility and control and appropriate practices which facilitated change in terms of training and long-term AMT projects. The authors concluded that implementation timing plays an important role as it is found that those firms which had recently implemented the technology outperformed those with older implementation (Lewis and Boyer 2002).

Machuca et al. (2004) in their paper look in depth the factors which might be considered to play a predominant role in terms of performance when companies invest in AMT technologies during the adoption and implementation process. Their study is based on the aeronautical sector in the south of Spain and employed a survey of 20 plants. Their results indicate that the training of personnel appears to have a significant impact on performance. They have also found that the lack of strategic planning contributes to the failure of investments (Machuca et al. 2004).

Dangayach and Deshmukh (2005) studied implementation of AMT in Indian small and medium enterprises (SMEs) of automobile, electronics, machinery, and process sectors. The authors based on the literature developed eight steps contributing to effective implementation. Those steps are planning, concept development, requirement analysis, cost/benefit analysis, technology assessment, development and implementation, training, post-implementation evaluation. Their results suggest that planning has ranked as the most important implementation step in general compared with requirement analysis and post-implementation evaluation which have attracted least attention (Dangayach and Deshmukh 2005).

Rahman (2008) studied AMT implementation within the perspective of buyer-supplier relationship. The author explored on the assumption that the relationship between technology buyers and suppliers play a crucial role to the successful implementation of AMT. The author obtained evidence from 147 manufacturing firms in Malaysia and used the structured equation modelling (SEM) technique to analyse the data collected. The results suggest that those firms which achieved a closer relationship with the technology suppliers appeared more likely to obtain high levels of performance than those that do not. It is also found that the majority of firms who have utilised the technology, they reported improvements in performance (Rahman 2008).

Thomas et al. (2008) in their research in relation to AMT implementation provided details of a survey conducted into 300 manufacturing SMEs. Their study investigated the barriers associated with the implementation of AMT and found that SMEs did not fully appreciate the benefits arising from the implementation of the technology in terms of improving business performance and customer satisfaction. In particular, their findings stressed the fact that SMEs considered the selection, purchasing and implementation of the technology too risky. On the other hand, companies which had implemented the technology found that the implementation phase was to be the most problematic area, and this was associated with the poor planning and selection of the technology before moving into the implementation phase. Their results also highlighted that in general lack of top management commitment combined with an unrealistic expectation about the implementation time-scale has resulted in failure to establish a technology – oriented culture (Thomas et al. 2008).

Costa and Lima (2009) in their research on AMT implementation have identified the importance of the organisational design process as part of a successful and coherent manufacturing technology. The authors have based their findings on a theoretical synthesis of two refined and tested frameworks: The organizational design and the strategic selection of AMT. Their results indicate that there is a strong correlation between the manufacturing strategy and in particular the manufacturing vision with the organisational design specifications. The authors have empirically tested the theoretical development in cases of competencies, capabilities, and manufacturing vision (Costa and Lima 2009).

Fulton and Hon (2010) identified the barriers to successful implementation of AMT technology and presented a process in order to assist organisations to overcome those obstacles. According to the authors common barriers of AMT implementation associated with lack of knowledge of AMT and low confidence in company capabilities and financial limitations. Their study suggests that appropriate tailored solutions including leading edge software, training and mentoring can have a positive impact on both tangible and intangible assets on the companies engaged (Fulton and Hon 2010).

García and Alvarado (2012) noted that although it is generally recognised that investments in AMT can provide a number of benefits to organisations, individual firms need to manage the technology properly in order to avoid problems associated with bankruptcy of the company. Therefore, AMT implementation, which remains a complex issue, needs to be explored thoroughly. Their study has employed a number of industrial plants which applied the AMT in order to identify areas related with the AMT implementation. The authors concluded that the main problems from the implementation of AMT can be found in maintenance, required special installations, suppliers are far away; there is no accomplishment of the production standards; there are no economic resources, fear risk to invest; and finally, custom’s problems (García and Alvarado 2012). Table 2.8 presents the studies on implementation of AMT.

Table 2.8: Studies on Implementation of Advanced Manufacturing Technologies
Source: The Author

Reference/Source	AMT Implementation issues
Gerwin and Tarondeau (1982)	Cultural and other differences among the firms.
Voss (1985;1988)	Technical success and business success.
Leonard-Barton (1988)	A process of mutual adaptation of both the new technology to the organization and the organization to the technology.
Gerwin (1988)	Technical infrastructure development, participation and installation in stages.

Park et al. (1990)	Factors of demand which can be found in quality and quantity of demand as well as the breadth of the variety of products.
Babbar and Rai (1990), Boer et al. (1990), Cooper and Zmud (1990), Orlikowski (1993), Afzulparkar at al. (1993), Buruncuk and Zarife (2001)	Computer Integrated Flexible Manufacturing (CIFM), Flexible Manufacturing Systems (FMS), Material Requirements Planning (MRP), Computer-aided software engineering (CASE), Group Technology (GT), Information Systems (IS).
Tyre and Hauptman (1992)	Preparatory research, collaborate with eternal technical experts, successfully integrate engineering and manufacturing functions engaged in start-up.
Tyre and Orlikowski (1993)	Technological developments do not follow a steady pattern but occur between sort events of intensive change activity and periods characterised by routine use
Ramamurthy (1995)	Successful implementation and strategic change are interlinked with the quality of the planning system
Small and Yasin (1997)	Integrated technologies are interlinked with successful strategic planning and team-based project management
Zhao and Co H C (1997)	Project team integrity, strategic planning and project championship, and technical knowledge as well as training at all levels.
Hamid (1997)	Internal factors such as strategy and human organization combined with external factors like government support and relationship.
Kakati (1997)	Market forces, critical success factors, key competitive factors and opportunity gaps
Frohlich (1998)	Different approaches of AMT implementation depending on the technological maturity.
Burcher et al. (1999)	Integration across the systems.
Laosirihongthing et al. (2001)	Principal ownership, size of company and labour union memberships.
Lewis and Boyer (2002)	Quality, delivery, and flexibility over costs.
Machuca et al. (2004)	Training of personnel.
Dangayach and Deshmukh (2005)	Cost/benefit analysis and technology assessment.
Thomas et al. (2008)	Poor planning and selection of the technology during the implementation phase.
Costa and Lima (2009)	Correlation between manufacturing strategy with the organisational design specifications.

Fulton and Hon (2010)	Tailored solutions including leading edge software, training and mentoring.
García and Alvarado (2012)	Problems can be found in in maintenance, required special installations, suppliers are far away; there is no accomplishment of the production standards; there are no economic resources, fear risk to invest; and finally custom's problems.

2.6.3 Advanced Manufacturing Technology Implementation frameworks

Voss (1986) in his study states that according to the existing research organisations face difficulties in relation to AMT implementation because the process should be carried out in accordance with the strategic objectives. As a result, technical considerations related with cost reductions have been given the main priority. According to the author implementation must be considered before the introduction of any AMT and the success of post-installation implementation will be greatly influenced by the strategic considerations of the organisation. In his research the author first has given priority to study in depth the literature on implementation on Materials Requirements Planning (MRP) and then proposed a framework for strategic implementation of AMT (Figure 2.15).

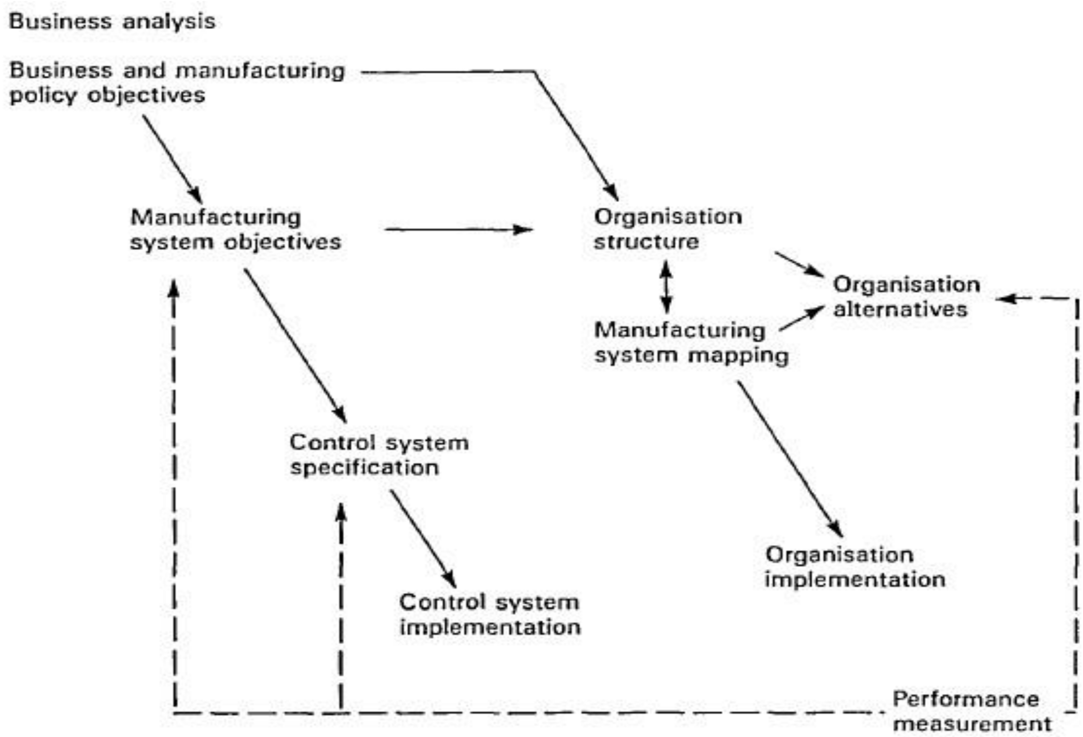
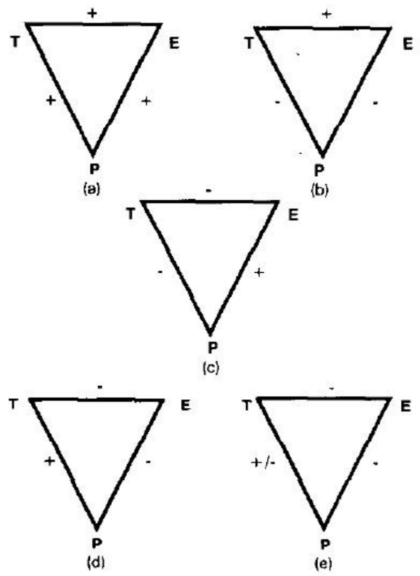


Figure 2.15: Framework for Strategic Implementation of Advanced Manufacturing Technology proposed by Voss (1986)

The proposed framework attempts to develop a general methodology for identifying the operating and business objectives of the technology, developing managerial controls in accordance with the performance objectives and finally specifying the organisational integration necessary to support computer integration (Voss 1986).

According to Dean et al. (1990) the implementation process involves a number of decisions related to system functions, resource commitments, location of pilot projects, and schedule. The purpose of those decisions is to address technical, economic and political issues. The authors have proposed a model which includes four major factors which impact the implementation process: the level of tolerance for acceptable decisions, the level of technical, economic, and political resources available for implementation, the direction of relationships among the three objectives, and the extent to which the objectives are balanced in decision-making (Figure 2.16, 2.17).



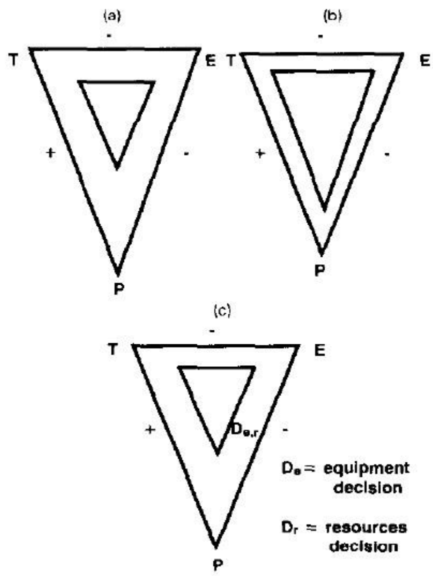


Fig 2.16 Patterns of relationships between technical condition
(T), economic (E) and political (P) objectives

Fig 2.17 Model for diagnosing
for implementing success

Proposed by Dean et al. (1990)

Their proposed technical, economic, and political (TEP) model contributes to the implementation of AMT with the following findings:

- It views the conceptualization of the implementation process as an interrelated decision stream;

- The AMT implementation relies upon on the on organizational context, decision-making, and outcome;
- Inclusion of politics as an integral factor to AMT implementation (Dean et al. 1990).

Sambasiva and Deshmukh (1994) in their research in relation to implementation of AMT have proposed a four-stage approach. The authors noted that when companies implementing AMT technologies they usually share the same objectives; however, the implementation process differs from one system to another. Therefore, a systematic approach is required to address the above issues. Their implementation framework on AMT systems (Figure 2.18) focuses in the field of Flexible Manufacturing Systems (FMS). The purpose of their framework is to eliminate the barriers associated with the implementation process when companies follow this four-stage approach outlined in the framework.

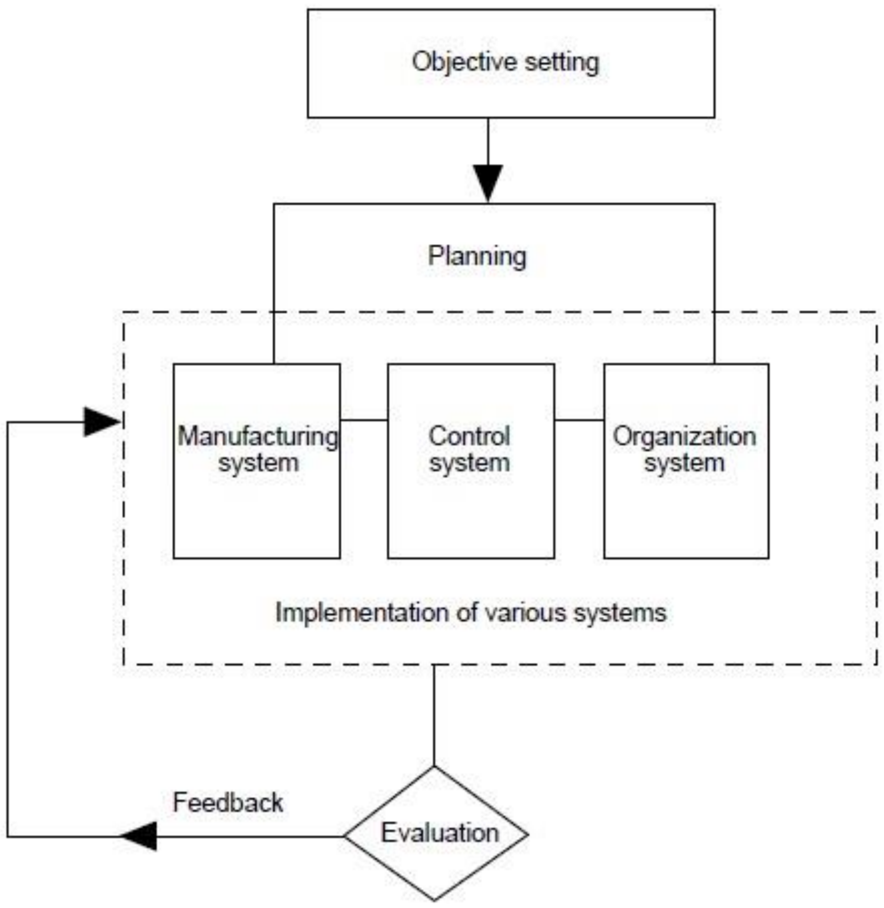


Figure 2.18: Strategic Framework for implementing the FMS proposed by Sambasiva and Deshmukh (1994)

Stage 1: Objective Setting

In the first stage management, should employ an investment decision strategy to set its objectives. Therefore, here clear guidelines should be provided in relation to the implementation of FMS.

Stage 2: Planning

This stage involves the planning for FMS and it plays a vital role for the successful implementation of the process.

Stage 3: Implementation of Various Systems

This success of this stage will depend upon the previous stage and how successful planning was.

Stage 4: Evaluation Process

The final stage involves evaluation of the process and here the financial investment on the new technologies need to be justified (Sambasiva and Deshmukh, 1994).

Chen and Small (1994) in their work investigated the requirements for successful implementation of AMT in terms of planning. The authors argue that successful implementation of the technology should include pre- installation planning and justification as well as purchasing, installing and evaluating the AMT under consideration. The authors have based their thoughts on the concept of 'implementation lifecycle' proposed by Voss (1988) according to which the sequential life-cycle model includes three phases: pre-installation, installation and commissioning and post- commissioning (Figure 2.19).

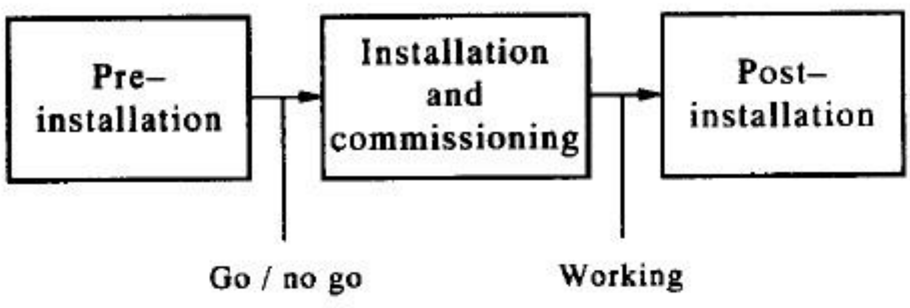


Figure 2.19: Voss's life-cycle of the process of implementation

The authors focus on the pre-installation (i.e. planning) phase, which includes factors that can have a positive or negative impact on the adoption of the technology. Therefore, this phase will determine to a great extent if managers will proceed to the installation phase, which involves the purchasing of the technology and its technical functionality. Only then, firms can reach the final stage where the aim is to achieve competitive advantage and fully gain from the benefits of the technology.

The authors proposed an integrated planning (IPL) model (Figure 2.20) to examine the acquisition of AMT. The model is presented as planning framework and it can be utilised by managers to better plan and implement AMT technology, by analysing their operational and organizational environments as well as making critical decisions about accepting or rejecting new technological developments. The IPL model is consisted of three phases: (1) definition of company objectives and determination of required product and process changes, (2) technology monitoring and (3) operational and organizational planning for the adoption of AMT, and financial and strategic justification (Chen and Small 1994).

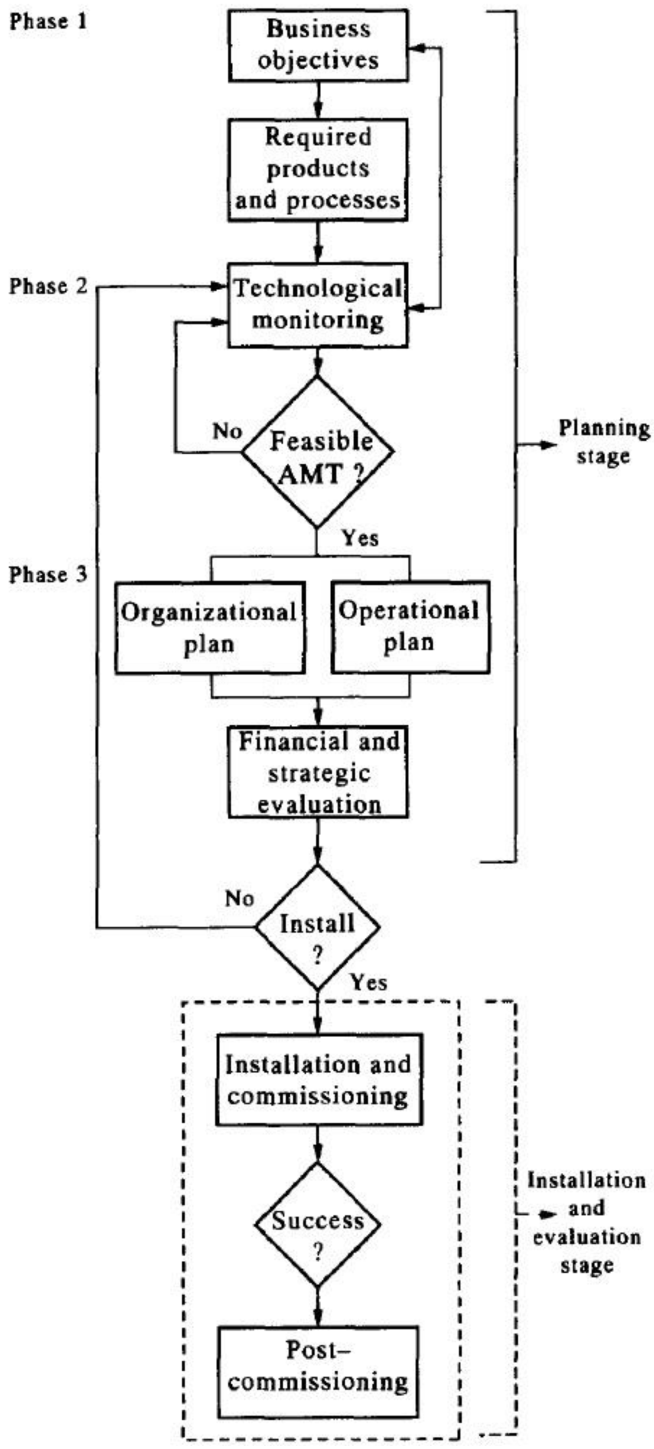


Figure 2.20: Integrated planning (IPL) model proposed by Chen and Small (1994)

Udo and Ehie (1996) in their study proposed a predictive model based on an analysis of the relationships between the determinants of AMT and the relevant benefits realized, in order to predict the success of AMT implementation (Figure 2.21).

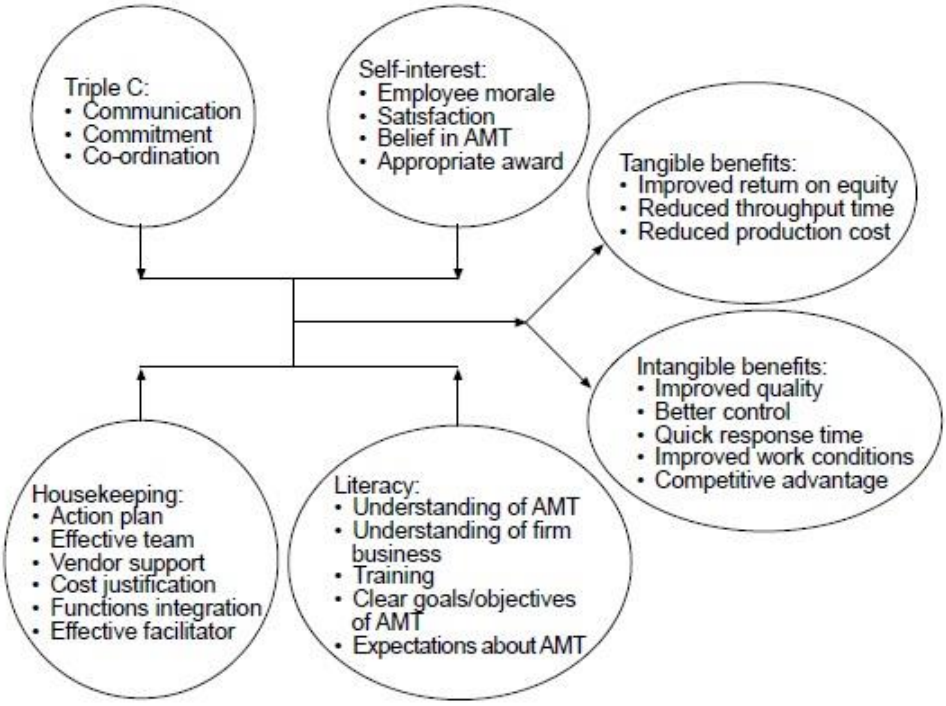


Figure 2.21: AMT Implementation Predictive Model proposed by Udo and Ehie (1996)

The model comprises 26 variables which are grouped into six broad categories:

(1) triple "C" factors;

(2) self-interest factors;

(3) housekeeping factors;

(4) literacy factors;

(5) tangible benefits; and

(6) intangible benefits.

The triple "C" factors explain how effective communication, coordination and commitment can impact AMT implementation.

The self-interest factors investigate the extent to which employees are personally interesting in AMT implementation and therefore are those factors which directly impact the employees.

The housekeeping factors are the basis conditions and play an important role as an introduction to the AMT implementation.

The literacy factors serve an educational purpose and aim to familiarise employees with AMT in relation to goals and objectives of the new technology.

The results indicate that first of all in relation to Triple “C” factors, that even if an effective coordination is achieved, without the commitment of managers and workers the full benefits of the technology cannot be realized. The most critical determinant for successful AMT implementation was found to be “Self-interest”. Therefore, management should have in place all the required programs which enhance the ‘self-interest’ on new technologies. A key factor for the successful AMT will be the employee involvement. Finally, the literacy factors will play a predominant role on assisting employees to understand and make use of the new technology (Udo and Ehie 1996).

Ghani and Jayabalan (2000) in their research presented a framework based on the proposition that low superior performance can be achieved by a planned change process. According to the authors although that the idea of AMT remains attractive, only modest benefits have been reported. In particular, the authors underline that the expected benefits of the AMT implementation in terms of increased productivity, superior quality and high customer satisfaction have not yet been obtained. They believe that the main reasons behind this involve human factors and organisational structure which needs to be adjusted to the needs of the new technology. Their framework (Figure 2.22) is based on a set of propositions according to which firms will achieve superior performance only when psychological barriers in the working environment in relation to new technology will be eliminated in order to allow new organisational structures to be compatible with the new technology through a planned process. In particular, the framework addresses the relationships between technology, structure and employees as an integral part of the planned change in terms of the new AMT process. Therefore, firms should match implementation of AMT with their existing resources as part of the planned change (Ghani and Jayabalan 2000).

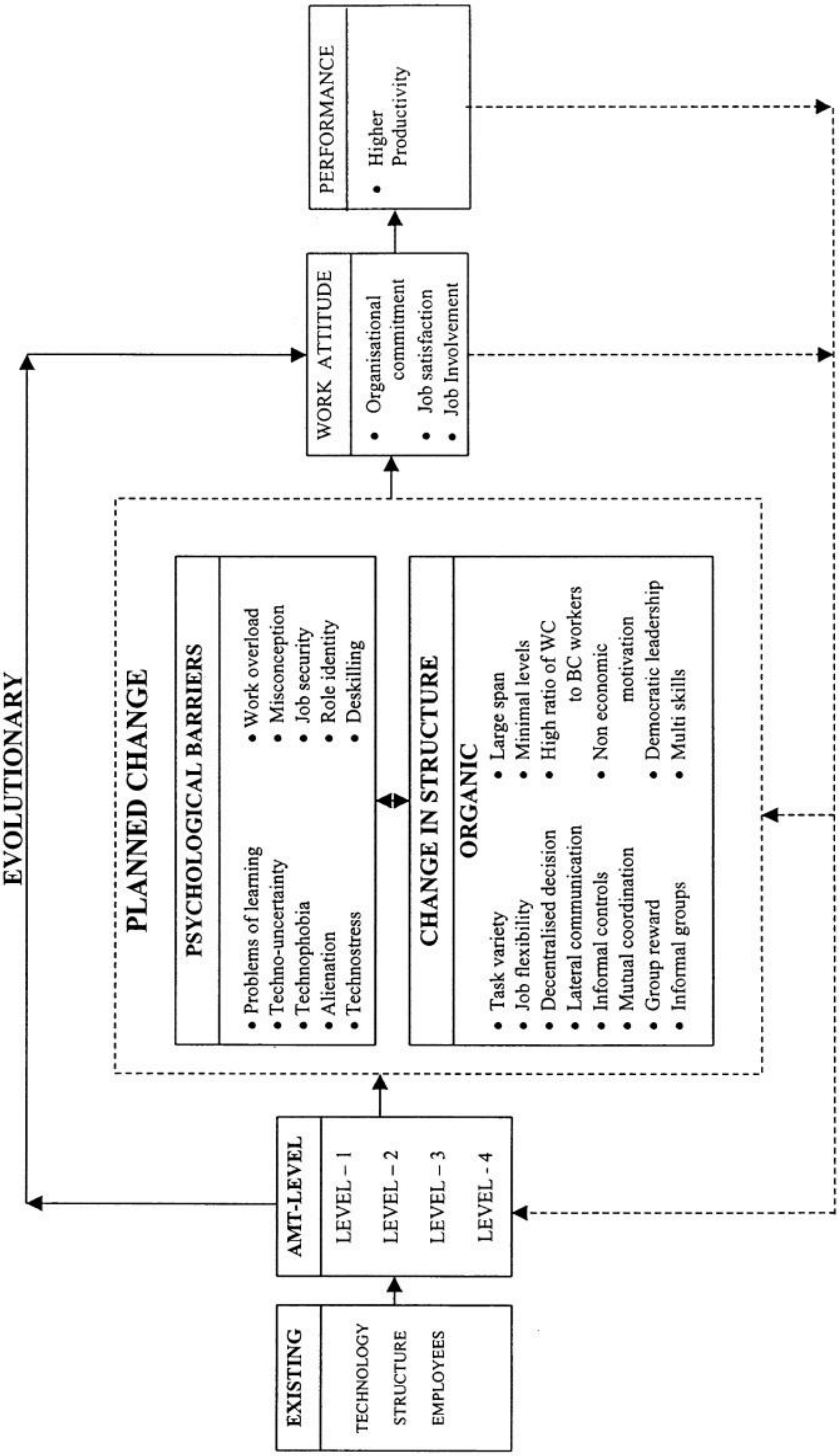


Figure 2.22: Implementation of Advanced Manufacturing Technology proposed by Ghani and Jayabalan (2000)

Yusuff et al. (2001) noted that substantial investment in the new technology is not enough to facilitate successful implementation of AMT. In order for companies to enhance on this process they need to consider changes in relation to the culture and the organisational structure of the company. Therefore, planning needs to take place at all levels in consistency with the desired goals. The authors proposed an analytical hierarchical process (AHP) to assist organisations with the planning of the implementation process. In particular, the AMT implementation process has been grouped into stages or modules where each stage or module is independent of the other. Those modules are the following: Institutionalization, Acceptance, Routinization and Infusion modules. The application of the AHP in the institutionalization module is shown on the following Figure 2.23.

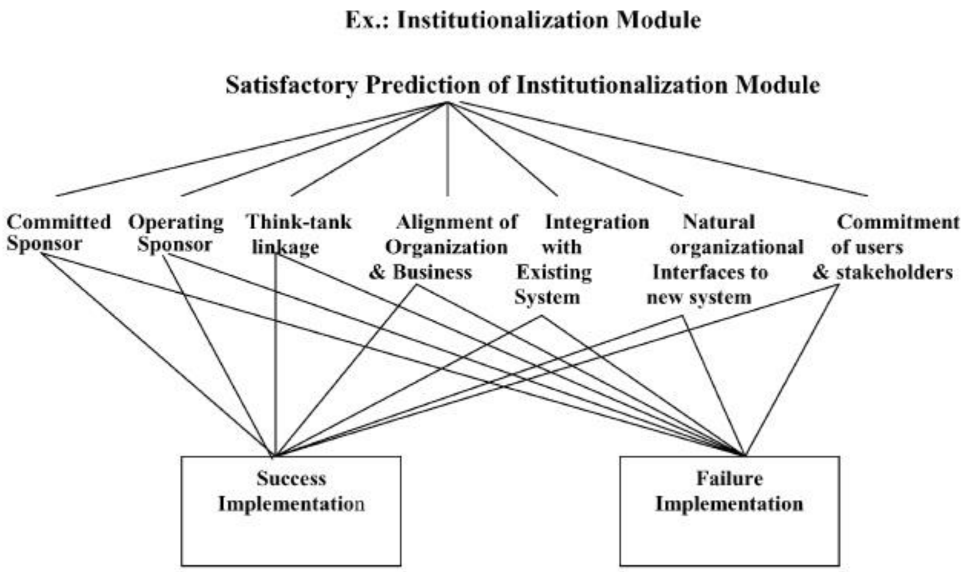


Figure 2.23: Three level hierarchy diagram of Institutionalization Module proposed by Yusuff (2001)

The predictive model based on the analytical hierarchical process (AHP) can assist companies with their implementation process as it can help managers analyse and identify appropriate actions to ensure the successful implementation of AMT. The model can also provide guidance regarding the information needed in order for users to cope with changes and it can also be utilised within the AMT decision-making process as it considers all major success factors. Therefore, organisations can further improve their decision - making process and consider appropriate actions to avoid any obstacles (Yusuff.et al. 2001).

In another study Ghani et al. (2002) has presented a framework for implementation of AMT in an existing environment with emphasis on the organic structure of the company. The authors based their research on Indian manufacturing industries and noticed that productivity based on the utilisation of AMT was found to be low even after years of the implementation of the technology. Their framework (Figure 2.24) suggests that the organisational structure in terms of the AMT implementation will be influenced by attributes such as task variety, job flexibility, decision making, control system, communication, leadership, coordination, informal groups as well as the ratio of white-collar to blue-collar employees. Therefore, the performance of the organisation will depend on the extent to which the above attributes have been managed as an organisational structure to fit with the AMT process (Ghani et al. 2002).

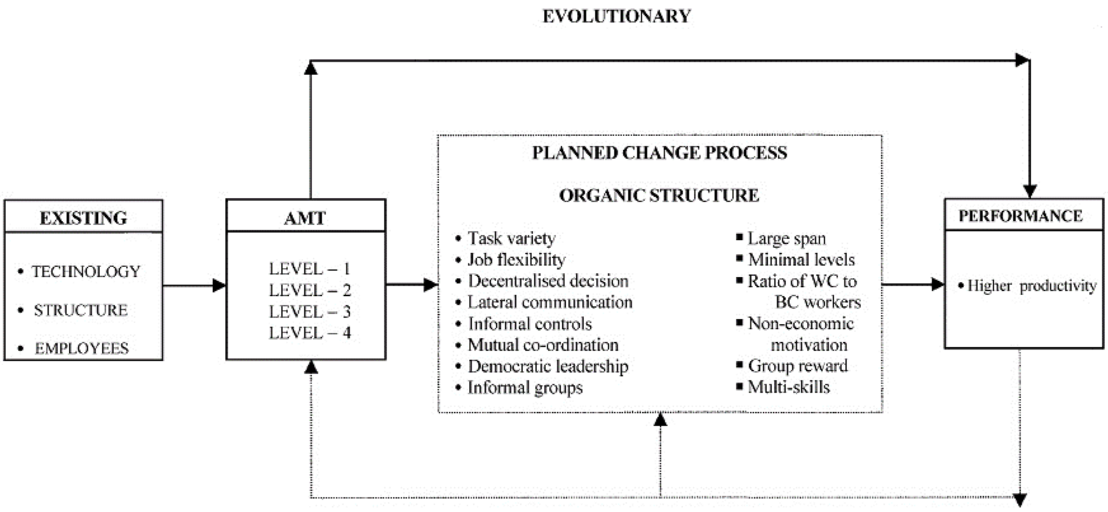


Figure 2.24: Implementation of AMT with organic structure proposed by Ghani et al. (2002)

Efstathiades et al. (2002) in their paper stressed that in order for companies to ensure successful AMT implementation they need to focus on the planning requirements for the utilisation of AMT. The authors by using a Cypriot manufacturing industry as a case study, extracted information regarding the implementation of AMT. As a result, they have developed a planning model which provides the framework for the correct justification and implementation of AMT (Figure 2.25).

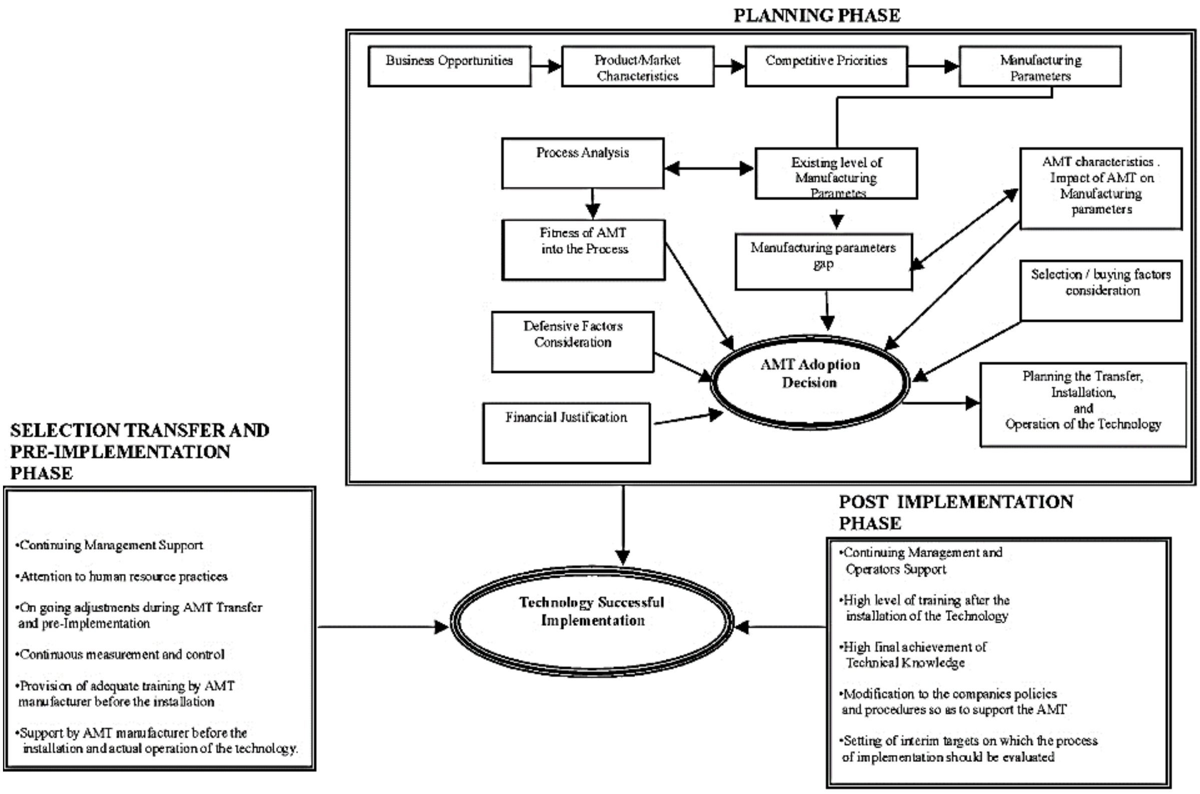


Figure 2.25: Integrated process plan for AMT implementation proposed by Efstathiades et al. (2002)

The proposed model ensures Technical, Manufacturing and Business Success within the overall AMT implementation process and includes all the necessary planning and implementation factors as an integral part of the technology application. In particular, the outlined framework provides a methodology to assist manufacturers with the justification and implementation of the technology based on an examination of the reasons behind the success and failure of the technologies. Their results indicate that the level of planning for human resource development, the continuing management and operators support, and the level of training given has a positive impact on the level of technical success. On the other hand, the lack of knowledge in the workforce and the limited managerial resources can restrict the level of technical success. In terms of the manufacturing success, a positive effect is strongly related with on-going adjustments during the AMT implementation, adequate training and support by AMT manufacturer as well as improvements on the existing policies. On the contrary, the fear of the personnel to cope with the new technology can limit the manufacturing success. In relation to the business success, a positive effect is strongly interlinked with the level of planning for human resource development, the level of management support as well as with ongoing adjustments during the AMT implementation process and improvements in modifications to policies and procedures. On the other hand, the fear of employees to cope with the new technology before AMT installation takes place and the level of foreclosing options at the design and selection stage of the technology can have a negative impact on the level of business success (Efstathiades et al. 2002).

Small and Yasin (2003) developed a conceptual framework for AMT implementation, which reviews the desirable roles, functions and activities of MIS/personnel/departments (Figure 2.26). The authors based their survey on US manufacturing firms in order to investigate the importance of MIS departments within the AMT implementation process. For this purpose, they have also included in their study information on firm performance based on several business and operational measures. Their results suggest that the proposed framework can be used as a guidance by managers to obtain a better insight in relation to the role of MIS departments in firms within the broader concept of integrating AMT and information technologies (Small and Yasin 2003).

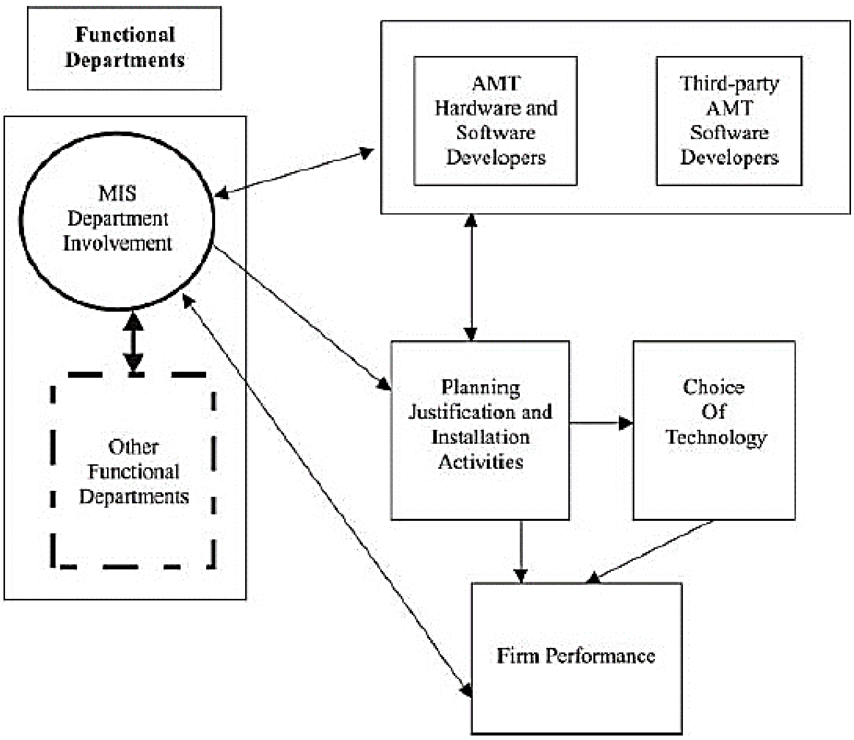


Figure 2.26: A Framework for MIS Involvement in the AMT Implementation process proposed by Small and Yasin (2003)

Marri et al. (2006) focused their research on SMEs and noted that they play a significant role in all aspects of competitiveness including production techniques and managements methods as well as human resource training. In particular, SMEs are constantly seeking for new ways to become more competitive in the market in terms of new products, marketing, manufacturing and sales and therefore the implementation of AMT becomes an integral part of their strategy. In their paper the authors reviewed the application of AMT in SMEs and proposed an implementation framework (Figure 2.27). The authors have identified four perspectives to address the issues related with the implementation of AMT in SMEs. Those include: Strategic, Tactical, Operational, and the Organizational perspectives.

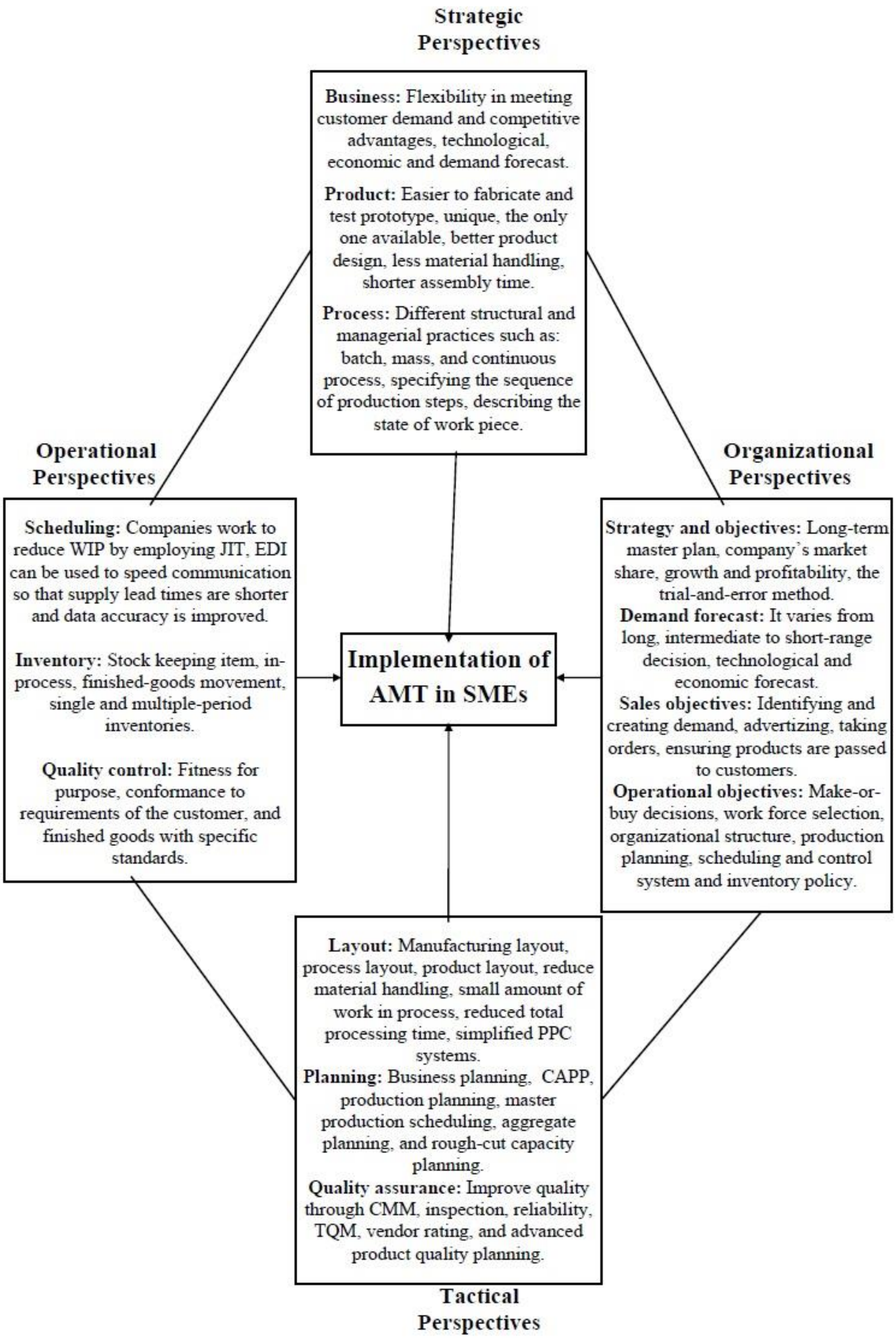


Figure 2.27: Framework of criteria for the implementation of AMT in SMEs proposed by Marri et al. (2006)

Based on the above framework mangers can take the following action to cover the various stages of the AMT implementation process:

- They need first of all to examine the strategic and operational needs in relation to the adoption of AMT. In order to achieve that they have to investigate the performance of the existing systems in terms of the company's ability to remain competitive in the broader business environment.
- SMEs need to have in place the appropriate requirements where organisational goals and performance benchmarks are in accordance with their strategic focus always within the framework of utilising new technologies. Therefore, SMEs should look for those new technological innovations which support the above objectives.
- SMEs should play particular attention to their organisational structures and in terms of utilising the new technology they should proceed to necessary modifications in relation to various production tasks such as: lot sizes, variety of part-types produced, operator output rates, number of tasks per worker, delivery lead times etc.
- SMEs should aim to match the benefits form the implementation of the AMT systems with their overall goal in a cost-effective manner based on required infrastructural changes. This is an on-going investment process.
- Finally, SMEs should constantly monitor and tack the implementation of AMT in terms of their effectiveness. For this purpose, first the AMT systems should be evaluated against the organisational goals and their ability to be managed in a cost-effective manner and secondly the AMT systems need to be assessed on their ability to meet revised organisational goals to cope with unexpected changes due to the external environment (Marri et al. 2006).

Singh et. al (2007) noted that the globalisation of markets along with the introduction of new technologies pose a number of challenges to organisations in order to sustain their competitiveness. Therefore, the implementation of AMT plays a very important part as it can assist companies to gain a cutting edge over their competitors. The authors in their paper aim to explore on the structural relationship among different factors for successful implementation of AMTs. In their research based on a survey**,** they have identified 14 critical success factors such as top management commitment, organization culture, sound financial condition, training, integration of departments, etc. As a result, they have developed an ISM-based model for implementation of AMTs (Figure 2.28).

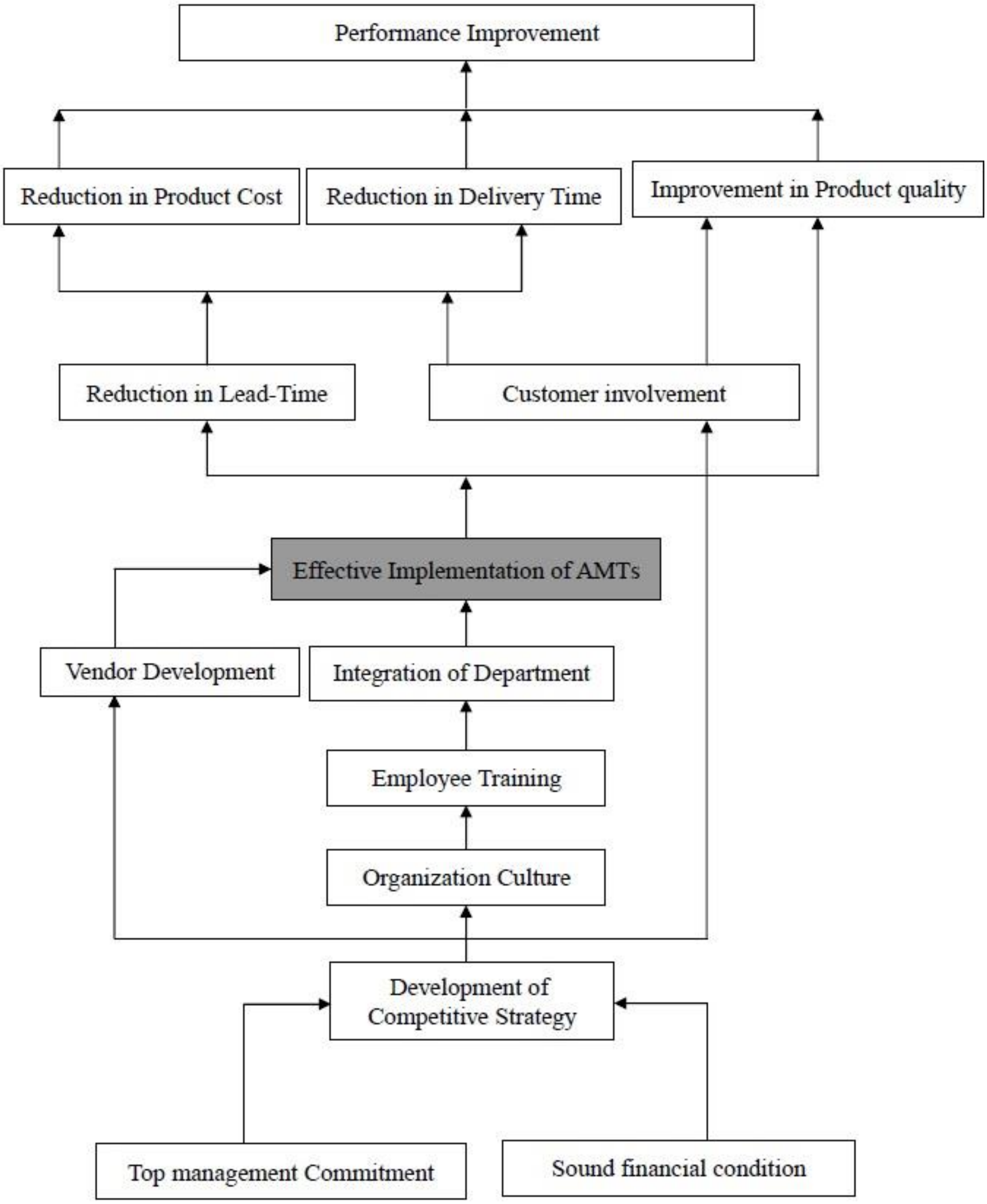


Figure 2.28: ISM-based model for implementation of AMTs proposed by Singh et. al (2007)

According to their findings the major drivers for implementing AMT can be found in top management commitment and sound financial condition. Therefore, in order for AMT implementation to be effective, managers need to look into the organisational culture, employee training, integration of departments as well as strategy development and customer participation. As a result, effective AMT implementation will lead to better organisational performance in relation to lead time, product cost, fast delivery and product quality (Singh et. al 2007).

Yasinshaikh et al. (2012) in their research investigated the progress of AMT systems which are characterised by limited application due to economic and other constraints during implementation. The authors have noted that although implementation of AMT by many organisations throughout the globe has become an integral part in manufacturing industries still the full benefits of the technology have not been captured. As a result, those systems are only partially implemented in small to large scale manufacturing enterprises. The authors in an attempt to address the various constraints associated with the implementation of the technology have proposed a conceptual framework (Figure 2.29). Their model focuses on critical aspects regarding the implementation of AMT which can be found in areas such as: Top Management support, Economic Aspects, and Technical aspects. Their results indicate that manufacturing companies which lack technical expertise and support have not fully implemented the above systems. They also suggest that those issues are more likely to arise when top management has low concentration on manufacturing firms. The authors suggest that companies should invest on proper training of their workers in relation to AMT systems and also provide the necessary financial resources to fully support the implementation process (Yasinshaikh et al. 2012).

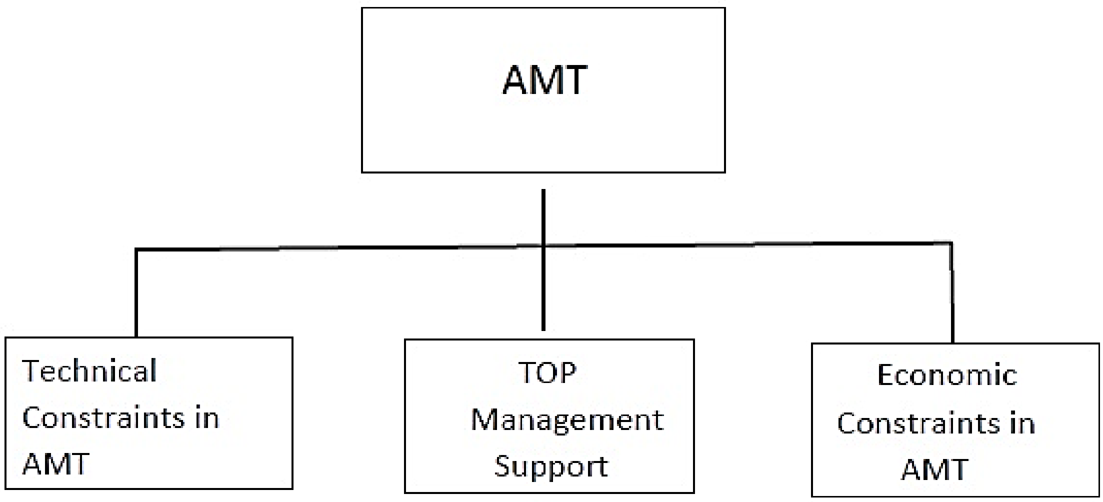


Figure 2.29: Conceptual framework for the implementation of AMT system proposed by Yasinshaikh et al. (2012)

Nagar and Raj (2012) in their study reviewed the various risks which can have a negative impact on the implementation of AMT. According to the authors the different types of risks associated with the fast-industrial development. Therefore, industries need to develop appropriate methodologies to prevent risks. The authors in their research have developed an interpretive structural modelling (ISM) for AMT implementation (Figure 2.30) which is employed to depict the relationship and priority among the various risks.

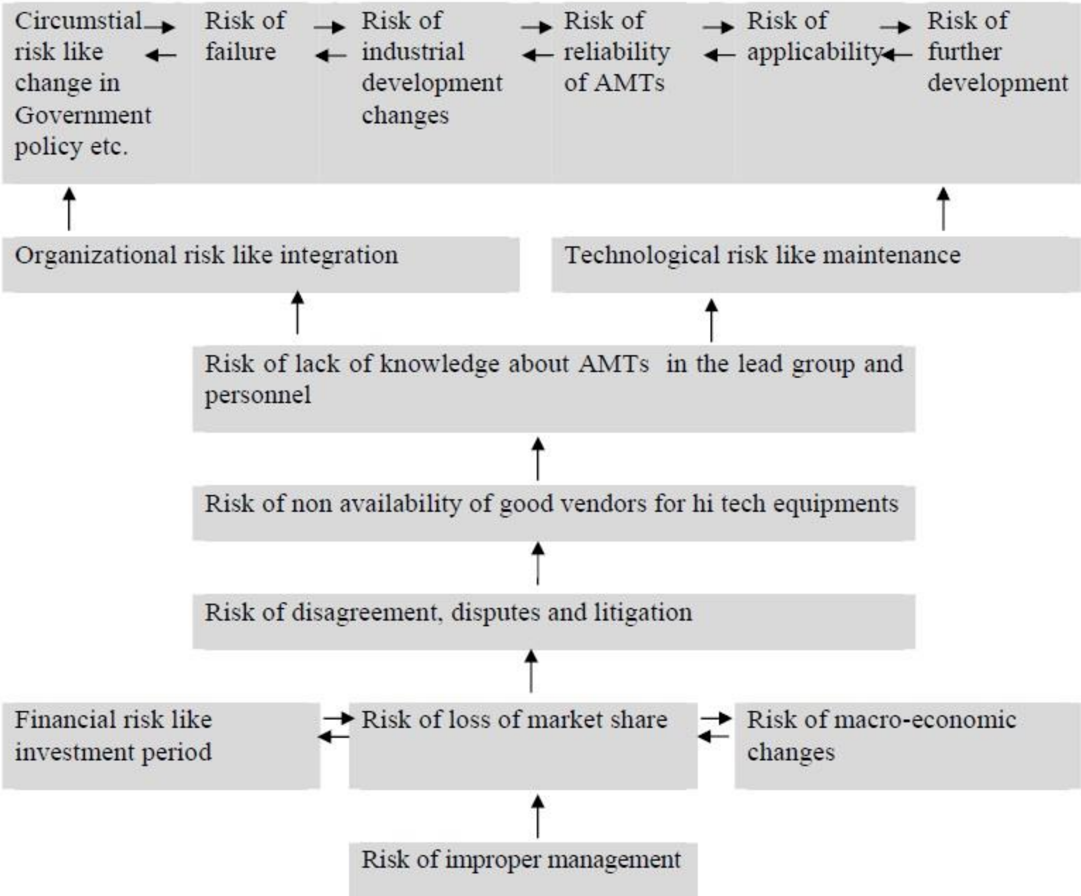


Figure 2.30: ISM model depicting different levels of risks proposed by Nagar and Raj (2012)

The framework provides guidance to managers in terms of classifying the relationship among various risks in AMTs implementation according to their driving power and dependence. The risks have been grouped into four categories: autonomous risks, linkage risks, dependent risks and independent risks. Therefore, based on this, managers can develop appropriate strategies to effectively handle the above risks and enhance on AMT implementation (Nagar and Raj 2012). The following Table 2.9 summarises the AMT implementation frameworks.

Table 2.9: Implementation Frameworks for Advanced Manufacturing Technologies Source: The Author

Source/ Reference	AMT Implementation Frameworks
Voss (1986)	A general methodology for identifying the operating and business objectives of the technology, developing managerial controls, specifying the organisational integration.
Dean et al. (1990)	Four major factors which impact the implementation process: the level of tolerance for acceptable decisions, the level of technical, economic, and political resources available for implementation, the direction of relationships among the three objectives, and the extent to which the objectives are balanced in decision-making.
Sambasiva and Deshmukh (1994)	Four stage approach: Objective Setting, Planning, Implementation of Various Systems, Evaluation Process.
Chen and Small (1994)	Integrated Planning (IPL) model consisted of three phases: definition of company objectives and determination of required product and process changes, technology monitoring and operational and organizational planning for the adoption of AMT, and financial and strategic justification
Udo and Ehie (1996)	A predictive model based on an analysis of the relationships between the determinants of AMT and the relevant benefits realized, in order to predict the success of AMT implementation.
Ghani and Jayabalan (2000)	Framework addresses the relationships between technology, structure and employees as an integral part of the planned change in terms of the new AMT process.
Yusuff (2001)	Analytical hierarchical process (AHP): Acceptance, Routinization and Infusion
Ghani et al. (2002)	Framework suggests that the organisational structure in terms of the AMT implementation will be influenced by attributes such as task variety, job flexibility, decision making, control system, communication, leadership, coordination, informal groups.
Efstathiades et al. (2002)	Proposed model including Technical, Manufacturing and Business Success within the overall AMT implementation process.

Small and Yasin (2003)	Framework which reviews the desirable roles, functions and activities of MIS/personnel/departments.
Marri et al. (2006)	Framework addressing four perspectives: Strategic, Tactical, Operational, and the Organizational perspectives.
Singh et. al (2007)	ISM-based model examining critical success factors such as: such as top management commitment, organization culture, sound financial condition, training, integration of departments.
Yasinshaikh et al. (2012)	Model focuses on critical aspects such as: Top Management support, economic aspects, and technical aspects.
Nagar and Raj (2012)	Interpretive structural modelling (ISM) classifying the relationship among various risks in AMTs implementation according to their driving power and dependence.

2.7 Supply Chain Fundamentals

2.7.1 Supply Chain

The term “supply chain” has different definitions. However, as it can be seen from the following definitions there seems to be a universal agreement regarding the definition of a supply chain.

Several authors define supply chain as a network of activities including the end customer. In particular Stevens (1989) states that a supply chain can be defined as a model which incorporates different activities through various participants in the form of a network. This network starts from the suppliers in the production and includes the end consumer. Lee and Billington (1995) and Ganeshan and Harrison (1995**)** describe supply chain as a network of facilities and distribution options that procure raw materials, transform them into intermediate and final products, and distribute these finished products to customers. Swaminathan et al. (1996) and Teigen (1997) define supply chain as a network of autonomous or semi-autonomous business entities which are collectively responsible for procurement, manufacturing and distribution activities associated with one or more families of related products.

Other authors emphasise that a supply chain is comprised from both upstream and downstream activities aiming the consumer. Here, Christopher (1992) highlights that a supply chain consists of multiple firms, both upstream (i.e., supply) and downstream (i.e., distribution), and the ultimate consumer. Slack et al. (2007) defines the supply chain as an interconnection of upstream and downstream organizations.

Some studies define supply chain as a coordination of functions and processes across business. Mentzer et al. (2001) outlined that a supply chain is "the systematic and strategic coordination of business functions within and across businesses". Chopra and Meindl (2007) provide the following definition for supply chain: "A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request. The supply chain includes not only the manufacturer and supplier, but also transporters, warehouses, retailers, and even customers themselves". Hugos (2011) describes the **s**upply chain as the "coordination of production, inventory, location, and transportation".

Thus, it clear from the above (Figure 2.31) that a supply chain is defined as a network of activities, which circulates from the suppliers in the production to the end consumer, with the coordination of all parties at upstream and downstream level including the end customer.

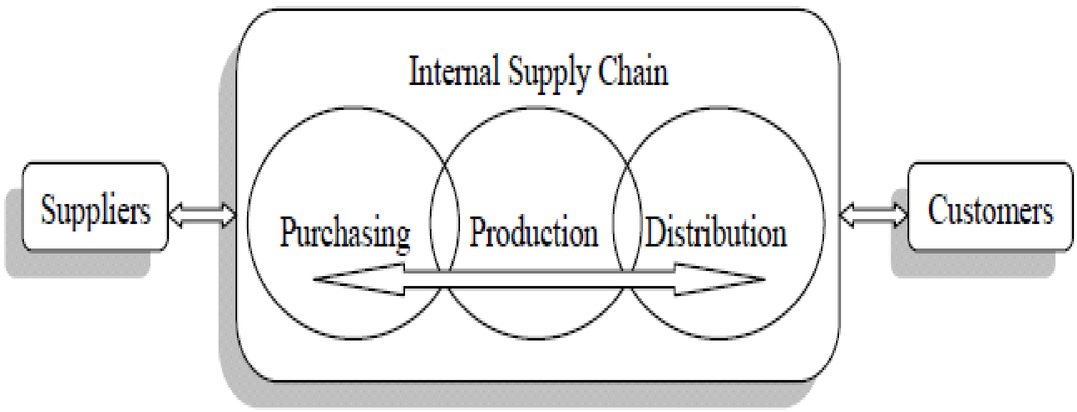


Figure 2.31: An illustration of a company's supply chain
Source: Chen and Paulraj (2004)

Different sizes of supply chains are often addressed in literature. According to Colin et al. (2011) a SC can be simple or extended. The authors explain that simple chains recognize a level above and below the focus organization, compared with the extended chains which look beyond the firms immediately upstream and downstream (Figure 2.32). Figure 2.32 also shows material and information flow according to which material flow forward from raw material extractors to the final customers while information and funds flow backward from final customers to raw material extractors (Beamon, 1998).

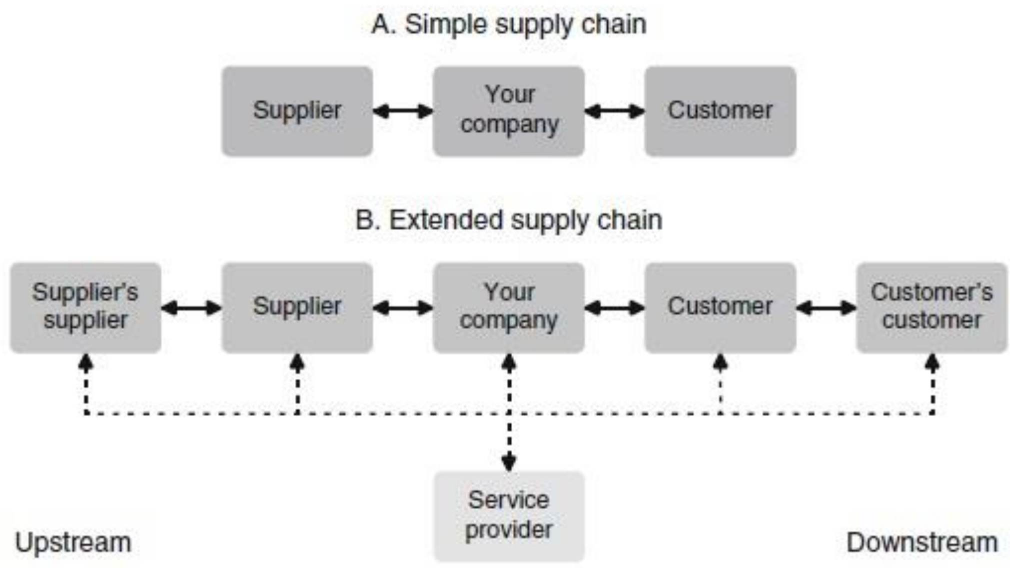


Figure 2.32: Supply chain structures

Source: Colin et.al (2011)

The following Table 2.10 categorizes the studies mentioned above in accordance with the supply chain definitions and the reference/source.

Table 2.10: Supply Chain defined

Source: The Author

Studies on Supply Chain Definitions	Reference/Source
A network of activities including the end customer	Stevens (1989), Ganeshan and Harrison (1995), Swaminathan et al. (1996), Teigen (1997)
Upstream and downstream activities aiming the consumer	Christopher (1992), Slack et al. (2007)
A coordination of functions and processes across business	Mentzer et al. (2001), Hugos (2011), Chopra and Meindl (2007), Chen and Paulraj (2004)
Supply chain structures	Colin et.al (2011), Mentzer et al. (2001), Beamon (1998)

2.7.2 Supply Chain Management (SCM)

Mentzer et al. (2001) has noted that although Supply Chain Management (SCM) has been particularly popular in academia and practice it is still unclear as to what exactly covers. Simchi-Levi et al. (2008) defines SCM as a set of different approaches used to integrate manufacturers, warehouses, suppliers and stores to ascertain that products are produced and distributed to the right location at the right quantities and at the right time, so they minimize and satisfy system requirements and costs. Bozarth and Handfield (2008) states that: "SCM is the active management of supply chain activities and relationships in order to maximize customer value and achieve a sustainable competitive advantage." Forslund and Johnson (2009) summarized SCM to be about the upstream and downstream process integration. On the other hand, Baharanchi (2009) suggests that efficient and effective SCM is dependent on integrated business processes. Mehrjerdi, (2009) provided the following definition: SCM can be defined as "set of approaches used to efficiently integrate suppliers, manufacturers, warehouses, and stores so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time in order to minimize system wide costs while satisfying service-level requirements"**.** According to Awad and Nassar (2010) SCM system coordinates organizations and facilitates collaborating them with business partners, suppliers and customers, which is expected to bring value to the system and add competitive advantage to the organization. Wisner et al. (2012) defines SCM as ''the integration of trading partners, key business processes from initial raw material extraction to the final or end customer, including all intermediate processing, transportation and storage activities and final sale to the end product customer."

2.7.3 Supply Chain Management in Manufacturing

According to Vrijhoef and Koskela (2000) the concept of SCM has its origins in the manufacturing industry where it has found several applications. Shingo (1988) noted that the concept of SCM was first applied in the Toyota Production System and the Just In Time (JIT) delivery system. The main objective of the JIT system was to reduce inventory levels and to integrate the suppliers with the production line in a more efficient way. Other management concepts such as value chain and extended enterprise, have played a significant part in the evolution of SCM. In accordance with Shingo (1988), Cooper et al. (1997) and Van der Veen and Robben (1997) highlighted that the concept of SCM involves more than just logistics and encompasses features from concepts including Total Quality Management (TQM), Business Process Redesign (BPR) and JIT. Vrijhoef and Koskela (2000) graphically demonstrates a generic configuration of a supply chain in manufacturing (Figure 2.33). This configuration is characterized by both information flow and material flow. Information flow includes orders, schedules, forecasts etc. moving continuously between customers, retailers, assemblers, manufacturers and suppliers. On the other hand, material flow involves supplies, production, deliveries, etc. and circulates from their manufacturing from raw materials through to their use within the manufactured product.

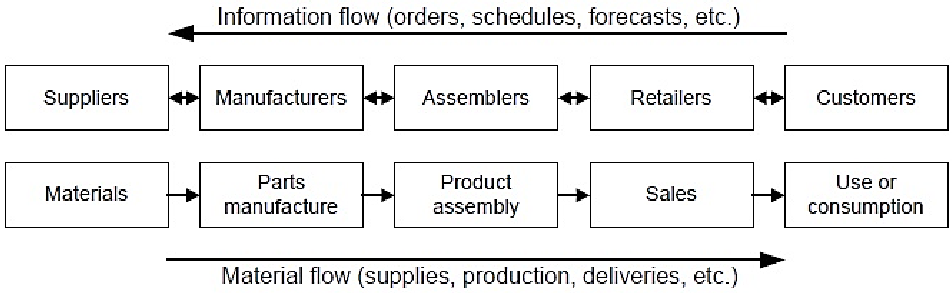


Figure 2.33. Generic configuration of a supply chain in manufacturing

Source: Vrijhoef, and Koskela (2000)

2.7.4 Key Supply chain models

Decelle et al. (2007) presents an overview of the literature on supply chain methods utilised in SCM. According to the author most models focus on logistical issues of the supply chain such as quality rates, inventory, lead-time and production cost. In particular, several studies have focused on analysing stock levels across the supply chain with the utilisation of models such as pipeline mapping, supply chain modelling and logistics performance measurement. Several other models such as the LOGI method, supply chain costing, value stream mapping and process performance measurement have been applied respectively to investigate controllability problems of the delivery process, cost build-up along the supply chain and process performance measurement (Decelle et al. (2007).

Examining the previous definitions on SCM, models are required to investigate all steps involved in the manufacturing process within the supply chain. One of the most popular models developed by the Supply Chain Council (2008) is the Supply Chain Operations Reference (SCOR) model that applies to all types of supply chains (Figure 2.34). The SCOR model is consisted of five distinct management processes which are the following:

Plan: Planning activities associated with operating a supply chain such as supply, production and customer demand.

Source: The source process of raw materials or intermediates that are required to produce the product. Sourcing includes activities such as ordering (or scheduling) and receipt of goods and services.

Make: Production of a product. The Make process involves all activities associated with the conversion of materials or creation of the content for services.

Deliver: The Deliver process involves all activities related to the notification and physical delivery of goods to the location where the product is required.

Return: The Return process describes the activities associated with the notification and physical return of goods.

Figure 2.34: SCOR Model (Supply Chain Council : SCOR 9.0 Overview Booklet, 2008)

Other models emphasise the importance of Supply Chain Integration (SCI) within the concept of SCM. Flynn at al. (2010, p.59) defines SCI as "the degree to which a manufacturer strategically collaborates with its supply chain partners and collaboratively manages intra and inter organizational processes, with the goal of achieving effective and efficient flow of products, services, information, funds and decision so as to provide maximum value to the customer at low cost and high speed." Therefore, those models underline that organisations do not compete in isolation but as a part of a broader network, which consists of several different players. Thus, taking into consideration the extent of the global supply chain competition, integration with the other partners in the network becomes necessary. (Flynn at al. 2010, p.59).

In particular, Saiz and Castellano (2006) defines supply networks (SN) as "a network that performs the function of materials procurement, transformation of these products into intermediates and finished products, and the distribution of those products to the final customers". The author adds that a supply network involves "production units (manufacturing and assembly processes, and inventories for temporary stocking) and storage points (distribution centres), connected by transportation of goods and by exchange of information, as well as their corresponding planning and control system" (Saiz and Castellano 2006, p. 163).

Childerhouse et. al (2011) presented a model which shows the integration of an organisation with the wider supply chain (Figure 2.35).

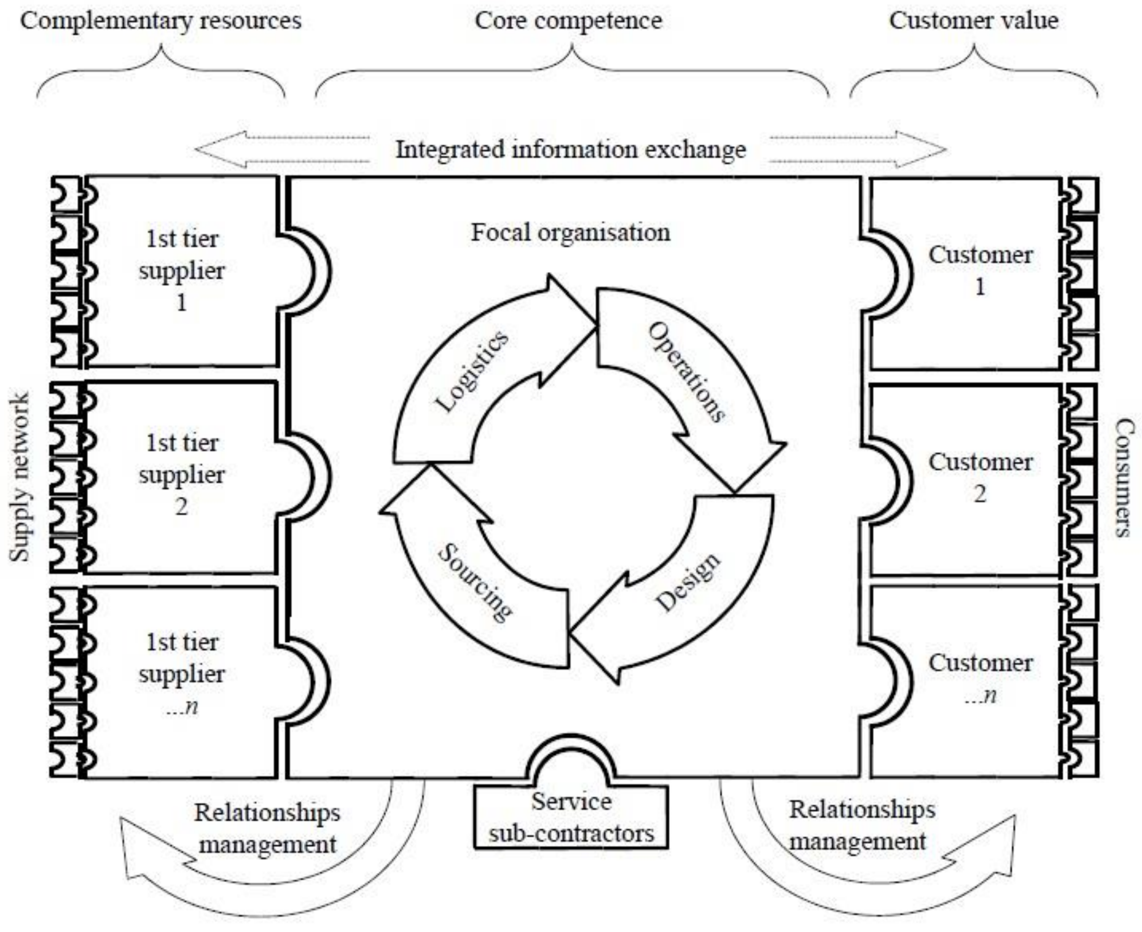


Figure 2.35: Supply Chain Integration

Source: Childerhouse et. al (2011)

2.7.5 Coordinating Functions Across Supply Chain Members

Thomas and Griffin (1996) noted that a supply chain is consisted of three traditional stages: procurement, production and distribution/logistics.

2.7.5.1 Procurement/Purchasing

Several authors (Clark, 1989; Eisenhardt and Tabrizi, 1994) have stated the importance for a manufacturing company to coordinate with its supplier on both current product's quality improvement and new product development (NPD). Improved product quality will benefit the manufacturer on selling more of the existing product in the market and in turn the supplier can expect to increase its profits as the manufacturer should buy more from the supplier. It was noted that in the past firms contracted with a large number of suppliers; however, the traditional model of buyer–seller relationship has been shifted towards a limited number of qualified suppliers. Burt (1989) highlights that a carefully selected and managed supplier offers the greatest guarantee of consistently high quality, namely, commitment to the product. Additionally, the integration of suppliers into NPD can lead to many benefits for the manufacturing company such as reduced cost and improved quality of purchased materials, reduced product development time, and improved access to and application of technology (Ragatz 1997).

2.7.5.2 Production

Every firm needs to invest in new products in order to stay competitive in the market. However, product development can only be successful if planned effectively and executed throughout the supply chain. This process can be quite complex where an organisation is required to utilise its management and technical skills to deliver a commercial product. Here, involvement of buyers and suppliers into the development process can be beneficial as it can assist the company in detecting early mistakes and avoiding disruptions in logistics and supply chain. Thus, it is clear from the above that effective SCM needs to integrate customers and suppliers into the product development process in order to better meet customer needs, produce products in a cost-effective manner and reduce time to market (Schilling and Charles 1998).

2.7.5.3 Distribution / Logistics

An important part of SCM is logistics. The Council of Supply Chain Management Professionals (2011) provides a widely-accepted definition of major logistics activities: "Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfilment, logistics network design, inventory management, supply/demand planning, and management of third party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution - strategic, operational and tactical. Logistics management is an integrating function, which coordinates and optimizes all logistics activities, as well as integrates logistics activities with other functions including marketing, sales manufacturing, finance, and information technology'' (The Council of Supply Chain Management Professionals 2011).

Russell (1997) explains that although the terms SCM and logistics are often used synonymously, they are different. According to the author logistics involves the coordination of logistical activities of supply. On the other hand, SCM refers to the management of all processes within the entire supply chain including also logistics activities. The following Figure 2.36 presents the logistics across the different stages of a product life cycle.

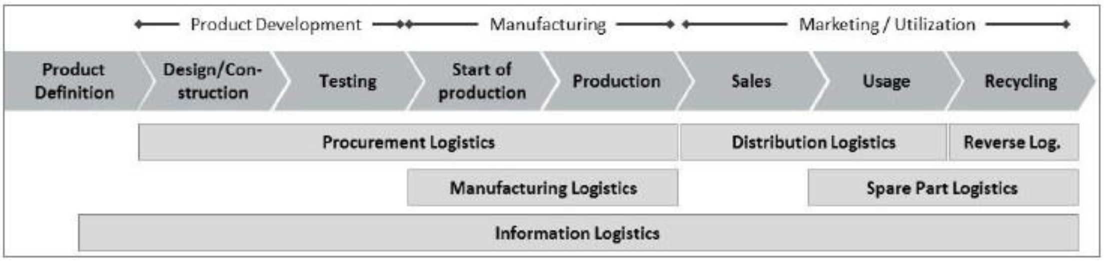


Figure 2.36: Logistics across a product life cycle

Source: Kersten et al. (2006, p.327)

2.7.6 Manufacturing technology adoption/implementation in Supply Chain

Patterson et al. (2003) in their research, state that the integration of supply chain activities and technologies have become an integral part in most industries. The authors have developed a model which includes the key factors in terms of the adoption/implementation of technology within the supply chain (Figure 2.37).

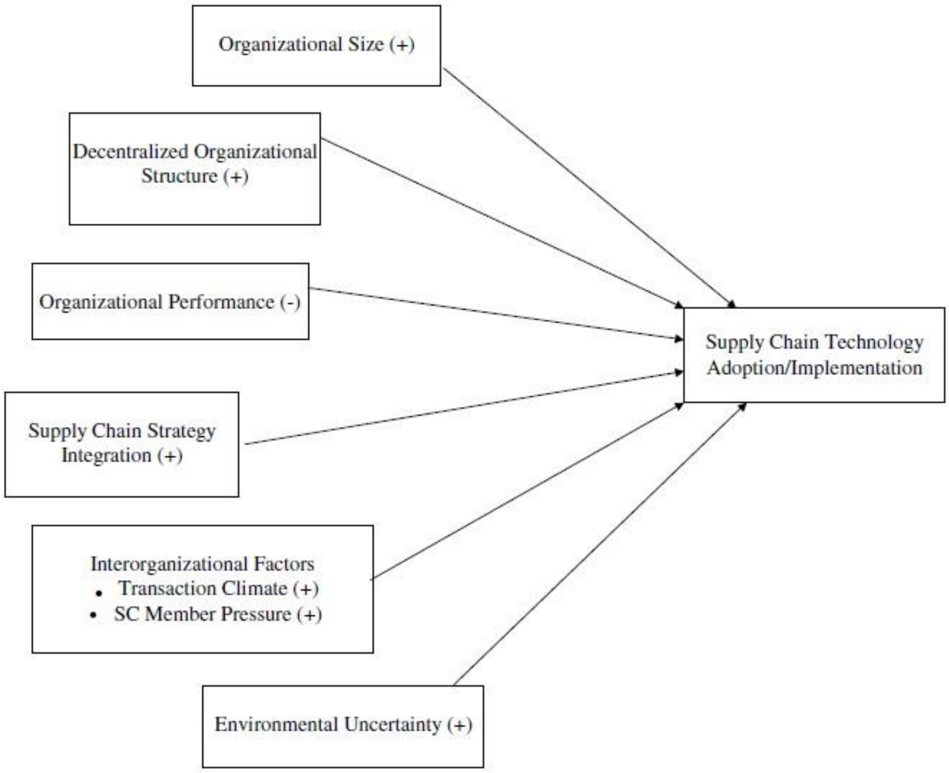


Figure 2.37: Antecedents of supply chain technology adoption proposed by Patterson et al. (2003)

The authors in their study have chosen to use the concept of ''adoption'' within the broadest sense which encompasses the generation, development, and implementation of the technologies based on the definition from Damanpour (1991, p. 556). According to their model a set of variables plays a significant part on the adoption/implementation of technology within the supply chain which includes the organisational size, structure and performance as well as the integration of supply chain strategy, interorganizational factors and environmental uncertainty. Their model can be utilised to provide to managers a better understanding in relation to supply chain technology diffusion process (Patterson et al. 2003).

Power and Simon (2004) in their research have conducted a survey of 553 Australian companies in order to investigate the main characteristics of organisations which implement technologies within their supply chain. Their survey has identified three groups of organisations based on the extent to which these technologies have been adopted and used in dealings with trading partners. The three groups are the following: strategic, tactical and reactive. The main differences between the three groups in terms of differentiation can be found on planning, reengineering of processes, and investment priorities. According to their results there is a strong correlation between company size, industry sector and the extent of implementation. The authors concluded that organisations which focus more on implementation tend to invest more in supporting infrastructure rather than just in technology and appear to be more proactive in relation to their planning (Power and Simon 2004).

Gunasekaran and Ngai (2004) in their paper underlined the importance of IT implementation within the SCM as a fundamental element for business survival and a major driver for improving the competitiveness of companies. According to the authors IT plays a significant part in achieving an effective SCM by integrating the various supply chain activities and thus it can streamline operations to improve quality service to customers. Based on a literature review survey the authors noted that IT enables six major areas of SCM including:

(1) strategic planning;

(2) virtual enterprise;

(3) e-commerce;

(4) infrastructure;

(5) knowledge and IT management; and

(6) implementation (Gunasekaran and Ngai 2004).

Nair et al. (2009) have also highlighted that the use of Information Technology (IT) within organisations and across the supply chain has played a major role in assisting firms to gain a competitive advantage. In their paper, they focus on the use of IT as an enabler for SCM and the potential benefits to companies when implementing a successful IT strategy. The authors have examined the deployment of various tools within the supply chain, based on IT such as EDI, ERP, bar codes, inventory management, transportation management and warehouse management systems. In their research, they have also addressed the new emerging tools such as RFID, software agents, decision support systems, web services, e-commerce, electronic supply chains etc. According to their findings companies must realise that IT can assist them to restructure the entire distribution set up to achieve higher levels and also to lower inventory and supply chain costs. At the same time companies, must use the power of technology to collaborate with their business partners (Nair et al. 2009).

Kamaruddin, and Udin (2009) in their study aimed to identify the relevance of technology adoption factors affecting SCT adoption at the implementation stage. The authors focused their research on automotive manufacturers and the impact of supply chain technology (SCT) within their organisation. Their results have identified the factors which can have a positive relationship with the SCT adoption. Those factors are associated mainly with the organisational size and organisational structure as well as supply chain member pressure (Kamaruddin, and Udin 2009).

Prajogo and Sohal (2013) in their study examine the use of supply chain technologies within the broader concept of SCM. According to the authors the utilisation of technologies in supply chains could lead to operational benefits in terms of cost reduction and service improvements as well as to other strategic benefits in relation to product planning and innovation. The authors classified the technologies into two categories: ‘internally focussed technologies’ and ‘externally focussed technologies”. Their findings indicate that the major technologies used in relation to the ‘internally focused category’ include warehouse management system, data capture systems (e.g. barcode scanning) and enterprise resource planning (ERP). On the other hand, it is found that in relation to the ‘externally focused category’ EDI/e-messaging was found to be the most widely used technology (Prajogo and Sohal 2013).

Bhandari (2016) in his study examined the impact of the various technologies used in logistics and SCM including information technology, communication technology and automatic identification technology. According to the author the emerging new technologies can create a number of strategic opportunities for companies in relation to many functional areas such as logistics and SCM. Therefore, the new technologies can be used within the supply chain to crease competitiveness and improve overall effectiveness and efficiency of logistics system. However, the author noted that the degree of the success of the application of new technologies will depend on the selection of the right technology in terms of application, availability of proper organizational infrastructure, culture and management policies. In particular, the application of information, communication and automation technologies in logistics, has led to a number of benefits in relation to increased speed of identification, as well as to high level of accuracy and reliability with regards to data gathering, processing, analysis and transmission (Bhandari 2016).

Mastrocinque et al. (2016) in their study have examined the importance of the selection of the manufacturing technology in relation to the supply chain and business performance. According to the authors technology selection can play a significant role in the operations of today's supply chains as there can be multiple benefits that can be achieved. In particular, technologies can assist companies to improve programmes and gain competitive advantage. The authors noted that this becomes particularly important for innovative sectors dealing with no standardised materials and technologies. Therefore, selecting a manufacturing technology will depend more on supply chain related factors such as suppliers, raw materials and capacity rather than the technology itself. The authors in order to investigate the factors affecting manufacturing technology selection within the concept of supply chain have utilised the Fuzzy Analytical Hierarchy Process, which can prove a powerful tool when dealing with problems affected by uncertainty. Their results show that factors such as supply chain performance and service level in terms of on time deliveries have proven to be the most influential factors, followed by return on investment, hire/train staff with new skills and environmental impact (Mastrocinque et al. 2016). The following Table 2.11 categorizes the studies mentioned above in accordance with the supply chain technology adoption/implementation and the source.

Table 2.11: Supply Chain Technology adoption/implementation

Source: The Author

Source	Supply Chain Technology adoption/implementation
Patterson et al. (2003)	A set of variables plays a significant part on the adoption/implementation of technology within the supply chain which includes the organisational size, structure and performance, the integration of supply chain strategy, interorganizational factors and environmental uncertainty.
Power and Simon (2004)	A strong correlation between company size, industry sector and the extent of implementation.
Gunasekaran and Ngai (2004)	IT implementation plays a significant part in achieving an effective SCM by integrating the various supply chain activities and thus it can streamline operations to improve quality service to customers.
Nair et al. (2009)	IT implementation can assist to restructure the entire distribution set up to achieve higher levels and to lower inventory and supply chain costs.
Kamaruddin, and Udin (2009)	Technology adoption factors associated mainly with the organisational size and organisational structure as well as supply chain member pressure.
Prajogo and Sohal (2013)	The utilisation of technologies in supply chains could lead to operational benefits in terms of cost reduction and

	service improvements and other strategic benefits in relation to product planning and innovation.
Bhandari (2016)	The application of information, communication and automation technologies in logistics, has led to a number of benefits in relation to increased speed of identification, high level of accuracy and reliability with regards to data gathering, processing, analysis and transmission.
Mastrocinque et al. (2016)	Factors affecting manufacturing technology selection can be found in supply chain performance and service level in terms of on time deliveries, followed by return on investment, hire/train staff with new skills and environmental impact.

2.8 Healthcare Supply Chain - SCM Practices in the Healthcare Sector

Mathew et al. (2013) states that currently hospitals aiming at cost cutting measures by looking for new sources of competitive advantage. For this reason, they re-examine their supply chain in order to look for new ways to improve the quality of service for efficient patient care. Therefore, the main aim of the SCM in healthcare is to establish visibility of information among suppliers, manufacturers, distributors and customers. According to the authors the healthcare supply chain involves the flow of many different product types and the participation of several stakeholders. Thus, in order to ensure that the needs of providers are fulfilled, products have to be delivered in a timely manner (Mathew et al. 2003).

In accordance with those functions the authors adapted Burns (2002) framework according to which stakeholders in the healthcare supply chain are comprised by three major groups: producers, purchasers, and providers. Ryan (2005) noted that within this system (Figure 2.38) there is also involvement and participation of governmental institutions, regulatory agencies, and insurance companies (Mathew et al. 2003; Burns 2002; Ryan 2005).

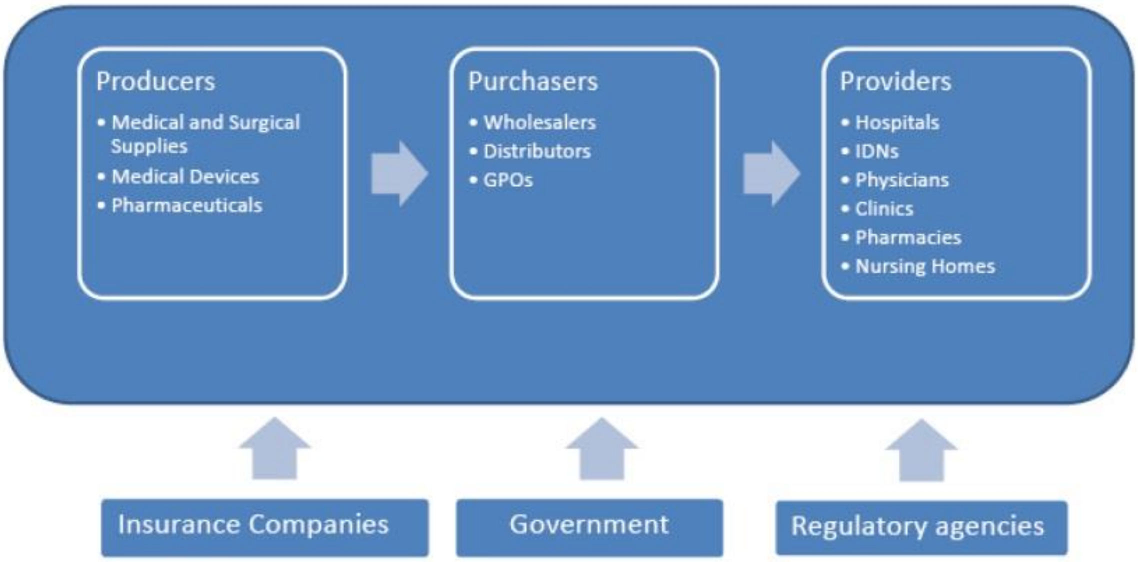


Figure 2.38: Healthcare supply chain configuration. Source Mathew et al. (2013), adapted from Burns (2002)

Schneller and Smeltzer (2006) highlighted that the healthcare sector starts with the manufacturer and ends with the final customer at the healthcare provider (Figure 2.39). It is often characterized as highly fragmented and relatively inefficient. The authors noted that a common problem with the traditional supply chain can be found on misaligned incentives and conflicting goals that prevent the supply chain from operating as a system. This is because every stage of the supply chain tends to operate independently (Schneller and Smeltzer 2006).

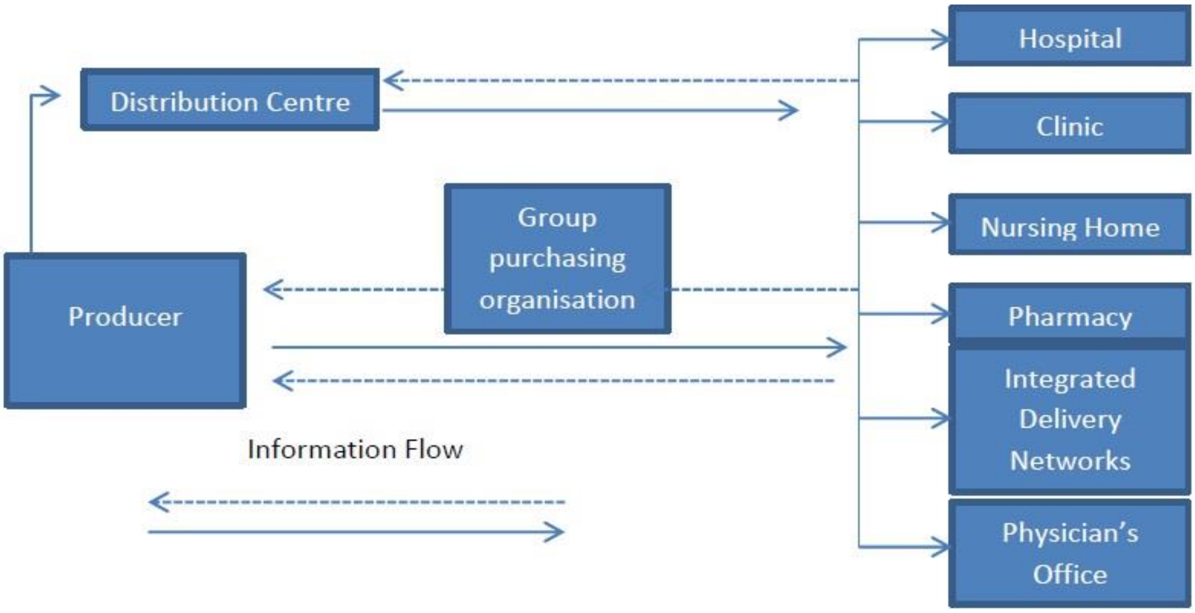


Figure 2.39: Healthcare Product flow, Source Mathew et al. (2013)

The following literature provides an overview of the practices for implementation of SCM principles within the healthcare sector which can be found mainly on material management practices, automated replenishment programs for inventory management such as Vendor Managed Inventory (VMI), integrated information systems, e-procurement and ERP systems.

Heinbuch (1995) proposed the hospital material management function approach in order to address the challenge of healthcare cost reduction. His study appraises the value of taking a proactive stance to meet the challenge of transferring technology across industry sectors (Heinbuch 1995).

Breier (1995) in his research focused on inventory management in the healthcare. According to the author hospitals fail to implement inventory management practices and this is because they hold high levels of safety stocks. It was noted that hospitals should focus on the use of personal judgment in determining safety stock levels, rather than using more scientific approaches (Beier 1995).

Brennan (1998) in his study underlined the importance of integrated delivery networks (IDNs) within the supply chain process, which can lead to substantial savings while dramatically improving the speed and quality of the service. However, the author noted that successful integration of the supply chain process can only be delivered if IDNs meet or exceed best practice performance in five supply management areas: demand, orders, suppliers, logistics, and inventory (Brennan 1998).

Burns (2002) proposed solutions to material management in the healthcare sector with the utilisation of information technology (IT). The author in order to address aggregation of suppliers and their products, suggested electronic catalogues, visibility of orders and materials, and efficiency in procurement (Burns 2002).

Alverson (2003) in his study highlighted the importance of disciplined inventory management for hospitals. The author proposed serious consequences of traditional hospital purchasing including lack of inventory control, missed contract compliance, excess inventory levels, frequent stock-outs and costly emergency deliveries, workflow interruptions, expensive rework, and increased health system labour requirements (Alverson 2003).

Kim (2005) in his study addressed Vendor Managed Inventory (VMI) issues. The author developed an integrated supply chain management system for optimizing inventory control and reducing material handling cost of pharmaceutical 12 products in the healthcare sector. The developed SCM system was based on an online procurement system for implementing Vendor Managed Inventory (VMI) to improve material handling and resulted to improvements of the procurement processes and inventory control of pharmaceutical products (Kim 2005).

Schneller and Smeltzer (2006) suggested that purchasing costs can be significantly reduced with e-procurement systems, which ensure the consolidation of supplier networks and creation of supplier partnerships. Furthermore, the authors suggested that the utilisation of ERP systems, which provide an automated and paperless format for information to flow throughout an organization, can assist in reducing transaction and administration costs **(**Schneller and Smeltzer 2006).

Kritchanchai (2012) in his study examined the problems and challenges in the healthcare area associated with SCM. The authors found that performance improvement can be achieved in healthcare supply chain when practices such as standardised drug coding, operational re-engineering and implementing information technology are applied (Kritchanchai 2012).

Phichitchaisopa, and Naenna (2013) in their study appraised the importance of information technology within the healthcare supply chain. Their study examined the factors influencing healthcare Information Technology (IT) services in relation to improving quality and performance. Their results found that the factors with a significant effect are performance expectancy, effort expectancy and facilitating conditions. The authors concluded based on the above findings that in order for healthcare information technology to be widely adopted, management should improve healthcare staffs' behavioral intention and facilitating conditions (Phichitchaisopa and Naenna, 2013).

Arya et al. (2015) in their paper explored on issues and challenges associated with high technology healthcare supply chains. The authors pointed out that the term 'high technology' refers to the technology which is a cutting edge and therefore it can be defined as advanced manufacturing technology. They noted that supply chains which utilise high technology can significantly improve competitiveness and respond faster to demand needs. However, in order for companies to fully benefit from the systems incorporated in high technologies they need to invest in information systems at the point of sale so that the real time demand can be updated. This will result in reduced cost for logistics and efficient management of the inventory levels. According to the authors, recently, the high technology supply chains have suffered numerous service issues mainly in relation to service levels and costs associated with inventories. Therefore, the integration of changes within the production schedule becomes necessary in order for companies to overcome the above issues which affect the entire supply chain (Arya et al. 2015).

Pinna et al. (2015) in their study focused in the transformation of the healthcare supply chain and logistics flow redesign. According to the authors three main conditions are required to achieve this: collaborative governance structures, efficient processes and integrated information system. Examining first the collaborative governance, the application of the right governance structure for SCM will assist hospitals to maintain the right balance between reducing costs and providing high-emerging trends in healthcare supply chain management. This appropriate governance structure will require the deployment of processes which will aim in eliminating errors in relation to ordering the right quantities. Here, the successful integration of IT becomes necessary as it will allow hospitals to better link their logistics processes in relation to the flow of information with the Central Warehouse and vice versa (Pinna et.al 2015). The following Table 2.12 categorizes the studies mentioned above in accordance with the supply chain management practices in the healthcare sector and the reference/source.

Table 2.12: Supply Chain Management Practices in The Healthcare Sector

Source: The Author

Source/Reference	SCM Practices
Heinbuch (1995), Breier (1995), Burns (2002), Alverson (2003)	Material management, Inventory Management
Brennan (1998)	Integrated delivery networks (IDNs)
Kim (2005)	Vendor Managed Inventory (VMI)
Schneller and Smeltzer (2006)	E-procurement systems, ERP systems
Kritchanchai (2012)	Standardised drug coding, operational re-engineering and implementing information technology
Phichitchaisopa, and Naenna (2013)	Healthcare Information Technology (IT)
Arya et al. (2015)	High technology supply chains
Pinna et al. (2015)	Governance structures, efficient processes and integrated information system

2.9 The impact of Additive Manufacturing (AM) on Supply Chain

The potential supply chain ramifications are many and substantive. In particular Waller and Fawcett (2014) state that AM can be very useful for materials and spare parts inventory management as it uses only the material needed and therefore less material required in the production process. As a result, the technology can have potential implications throughout the stages of the supply chain from purchasing towards inventory management and transportation. Furthermore, AM allows for more agility and responsiveness to market changes as the technology is used for rapid prototyping and therefore the time required for product development is significantly less. Hence, according to the authors and based on the above, the technology is more appropriate for low volume production and thus meets particular customer needs with high value/specialist production. Finally, as the technology is based on digital data which can be sent to any printer and thus is location independent it has the potential to 'push' goods into different markets close to the end users and hence to achieve distributed – decentralised manufacturing (Waller and Fawcett 2014).

2.9.1 Management Considerations

There are several studies which examine the key aspects which need to be considered by managers when incorporating AM within their supply chain. Kieviet (2014) in his study noted that at the moment the research in relation to commercializing AM and integrating it into global supply chain networks is quite limited. For this reason, he developed a model focusing on how to use AM to reconfigure supply chains. His comprehensive tool incorporates all aspects of supply chain performance (costs, service, quality, and lead time) within the field of complexity management (Kieviet 2014).

Sebastian and Omera (2015) in his article, noted that AM could potentially disrupt many areas of the supply chain. The authors suggested that in order for managers to eliminate the effects of disruption to their future supply chains they need to produce a flexible management strategy which will take advantage of the resulting opportunities. They highlighted that those managers who will not act proactively they will be left out of the competition as the influence of the technology on supply chains is expected to grow (Sebastian and Omera 2015).

Rylands (2015) in his paper provided an overview of AM including examples of industries where the technology is currently deployed and examined areas and aspects of the supply chain which could be potentially impacted when the technology is adopted. The author has developed a framework in order to investigate the various aspects which need to be considered when the technology is utilised within supply chains and as part of the production process. He concluded that when managers consider deploying AM within production, they need to examine all key aspects categories which include technical, social, managerial and environmental. Therefore, the challenge for business is to incorporate the cost of the technology within their processes (Rylands 2015).

2.9.2 Global Supply Chains, Transportation, Inventory and Logistics

Other studies focus on the potential disruptions of AM in global supply chains, transportation, inventory and logistics. Bhasin and Bodla (2014) in their thesis aim to quantitatively estimate the potential impact of AM on global supply chains. The authors have developed a model to compare the processes and cost of the current supply chains with the processes and cost of the future supply chains after AM was adopted. Therefore, their model focuses on the future trends in AM adoption and costs within the concept of supply chain. Their research suggested that AM will significantly reduce transportation and inventory costs as production in future supply chains will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer. Their model also shows that there will be a change in the supply chain costs as they are projected to decrease while the adoption of the technology will increase. Finally, their analysis indicates that there will be an opportunity for Third- Party Logistics (3PL) companies to provide AM services in warehouses and this could lead to a reduction in the volume of freight business, which could affect the dynamics of the logistics industry (Bhasin and Bodla 2014).

Janssen et al. (2014) in their research explored how AM impacts the design and management of global supply chains. The authors based on the Supply Chain Operations Reference model (SCOR) - consisted of five main processes: make, source, deliver, return, enable and plan - investigated the impact of AM across the entire value chain for all these supply chain processes. They concluded that firms within their broader concept of strategic decision-making, they need first of all to make decisions in relation to where and how to manufacture their products as well as which channels to use to distribute a product. Further decisions within the design of global supply chains can be found in the areas of sourcing the raw materials and outsourcing the physical distribution to a service provider (Janssen et al. 2014).

Ye (2015) in his research examined the impact of AM on the world container transport. According to the author AM can be a disruptive technology for future manufacturing, supply chains and thus transport in general. The author developed an AM Competitiveness Score Model to assess and quantify its competitiveness (or impact) in centralised as well as decentralised manufacturing setups. His findings suggest that the location of AM deployment impacts the supply chain and its logistics. In particular, decentralized AM deployment can impact the supply chain by eliminating the need of transport on the demand side (manufacturer-consumer). The author noted that in relation to the implications of a decentralised manufacturing setup, the maritime transport on the demand side will be replaced with material transport of the raw material on the supply side (Ye 2015).

Mashhadi et al. (2015) in their paper described the changes AM will bring into the current structure of supply chain, taking also into consideration the characteristics and requirement of a supply chain. The authors in order to address the above issues they have provided insights in relation to how these changes impact the configuration of a supply chain. In their research they have utilised simulation tools such as Agent Based Simulation (ABS) and System Dynamics (SD) to evaluate AM supply chain. Their ABS results show that lead time reduction in AM based supply chain is possible, where the SD model explains the potential for less 'pipeline' effect in AM compared to traditional supply chain (Mashhadi et al. 2015).

Manners and Lyon (2012, p3) investigated the implications of this new manufacturing technology for the logistics industry which can be found mainly in six areas: a) North America and Europe have the potential to source a proportion of goods which were previously produced in China or other Asia Markets. b) Goods can be made to order which means low inventory levels and new implications for the 'mass customisation' concept. c) Manufacturing processes are likely to take place within a single facility as there will be fewer opportunities for logistics suppliers to be involved in companies' upstream supply chains. d) The manufacturer-wholesaler-retailer relationship will be impacted as production strategies based on build-to-order will affect the downstream logistics. e) It is likely that a new sector of the logistics industry will emerge to deal particularly with the storage and movement of the raw materials. f) Finally, further implications could be found to the Service Parts Logistics sector (Manners and Lyon 2012, p.3).

Ray (2013) in his research calculated the effectiveness of AM within the supply chain by looking the total ownership cost of a unit rather than only considering the per-unit cost of production. The author noted that many of these high total-ownership costs can be reduced. This is because the technology has the potential to achieve local manufacturing which will lead in reducing lead-times and transportation costs. Therefore, as objects can be digitally altered before printing in order to meet individual needs and avoid efforts to promote standardization, costs per producer are minimized. Ultimately, when the per-unit cost is no longer a factor, companies can move on-demand manufacturing where production will be based on consumer demand. The author, based his research on the military, examined the potential benefits when an AM machine could be accessed on the ship to print enough parts to justify the initial investment in the technology, and concluded that the technology could save time and money on transportation costs, and thus increase overall mission readiness (Ray 2013).

Durach et al. (2017) have examined empirically AM in relation to processes as well as barriers to their adoption and a timeline of expected impacts on the supply chain in the manufacturing industry. The authors concluded that scenarios which involve an increase in decentralized manufacturing or the rise of AM printing services have a strong potential to become true rather than mass customization or a significant reduction of inventory (Durach et al. 2017).

2.9.3 Social Impact / Sustainability

Further studies investigate the social impact/sustainability of AM. Reeves (2009) in his paper reviewed some of the current commercial applications of AM in relation to the benefits of technology adoption. The author has addressed the Design-For-Manufacturing (DFM) rules associated with applications of AM to manufacture lighter weight, energy efficient products with fewer raw materials as a sustainable alternative to conventional machining. In particular, the author examined the technology when it is utilised to make fully dense tool cavity inserts with highly efficient heating and cooling channels. He found that this approach can be significant useful in terms of economic benefits for the supply chain as it can result in reduced lead times, higher moulding quality and a lower carbon footprint. He concluded that the technology plays an important part within the supply chain as it can be applied from concept design to mass production (Reeves 2009).

Huang et al. (2013) review the societal impact of AM from a technical perspective. In their view promises of AM were found to support customized healthcare products to improve population health, sustainable manufacturing as a result of reduced environmental impact and simplified supply chain to facilitate efficiency and responsiveness. In relation to customized health products the technology is expected to play a significant role in personalized healthcare in terms of improving quality, safety and effectiveness for the general population. In terms of reducing environmental impact for manufacturing sustainability the technology when compared with conventional manufacturing can be more efficient in relation to virginal material consumption and water usage. Finally, the technology offers an enormous potential for simplifying supply chains as it can assist companies to be more responsive with their demand fulfilment. This is because the technology can reduce the need for warehousing, transportation and packaging and therefore appropriate supply chain configuration can lead in cost efficiency while at the same time maintain customer responsiveness. The authors concluded that further research needs to be conducted to address areas of life-cycle energy consumption evaluation and potential occupation hazard assessment for additive manufacturing (Huang et al. 2013).

White and Lynskey (2013) in their research compared aspects of traditional subtractive technologies and AM, such as cost of production, supply chain infrastructure, and sustainability in order to justify the potential economic benefit of using AM in application to end-useable parts. In particular, the information that the authors reviewed in relation to the benefits of the technology in terms of economic impact were found on reduction of waste, lead times, potential for mass customization, simplified supply chains and finally the ability of the technology to produce components which could not be generated by conventional techniques. The authors concluded that AM demonstrates many opportunities in production which can be utilised to make manufacturing industries more sustainable. Therefore, as the growth of the technology will continue, AM will play a significant part for industry sustainability (White and Lynskey 2013).

Wigan (2014) in their study noted that a range of characteristics which included in AM can contribute to sustainability; however not all AM processes are parsimonious in their use of power. In particular, according to the authors AM technology can offer significant benefits across the supply chain in terms of the final product; however, although that aspects of sustainability are quite important, the technology cannot fully address the different product types or market needs. The authors concluded that the advancements in home production as well as in mass customisation in economic small runs have resulted in lowering the barriers to entry of AM. Therefore, there is strong evidence in terms of sustainable contributions of the technology with many more to come (Wigan 2014).

Despeisse and Ford (2015) in their paper addressed examples from a wide range of products and industries in order to provide a better understanding of the technology associated with the role of AM in sustainable industrial systems. In particular, they noted that opportunities for AM implementation can be found in the product life cycle for sustainability improvements._The authors identified four main areas in which the adoption of AM is leading to improved resource efficiency: (a) product and process design; (b) material input processing; (c) make-to-order product and component manufacturing; and (d) closing the loop. They concluded that although the technology still has a long way to go in order to significant transform industrial systems there are already many signs of how the utilisation of technology can lead to advances in industrial sustainability. The authors suggest that in order for the technology to be more widely adopted, as so far it is utilised mainly by innovators and early adopters, further improvements in service-based business models must be produced which will support the social and economic value of the technology in relation to environmental impacts and subsequently increase the companies' sustainability performance (Despeisse and Ford 2015).

Kellens et al. (2017) have noticed that the available quantitative data on how AM manufactured products compare to conventionally manufactured ones in terms of energy and material consumption is quite limited. The authors concluded that from an environmental perspective, AM can be a good alternative for producing customized parts or small production runs as well as complex part designs creating substantial functional advantages during the part-use phase (Kellens et al. 2017).

2.9.4 Spare Parts Supply Chain

A number of studies examine the potential impacts of AM on spare parts supply chain. Walter et al. (2004) in their research aimed to highlight the impact of the technology on supply chain and presented new supply chain solutions made possible by both centralised and decentralised applications of AM. The authors demonstrated the benefits of AM technologies in the supply chain by focusing on the aircraft spare parts because of its current high costs and performance requirements. In order to support their research, they have utilised a periodic process consisted of a number of steps to identify when it is really valuable to produce parts with the application of the technology within the supply chain. Those steps have mainly focused on technical feasibility analysis, business benefit analysis, production costs analysis and supply chain impact analysis followed by decision based on total cost trade-offs on implementation. According to their results centralised has the potential advantage of cutting high inventory costs (of slow moving parts) and reducing the need to subsidise costs with profit of fast moving parts. In contrast the potential of distributed manufacturing can be found where demand is sufficient enough at a given location (Walter et al. 2004).

Hasan and Rennie (2008) following Walters (2004) study on spare parts, presented a paper which investigates the applications of AM in the spare parts industry. Their findings reinforced the case that in order for AM technologies to be widely adopted, fully functional supply chains are required. The authors in an attempt to enable such a supply chain proposed a business model based on an e-business platform (Hasan and Rennie 2008).

Hasan et al. (2013) in another study investigated the structure of an efficient ICT to enable an e-business model for AM technologies. For this purpose, the authors proposed a Virtual Trading system (VTS) based on an e-business platform which potentially could improve supply chain functionality and provide an alternative to the AM industry. The rationale for the development of this model was that a business model is required to establish communication between all components of the supply chain who are geographically apart including the network of suppliers, original equipment manufacturers, designers, engineers and customers (Hasan et al. 2013).

Mokasdar (2012) in his study focused on the impact of AM on the aircraft supply chain. The authors noted that the particular supply chain can be very critical where even a small shortage of spare part can lead to heavy financial losses. Therefore, aircraft companies and operators invest a lot of money in the inventory as they are required to keep large stock in relation to spare parts throughout the year. The authors investigated possible configurations in which AM can be incorporated along with conventional manufacturing in the supply chain and focused on lesser safety inventory, savings in inventory holding cost and better availability of spare parts in the aircraft industry. Their research attempts to demonstrate how the application of the technology with its benefits in relation to lead times compared with conventional manufacturing can significantly reduce total inventory of spare parts held in an aircraft spare parts supply chain (Mokasdar 2012).

Khajavi et al. (2014) in their research aimed to investigate the potential impact of AM improvements on the configuration of spare parts supply chains. In order to achieve their goal, they applied a scenario modelling of a real-life spare parts supply chain in the aeronautics industry. For this purpose, a number of scenarios in relation to supply chain configurations and the application of the technology has been examined. In order to compare the different scenarios, they have used parameters such as total operating cost including downtime cost. They found that initial investment in AM machines and the significant increases in personnel costs make distributed manufacturing more expensive than centralized production in the case example. However, distributed spare parts production can be feasible if AM machines become less capital intensive, more autonomous and offer shorter production cycles (Khajavi et al. 2014).

Holmström et al. (2010) in their research also highlighted the potential impacts of AM methods on service supply chain design. The authors focused on centralised and decentralised deployment of the technology in the spare parts supply chain. According to their findings, the distributed deployment of AM can be very interesting for spare parts supply chain as it has the potential to improve service and reduce inventory. However, currently on demand centralized production of spare parts or deployment close to the point of use by generalist service providers of AM is the most likely approach to succeed considering the trade-offs affecting deployment (Holmström et al. 2010).

Sirichakwal1 and Conner (2016) have utilised an approximate one-for-one inventory model for spare parts to analyse how inventory-related benefits can be derived from reductions in holding cost and production lead time. The authors concluded that (a) a reduction in holding cost has more impact on reducing the stock-out probability when the average demand rate for spare parts is low and (b) lead time reduction may negatively affect the stock-out probability (Sirichakwal1 and Conner 2016).

2.9.5 Supply Chain Designs

A few studies address the impact of AM on supply chain designs. Nyman and Sarlin (2014) in their research explored on barriers and opportunities of AM within the supply chain context. In particular, the authors concentrated on aspects like timing of production, product properties, and positioning of inventory in the chain within the broader concept of operative characteristics of different SC strategies. They have proposed a conceptual model for AM in the supply chain context based on an analysis of SC strategies as well as AM to provide an understanding of how AM can impact SC strategies (Nyman and Sarlin 2014).

Aliakbari (2012) in his research examined the opportunities of AM in relation to its application and cost drivers. For this purpose, the different processes and techniques are examined and their application in diverse industry sectors is presented. The author described the impact of AM in production systems associated with lean and agile systems within the concept of supply chain management. His findings suggest that time and cost are the most important drivers for the production systems to be more responsive. He concluded that AM has impacts on supply chain as it will remove some stages and units and therefore the influence of AM on supply chain clarifies the need for adoption of it to the current system, weather it is a Lean, Agile, or Leagile based system (Aliakbari 2012).

Tuck and Hague (2006) in their research looked into the effects that will occur to the logistics and supply chain infrastructure with the application of AM. They found that that AM has the opportunity to truly achieve a leagile supply chain as it can provide goods at low cost and at fast response which is required in volatile markets. Subsequently, the production of goods through AM could result in reduced stock levels and logistics costs while increase the flexibility of production in terms of time and cost. The authors added to their findings the contribution of the technology to increase value in products through the realisation of customised production. They concluded that although many questions remain to be answered in relation to the development of AM and the implementation of full customisation, the technology has an enormous potential to impact manufacturing (Tuck and Hague 2006).

The following Table 2.13 categorizes the studies mentioned above in accordance with the impact of AM on supply chain and the reference/source.

Table 2.13: Studies on impact of Additive Manufacturing on the supply chain

Source: The Author

Studies	Reference/source
Management considerations	Kieviet (2014), Sebastian and Omera (2015), Rylands (2015)
Global supply chains, transportation, inventory and logistics	Bhasin and Bodla (2014), Janssen, et al. (2014), Ye (2015), Mashhadi et al. (2015), Manners and Lyon (2012), Ray (2013), Durach et al. (2017)
Social impact / sustainability	Reeves (2009), Huang et al. (2013), White and Lynskey (2013), Wigan (2014), Despeisse and Ford (2015), Kellens et al. (2017)
Spare parts supply chain	Walter et al. (2004), Hasan and Rennie (2008), Hasan et al, (2013), Mokasdar (2012), Khajavi et al. (2014), Holmstrom et al. (2010), Sirichakwal1 and Conner (2016)
Supply chain designs	Nyman and Sarlin (2014), Aliakbari (2012), Tuck and Hague (2006)

2.10 Additive Manufacturing (AM) Implementation Models/Frameworks

This section will examine the developed AM implementation frameworks. However, the researcher will first present a recent developed AMT (Advanced Manufacturing Technology) implementation framework proposed by Saberi and Yusuff (2011) as it will be utilised later by Deradjat and Minshall (2015) to develop their own AM implementation model.

Saberi and Yusuff (2011) state that Advanced Manufacturing Technologies (AMT) are perceived by companies to be an important element in surpassing competitiveness. However, the authors noted that only the acquisition of new technologies alone is not enough to assist companies to excel in today's market. Companies when acquire new technologies need to ensure that an appropriate structure and infrastructure is in place to facilitate the expected benefits of the implementation of new technologies. As a result, a framework is required which will match the right mix of strategic elements of the organisation with the requirements of AMT adoption. Focusing on factors influencing AMT implementation, Saberi et al. (2011) proposed a framework of effective factors that have an influence on AMT implementation, which distinguishes between technological, organisational and internal and external variables. In particular, the developed framework illustrates a set of propositions indicating that company performance is highly depended on the alignment of organisational structure, culture, operational strategy and human resource-management practices with AMT implementation (Figure 2.40).

“Proposition 1: The performance of companies with investment in AMT is higher compared with companies that have less AMT investment.

Proposition 2: Flatter, less complex structures with maximum administrative decentralization companies who have invested in AMTs, have higher performance compared with companies with more centralization, formalization and complexities.

Proposition 3: The organization with flexibility-oriented culture, whether internal or externally -oriented, achieved higher performance in implementing AMT.

Proposition 4: Performance of the companies implementing AMT that simultaneously focused on flexibility, delivery, quality and cost strategies will be higher compared with other companies which focus on one of the strategies only.

Proposition 5: Firms with more emphasis on human resource and management practices have higher performance in applying AMT compared with others” (Saberi and Yusuffb 2011, p.146).

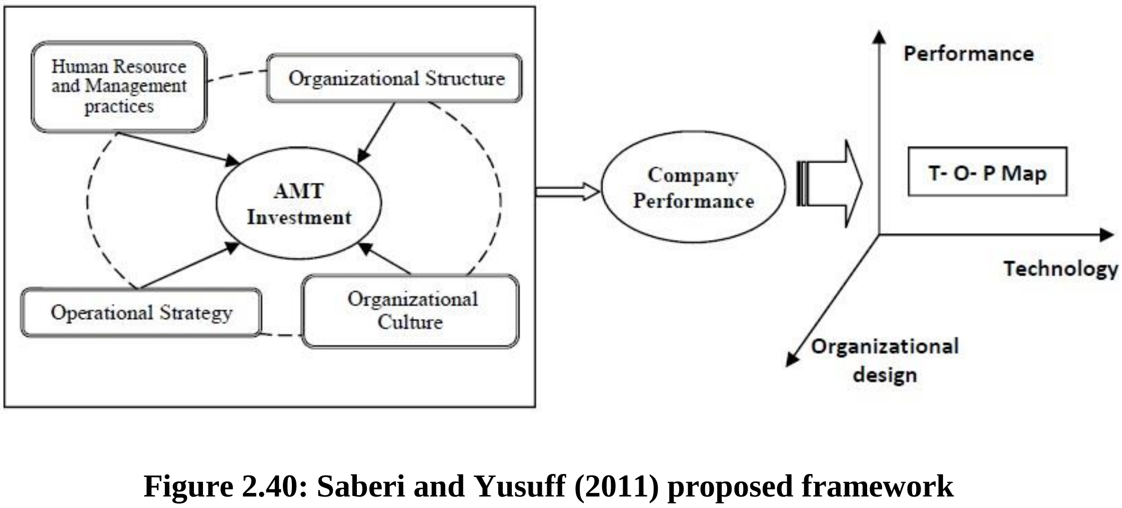


Figure 2.40: Saberi and Yusuff (2011) proposed framework

Mellor et al. (2014) developed an implementation framework for AM (Figure 2.41). The authors suggest that both external and internal policy equally play a significant part in the implementation of AM as a method of manufacture. According to their conceptual model the process of AM implementation will be affected by influences that can be clustered into five groups (strategic factors; organisational factors; operational factors; supply chain factors; and technological factors) (Mellor et al. 2012). However, the proposed framework does not examine in depth supply chain considerations.

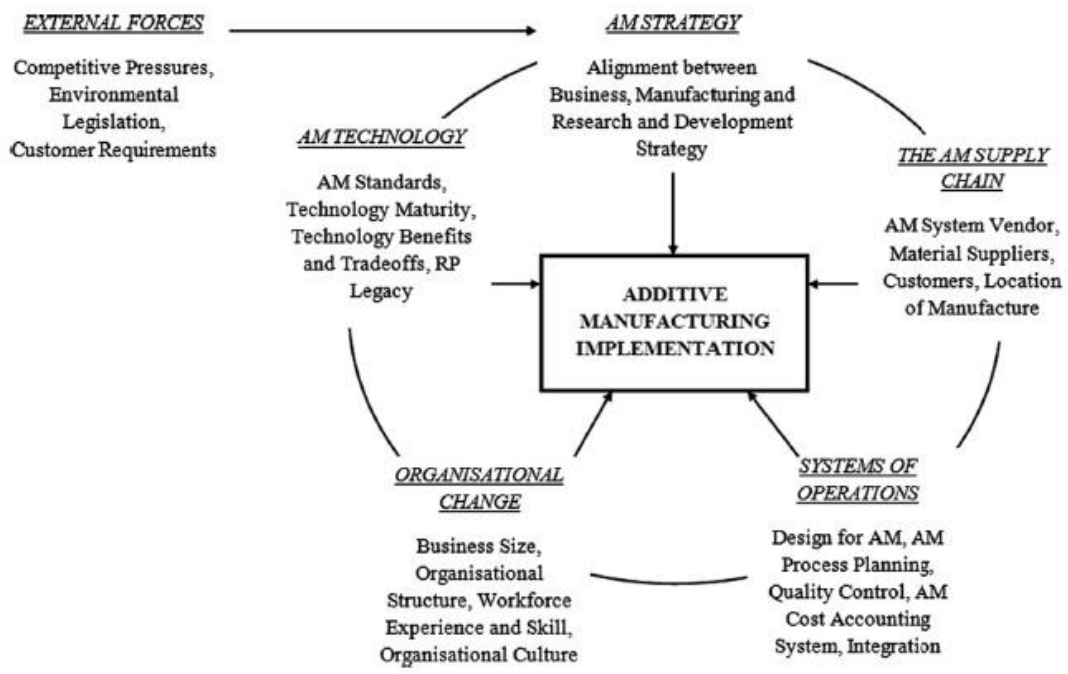


Figure 2.41: Mellor et al. (2012) proposed framework of AM implementation

Deradjat and Minshall (2015) have developed a framework on AM implementation which adopts and modifies the framework proposed by Saberi et al. (2010) and Mellor et al. (2014) and focuses on technological variables (Figure 2.42). The purpose of their framework is to ascertain the importance of different factors influencing the implementation of AM for Mass Customisation (MC). According to the authors these factors are categorised into technological, operational, organisational and internal/external factors (Deradjat and Minshall 2015).

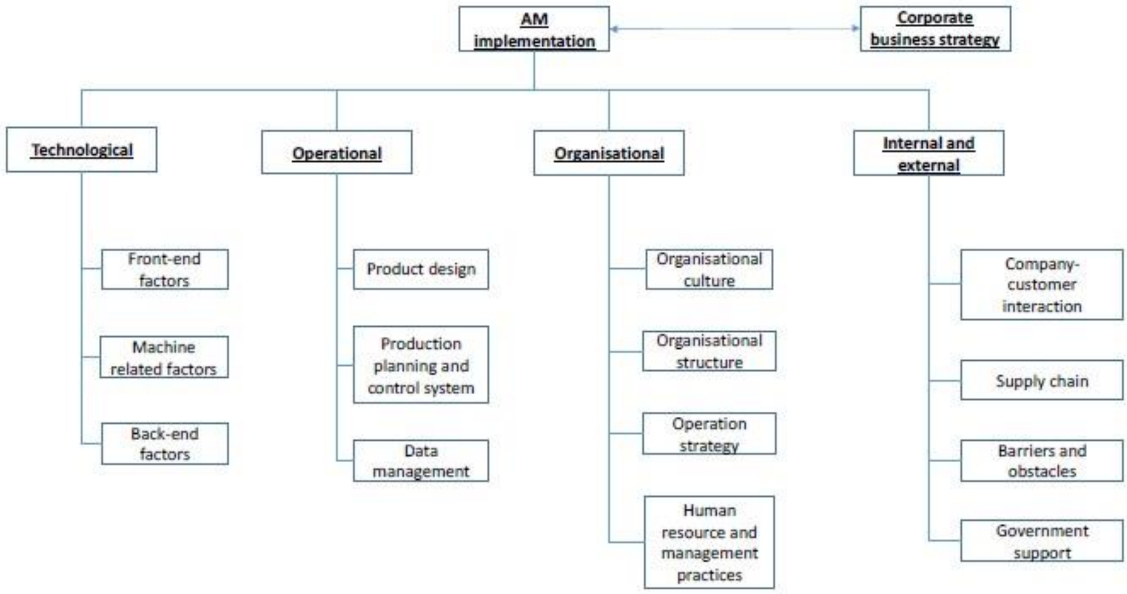


Figure 2.42 Framework for AM implementation for MC proposed by Deradjat and Minshall (2015)

Thus, it is clear that the research on developed AM implementation frameworks is very limited and currently there is no AM implementation framework particularly focusing on supply chain.

2.11 The Research Gap on AM Implementation Research on Supply Chain

The manufacturing supply chain is formed by various companies, which can play an active role within the different stages of a supply chain from raw material/equipment suppliers to product manufacturing and towards the delivery of goods to customers (Huang et al. 2013). AM can have an impact at every stage of the supply chain from the selection of suppliers in relation to materials/AM machines, the most detailed aspect of CAD model within a product design, to logistical decision across the supply chain. At each of these stages AM can offer significant opportunities for improvement and renovate the supply chain (Mashhadi et.al. 2015). Examining the studies above in relation to the various stages within the supply chain (section 2.9) it is clear that most studies address the potential disruptions of AM in distribution /logistics and therefore on location of manufacturing. Additionally, there is no implementation framework focusing on supply chain (section 2.10). Therefore, a study is required, which will examine in depth the key factors influencing AM implementation within the various stages of a supply chain from the selection of raw material-equipment suppliers towards the customers.

2.12 Medical Device Manufacturers

Healthcare providers are constantly seeking opportunities to reduce costs while at the same time maintaining the quality of patient care. In order to achieve this, they mainly target medical device and ask medical manufacturers for significant cost reductions. Subsequently medical manufacturers respond by eliminating waste and improving functionality in the medical device supply chain. However, operational improvements are required to implement the above. Here the utilisation of new technology plays a predominant part in order to see a product's entire part through the supply chain. This study focuses on the medical sector. The medical sector is the largest adopter of AM and applications have moved from prototyping to customised products (Penny et al. 2013; PwC 2014). In the medical sector implementation of AM technology can streamline a product's supply chain and thus assist medical device manufacturers to deliver customised production, increase overall cost benefit, reduce overall total lead times and improve significantly inventory management (Snyder et al. 2014). In particular, medical device manufacturers can decrease their inventory levels by manufacturing on demand and hence save on the cost of inventory. They can also combine multiple processes to reduce the number of parts in a product and therefore simplify the links in the supply chain. Finally, device manufacturers have the choice to use this technology close to the site of patient care in order to establish a leaner, cost effective, efficient, and faster supply chain. Hence, medical manufacturers can improve supply chain competitiveness by collaborating closely with partners to leverage this innovative technology in order to serve existing customers more efficiently and improve their service delivery capabilities (Khanna and Balaji 2015). An AM supply chain for a medical device manufacturer is shown on the following Figure 2.43.

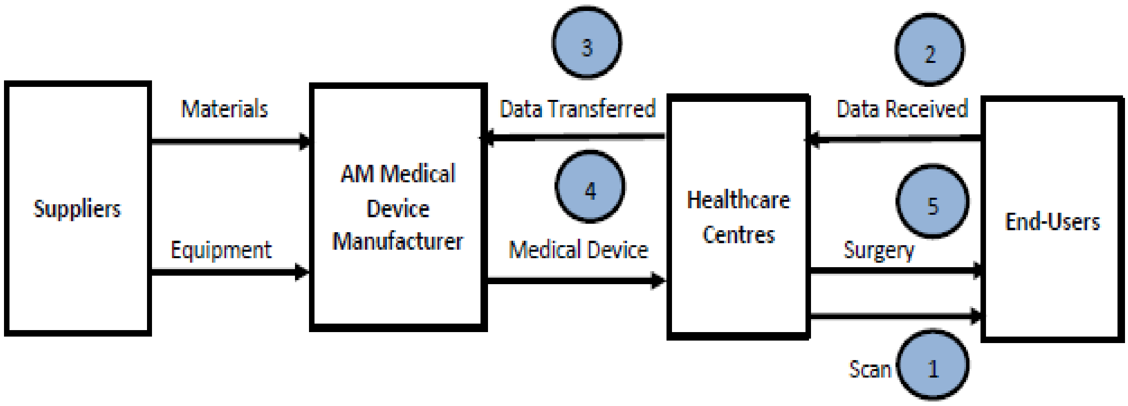


Figure 2.43: Additive Manufacturing supply chain for Medical Device Manufacturers. Source: The Author

2.13 Summary of the chapter

This chapter presented the literature review used in accordance with the research questions-objectives. The first part of this chapter explained in detail the AM technology providing information in relation to the types of AM processes and industry applications. The second section examined Advanced Manufacturing Technology Implementation. The third part provided an overview of the Supply Chain Management, current studies addressing the impact of AM technology on supply chain and existing AM implementation research in order to identify the research gap and prepare the ground for the development of the AM implementation framework focusing on the supply chain.

CHAPTER 3

RESEARCH METHODS

3.0 Introduction

The third chapter describes the overall research approach adopted in the current study to answer the proposed research questions and achieve the research objectives. First it presents the philosophical underpinnings of the research in accordance with the qualitative research approach. Then the research design is explained including the case study approach and the data collection tools. Finally, the chapter concludes with the presentation of the methodology used for analysing the data collected.

3.1 Essential Philosophical Considerations

Numerous researchers have underlined the importance of research paradigms. Guba and Lincoln (1994) highlights that a paradigm may be viewed as a set of basic beliefs which represents a worldview. Here, the researcher needs to define the nature of the world, the individual's place in it, and the range of possible relationships between the world and its parts. Therefore, researchers must accept (or even argue) those beliefs simply based on faith as it is not possible to establish their ultimate truthfulness (Guba and Lincoln 1994, p.107).

Easterby-Smith et al. (2012) highlighted that the investigation of the philosophical underpinnings can lead to the employment of appropriate methods to conduct the research at the early stages and therefore can have a significant impact on the quality of the research outcome. Thus, research paradigm as part of the overall investigation, is necessary to first identify suitable sources of evidence and then analyse them in a manner which will form the answer to the proposed research problem (Easterby-Smith et al. 2012).

Kagioglou et al. (1998) in their study on research paradigms have presented a model known as the ‘nested approach’ (Figure 3.1) according to which the research process is consisted of three elements: The Research Philosophy, the Research Approach and the Research Techniques (Kagioglou et al. 1998).

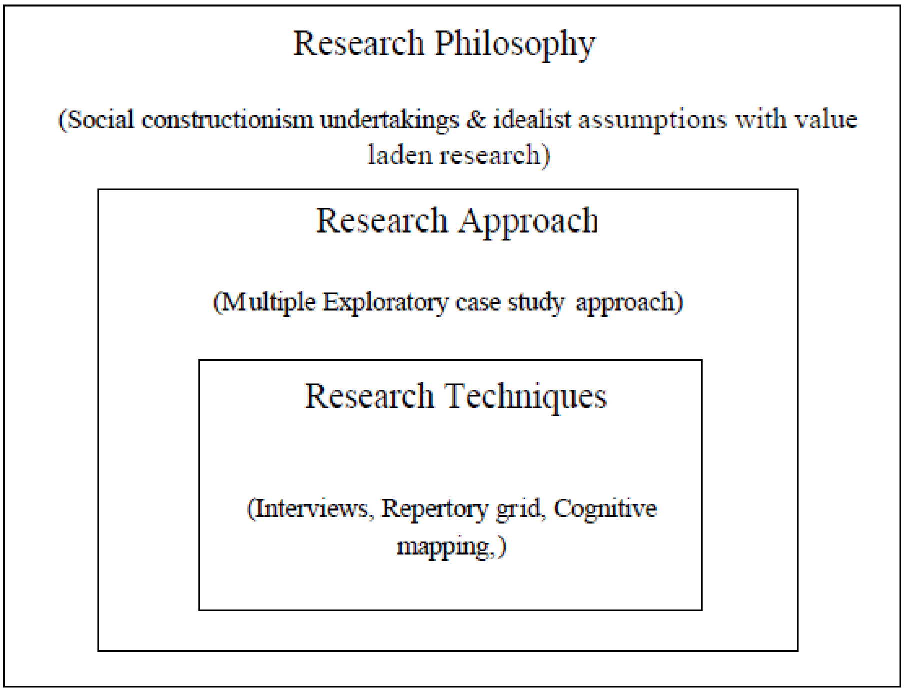


Figure 3.1 Nested Approach

Source: Kagioglou et al. (1998)

Saunders et al. (2009) in his view of research paradigm, developed a research model known as the research onion, which can be seen as an extension of the 'Nested Model' (Dugatkin, 2001) and according to which the research process is consisted of six stages and includes philosophies; approaches; strategies; choices; time horizons; techniques and procedures (Figure 3.2). Once the researcher has successfully chosen a research paradigm then will be able to move to the next stages to collect the data within a 'time horizon' (Saunders 2009).

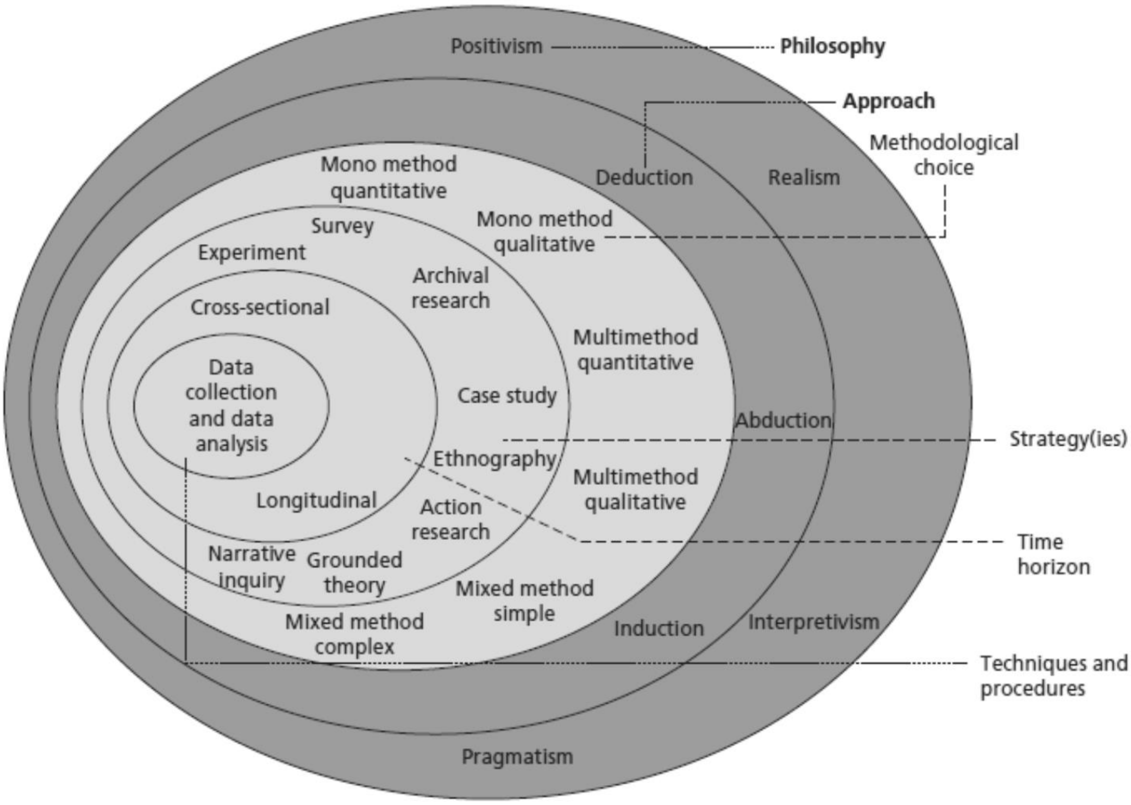


Figure 3.2: The Research Onion: Adapted from Mark Saunders, Philip Lewis and Adrian Thornhill 2009

On the other hand, Crotty (1998) explains that a paradigm consists of the following four components: epistemology, theoretical perspective, methodology, and, methods (Figure 3.3). According to the author methods are concerned with the techniques or procedures utilised to later assist with data analysis based on the proposed research question. Methodology can be seen as the overall plan of action which links the methods with the outcomes. Theoretical perspective defined as the philosophical stance which is employed to inform methodology and finally epistemology as the theory of knowledge is embedded in the theoretical perspective (Crotty 1998).

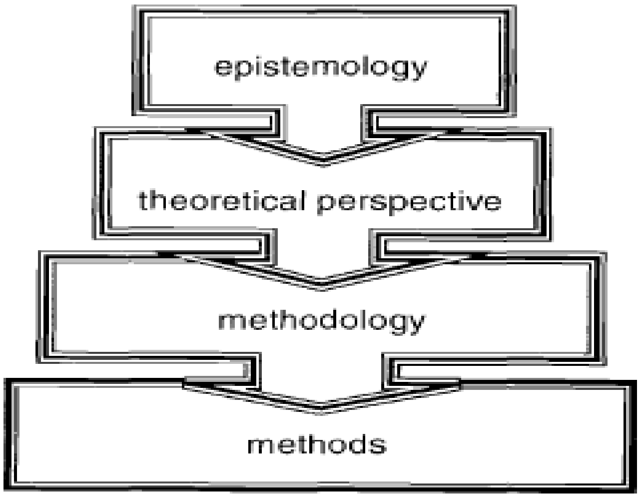


Figure 3.3: Research main stages. Adapted from Crotty (1988)

Scotland (2012) states that every paradigm is based upon its own ontological and epistemological assumptions. According to the author the philosophical underpinnings of each paradigm cannot empirically proven or disproven since all assumptions lack sufficient evidence for proof. Therefore, each paradigm includes different assumptions in terms of knowledge and reality and thus differ in their ontological and epistemological views. Consequently, this is reflected in their methodology and methods (Scotland 2012).

According to Saunders et al. (2009) ontological assumptions are concerned with the nature of reality, in other words the perceptions that researchers make in relation to the way the world operates. Bryman et. al (2010) points out that ontological assumptions are concerned with the nature of social entities and thus the question is whether social entities can and should be considered objective entities that have a reality external to social actors, or whether they can and should be considered social constructions built up from the perceptions and actions of social actors. Thus, according to the authors the first aspect of ontology is objectivism which represents the position that social entities and their meanings have an existence that is independent of social actors. On the other hand, constructionism is an ontological position which asserts that social entities and their meanings are continually being accomplished by social actors. Therefore, researchers need to take a position regarding their perceptions of how things really are and how things really work (Scotland 2012).

Cohen et al. (2007) states that epistemology is concerned with the nature and forms of knowledge. In other words, epistemology investigates how knowledge can be created, acquired and communicated. It asks the question ‘What is accept knowledge’ and whether social sciences can be investigated in the with the same foundations that nature sciences can be investigated. Therefore, the epistemological assumptions on the issues investigate of whether knowledge is something which can be acquired on the one hand or is something which has to be personally experienced on the other **(**Cohen et al. 2007).

Thus, it clear from the above that ontology deals with reality that researchers investigate, while epistemology examines the relationship between the reality and researcher (Healy and Perry 2000).

Based on the above many scholars generally agree that axiology should also be considered within the research paradigms and therefore there are three underlying assumptions relevant to Research Philosophies: Ontological assumptions, Epistemological assumptions and Axiological assumptions (Miles and Huberman, 1994; Gomez and Jones, 2010).

Saunders (2009) defines axiology as a branch of philosophy that studies judgements about value. The focus here is on the process of social entity and what roles values play in all stages of the research process in order to establish credibility of results. Easterby-Smith et al. (2012) noted that axiology is classified based on whether the reality is value free or value driven. In value neutral research, the choice of what to study and how to study, can be determined by objective criteria, whilst in value laden research choice is determined by human beliefs and experience. The following Table 3.1 presents an overview of these three main assumptions or paradigms.

Table 3.1: Research Paradigms, Source: The Author based on Saunders et al. (2009); Bryman et. al (2010); Cohen et al. (2007); Easterby-Smith et al. (2012)

Research Paradigm	Key Points
Ontology	• Concerned with the nature of reality and the nature of social entities. • Perceptions that researchers make in relation to the way the world operates. The question is: • Whether social entities can and should be considered objective entities or whether they can and should be considered social constructions.
Epistemology	• Concerned with the nature and forms of knowledge. • Investigates how knowledge can be created, acquired and communicated. • Examines the relationship between the reality and researcher. The question is: • What is accept knowledge? • Whether knowledge is something which can be acquired on the one hand or is something which has to be personally experienced on the other.
Axiology	• A branch of philosophy that studies judgements about value. • Classified based on whether the reality is value free or value driven.

There are several well-known research philosophies based on the above research paradigms and mainly on ontological and epistemological assumptions: Positivism, Post – Positivism, Intepretivism, Realism, Pragmatism.

3.1.1 Positivism

According to Orlikowski (1991) the purpose of the positivism paradigm is to identify and examine relationships that lead to generalization through deductive method for theory building. The author underlines that in this approach the phenomenon is tangible and any aspect can be described. Additionally, the researcher and the object of inquiry are independent (Orlikowski 1991).

Cooper et al. (2002) states that positivism is widely understood to be based on the following principles:

- Only knowledge confirmed by the senses can genuinely warranted as knowledge.
- By generating hypotheses through theories which can be tested and explained by certain laws.
- Knowledge is arrived at by gathering facts that provide the basis for the laws.
- Science must be conducted via an objective approach.

Scientific and normative statements have a clear distinctive and the former is the true domain of a scientist (Cooper et al. 2002).

3.1.2 Post – positivism

Post – positivism has similar ontological and epistemological beliefs as positivism. Similarly, with the positivism approach post- positivisms seek to explain casual relationships and therefore experimentation and correlational studies are utilised. Creswell (2009, p.7) argues that the knowledge acquired with post-positivism approach is more accurate and objective than the knowledge which originated from other paradigms. This paradigm represents the thinking after positivism and it challenges the traditional notion of the absolute truth of knowledge. The rationale behind this paradigm is that when researchers study behaviour and actions of humans cannot be positive in their claims of knowledge. Post - positivism acquires knowledge based on careful observation and measurement and for this purpose it has the intent to reduce the ideas into small and discrete set to test such as the variables that comprise hypotheses and research questions. Hence, the paradigm aims to test, verify and refine laws or theories that govern the world and for this purpose the researcher begins with a theory and then collects the data which either supports or refutes the theory and finally makes necessary revisions and conducts additional test (Creswell 2009, p.7).

3.1.3 Interpetivism

Walsham (1995) noted that according to the interpretivism paradigm, knowledge of reality is a social construction by human actors and the data gathered for researchers is value laden by the researcher as the researcher uses their assumptions to guide the enquiry process. The author outlines that this paradigm is based more on an inductive method as it aims to generate descriptions, insights, and explanations of events. Here, the researcher becomes part of evolving events and the structuring process. In other words, “reality is determined by people rather than by objective and external factors” (Easterby-Smith et al. 2002, p 30). Gioia et al. (1990) pointed out that within this paradigm the analysis, theory generation and further data collection are carried out simultaneously. Goulding (1998) found that at a methodological level the intepretivism paradigm is associated with qualitative analysis and employees' techniques such as case studies, textual analysis, ethnography and participant/observation. On the other hand, the positivism paradigm is usually employed in quantitative analysis. The following Table 3.2 compares the two paradigms: positivism and interpetivism.

Table 3.2: Positivism versus Intepretivism paradigm

Source: Collis and Hussey (2003); Saunders et al. (2003)

Positivism Paradigm	**Intepretivism Paradigm**
• Tends to produce quantitative data • Uses large samples • Concerned with hypothesis testing • Data is highly specific and precise • The location is artificial • Reliability is high • Validity is low • Generalises from sample to population **Deduction (Quantitative) Emphasises** • Scientific principles • Moving from theory to data • The need to explain causal relationships between variables • The collection of quantitative data • The application of controls to ensure validity of data • The operationalisation of concepts to ensure validity of data • A highly-structured approach • Researcher independence of what is being researched	• Tends to produce qualitative data • Uses small samples • Concerned with generating theories • Data is rich and subjective • The location is natural • Reliability is low • Validity is high • Generalises from one setting to another **Induction (Qualitative) Emphasises** • Gaining an understanding of the meanings humans attach to events • A close understanding of the research context • The collection of qualitative data • A more flexible structure to permit changes of research emphasis as the research progresses • A realisation that the researcher is part of the research process • Less concern with the need to generalise

Saunders et al. (2009) presents another philosophical position related to scientific enquiry the 'realism'. This position is based on the assumption that reality is guided by senses and that objects can exist independently from the human mind. Therefore, this philosophy underlines that reality is quite independent of the human mind and also shares similar view to positivism in the respect that both follow a scientific approach to the development of knowledge. This philosophical position is particular relevant to business and management research when two forms of realism are presented and contrasted. The first type of realism is called ‘direct realism’ according to which what we see is what is true which means that our view of the world is based on our senses. In contrast ‘critical realism’ argues that what we experience are sensations and images of things which do not present the real world directly and thus senses can deceive us (Saunders et al. 2009).

3.1.4 Pragmatism

Another research paradigm which is not committed to any one system of philosophy and reality
is the ‘pragmatism’. Saunders et al. (2009) explains that according to this paradigm the most important determinant when conducting research is the formulation of the research question that it has to be more appropriate than others within the broader perspective of the epistemology, ontology and axiology. Therefore, when the research question is constructed, and it does not fit with any of the well-known perspectives such as positivism or intepretivism, then it is possible for the pragmatism view to fit perfectly with the requirements of the research (Saunders et al. 2009).

Creswell (2009) noted that this philosophical position applies to mixed methods of research and draws conclusions from both quantitative and qualitative assumptions employed for the subject under research. According to the author this paradigm provides the freedom for researchers to choose the methods, techniques, and procedures of research that best meet their needs and purposes. Additionally, this pragmatism does not view the world as an absolute unity and pragmatists agree that research always occurs in social, historical, political, and other contexts. In this way, mixed methods studies may include a postmodern turn, a theoretical lens that is reflective of social justice and political aims (Creswell 2009). The following Table 3.3 compares the four research philosophies in management research.

Table 3.3: Comparison of four research philosophies in management research

Source: Saunders et al. (2009)

	Positivism	**Realism**	**Interpretivism**	**Pragmatism**
Ontology: the researcher's perspective of the way of reality or being	External, does not depend on social factors and it is objective	Is objective. Unbiased, its existence is independent of the beliefs and thoughts of human or facts of their existence (realist),	Constructed socially, it is subjective, might change, numerous	External, many, best interpretation that will answer the research question best is chosen

		but then, it is interpreted through social conditioning (critical realist)		
Epistemology: The researcher's perspective with respect to what makes knowledge acceptable	Only evident phenomena can deliver data that is credible, facts. Emphasis is laid on causality and law like generalisations, phenomena is reduced to the simplest elements	Observable phenomena provide reliable data, proofs. When data is Insufficient it means inaccuracies in sensations (direct realism). Otherwise, phenomena create sensations which are open to misinterpretation (critical realism). Emphasis is on explanation in a context or contexts	Meanings are subjective and social phenomena. Concentrate on the situation details, a reality behind these details, motivates actions	Any or both visible phenomena and subjective meanings provides suitable understanding based mostly on the research question. Centre on practical applied study, incorporating different views to aid in the data interpretation
Axiology: the re- searcher's opinion of role of values in research	Study is carried out in value-free method, the researcher does not depend on the data and keeps an objective stand	Research is quality loaded; the researcher is influenced by the views of the world, traditional understandings and background. These will have impact on the study	Value of study is certain, the researcher is a component of what is researched on, cannot be detached and as such, will be subjective	Values play a major role when results are being interpreted, the researcher adopts both objective and subjective perspectives
Data collection methods that is frequently used	Extremely structured, huge samples, measurement, quantitative, but can also utilize qualitative	Methods chosen method must match the subject matter, quantitative or qualitative	Small samples, investigations are in-depth, qualitative	Quantitative and quantitative (Mixed or multiple method designs)

3.1.5 Justification of the Interpretivism approach for this study

The main objectives of this research are:

- To investigate the impact of AM process on supply chain.
- To develop a conceptual framework for implementation of AM on supply chain.
- To examine and enhance the proposed implementation factors on supply chain using real case studies.

In order to satisfy the above research, it is essential to consider a research paradigm and research methodology that provides an opportunity to the researcher to become a participant in the subject that is being researched. The underlying philosophy for this study is based on an epistemological position and the interpretive paradigm. The motivations for choosing the interpretive paradigm over the positive paradigm is that this study involves implementation and therefore is an on-going process. The aim of the study is to investigate the implementation of AM on supply chain and the researcher is called to explore on the issues which emerge during this process.

3.2 Selection of the research approach

3.2.1 Deductive, Inductive, Abductive

Creswell (2009) points out that deductive theory is used for testing or verifying a theory rather than developing it. Here, the researcher collects data to test it and then based on the results refers to this data to confirm it or disconfirm it. The researcher will examine hypotheses or questions derived from the theory which contain variables that need to be defined in order to verify the developed theory. Saunders (2009) noticed that in deductive approach, which is prevalent in positivism, theoretical or conceptual frameworks are developed based on the existing literature which then will be tested using data. Denzin and Lincoln (2000) underlined that deductive approaches usually employ quantitative methods based on hypothesis to allow for generalisations of results.

On the other hand, in inductive theory the researcher will begin by gathering detailed information from the participants and then forms this information into categories or themes. These themes will then be developed into broad patterns theories, or generalizations with a view to be compared with personal experiences or with existing literature on the topic. This approach is more suitable for qualitative studies (Creswell 2009). In accordance with the previous author Saunders (2009) states that in some projects this method is more suitable where the focus is on exploring the data and developing theories from them which can then relate back to the literature. This approach can only be taken if the researcher has a competent knowledge of the existing area. Here, followers of the induction approach argue that deduction is based on a rigid methodology which consequently does not provide with any flexibility in terms of alternative explanations when a research subject is under study. As a result, this approach tends to finalise the choice of theory and definition of hypothesis. On the other hand, when an inductive approach is employed the focus is on the context in which such events were taking place and thus many times can be more appropriate particularly when it concerns a small sample of subjects than a large number as with the deductive approach. This approach is prevalent in interpretivism. Bryman et. al (2010) highlighted that with an inductive approach, theory is the outcome of the research where the process begins with theory then observations and finally findings, compared with the deductive approach which begins with observations, then findings and finally theory. The following Table 3.4 provides a comparison of the deductive and inductive approaches.

Table 3.4: A comparison of deductive and inductive approaches

Source: Saunders et al. 2009

Deductive	Inductive
• Scientific principles • Moving from theory to data • The need to explain causal relationships between variables • The collection of quantitative data • The application of controls to ensure validity of data • The operationalisation of concepts to ensure clarity of definition • A highly-structured approach • Researcher independence of what is being researched • The necessity to select samples of sufficient size in order to generalise conclusions	• Gaining an understanding of the meanings humans attach to events • A close understanding of the research context • The collection of qualitative data • A more flexible structure to permit changes of research emphasis as the research progresses • A realisation that the researcher is part of the research process • Less concern with the need to generalise

A third fundamental mode of logical reasoning is the abductive approach. According to Danermark et al. (1997) the main difference between abduction and deduction can be found on that abduction shows how something might be, whereas deduction proves that something must be a certain way. When the research is theory driven then the findings might confirm or disconfirm the theoretical frame. Here, by using a deductive approach the theory is proved or disproved. However, according to the authors with deductive reasoning findings that are outside the initial theoretical premise may remain analysed. When an abduction reasoning is followed then the researcher can form associations to formulate new ideas in a different context, which otherwise are not evident or obvious. Thus, the aim is to identify data which is not included in the initial theoretical premise. De Brito and van der Laan (2000) suggests that abductive reasoning involves pursuing a variety of potential reasons to explain the evidence (by matching it with additional theory). In the end, some reasons will be more compelling than others, i.e., some reasons will 'abduct' others (Table 3.5).

Table 3.5: Characterization of abductive, inductive and deductive reasoning adapted from De Brito and van der Laan, (2000)

Reasoning	**Departing point**	**Aim**	**Drawing conclusions**
Abduction	Empirical observations (unmatched by/deviating from theory)	Developing new understanding	Suggestions (for future directions, theory/paradigm/tool)
Induction	Empirical observations (theory is absent)	Developing theory	Generalization/ Transferability of results
Deduction	Theoretical framework	Testing evaluating theory	Corroboration or falsification

3.2.2 Justification of the Inductive approach for this study

The researcher has followed an inductive research approach. Thomas (2006) states that this type of approach begins with the examination of specific information in relation to the research area, then an initial theory begins to emerge, which will be explored later with a view to develop a concept or a framework. The author states that the purpose of the framework is to incorporate the key themes in relation to the research area (Thomas 2006). The researcher has previously identified (Literature Review Chapter - 2.11 The Research Gap on AM Implementation Research on Supply Chain) the lack of implementation studies in the field of AM. Therefore, he will use existing knowledge on process technology implementation in order to develop an AM implementation framework on supply chain, which will incorporate the key themes of the research area.

3.3 Research Methods and Methodology

3.3.1 Qualitative research versus Quantitative

Bryman et al. (2010) states that quantitative and qualitative research are two distinguishable strategies where the main difference can be found that quantitative methods employ measurement and qualitative methods do not. Qualitative methods are a broad term which can be applied to a range of approaches that have their theoretical origins in many disciplines including anthropology, sociology, philosophy, social psychology and linguistics. Although considerable diversity exists in the type of studies that can be described as 'qualitative' there are some key elements in qualitative research. These include:

- Aims which are directed at providing an in-depth and interpreted understanding of the social world of research participants by learning about their social and material circumstances, their experiences, perspectives, and histories.
- Samples that are small in scale and purposively selected on the basis of salient criteria.
- Data collection methods which usually involve close contact between the researcher and the research participants, which are interactive and developmental and allow for emergent issues to be explored.
- Data which are very detailed, information rich and extensive.
- Analysis which is open to emergent concepts and ideas and which may produce detailed description and classification, identify patterns of association or develop typologies and explanations.
- Outputs which tend to focus on the interpretations of social meaning through mapping and 're-presenting' the social world of participants (Snape and Spencer 2003, p.5).

Cooper and Shindler (2014) highlighted that qualitative research includes methods which aim to describe, decode and translate, and techniques are used at both the data collection and data analysis stages of a research project. Referring to the data collection stage, techniques employed here include: focus groups, individual depth interviews (IDIs), case studies, ethnography, grounded theory, action research, and observation. During the analysis stage the researcher uses content analysis of written or recorded materials drawn from personal expressions by participants, behavioural observations, and debriefing of observers, as well as the study of artifacts and trace evidence from the physical environment (Cooper and

Shindler 2014, p.144). It is an inductive process of building from the data to broad themes to a generalized model or theory (Creswell 2009).

On the other hand, quantitative research methods focus on maximizing objectivity, replicability, and generalizability of findings, and are usually aiming at prediction. The researcher here will be expected to exclude his or her experiences, perceptions, and biases to increase objectivity of the subject under research and the conclusions that are drawn. Research instruments utilised in this type of method include tests or surveys to collect data, and reliance on probability theory to test statistical hypotheses that correspond to research questions of interest. This method is generally employed when inferences from tests of statistical hypotheses can lead to general inferences about characteristics of a population and therefore it has often been described as deductive in nature. Quantitative methods are also frequently characterized as assuming that there is a single "truth" that exists, independent of human perception (Lincoln and Guba 1985). Figure 3.4 provides a comparison between qualitative and quantitative research methods.

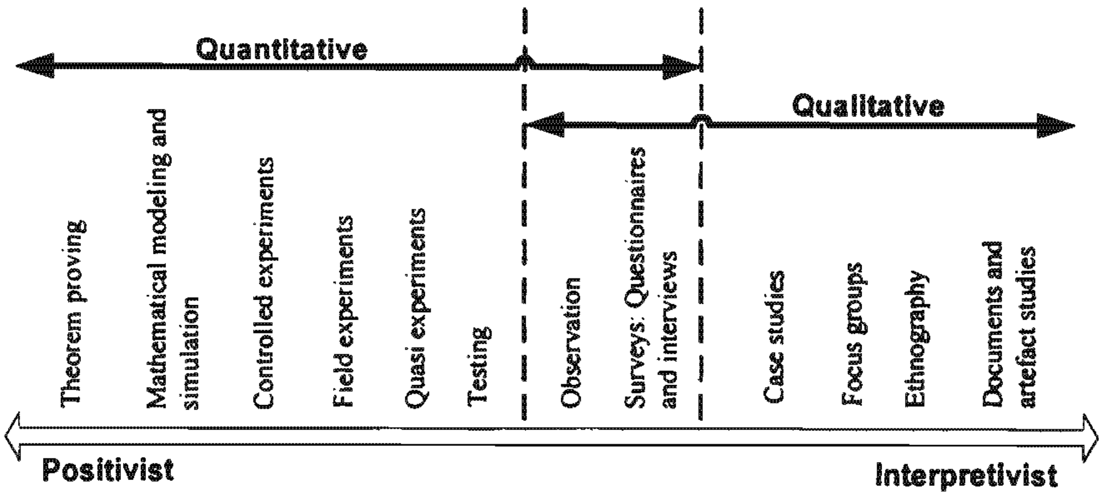


Figure 3.4: Research Methods/Strategies

Source: De Villiers (2005)

Saunders (2009) noted that also mixed methods approach can be employed in a research design and represent a general term for both quantitative and qualitative data collection techniques and analysis procedures. This approach can be subdivided into two types. According to the first type mixed method research uses both types of data at the research method stage where quantitative data are analysed quantitatively and qualitative data are analysed qualitatively. On the other hand, in the mixed-model research, quantitative and qualitative data collection techniques and analysis procedure are combined and can be applied to other stages of the research such as research question generation. Driscoll et al. (2007) state that mixed methods designs when exploring complex research questions can provide pragmatic advantages. Here the qualitative data can assist with gaining a deep understanding of survey responses and at the same time when quantitative methods followed then the statistical analysis can provide a detailed assessment of patterns of responses. However, the authors argue that the analytic process of combining qualitative and survey data by quantitizing qualitative data can be time consuming and expensive and consequently mixed methods designs might be more appropriate for conducting research which does not require either extensive, deep analysis of qualitative data or multivariate analysis of quantitative data. Table 3.6 provides a comparison between qualitative, quantitative and mixed research methods.

Table 3.6: Comparison of Quantitative, Mixed, and Qualitative Approaches to Educational Research, Adapted from Johnson and Christensen (2004)

	Quantitative Approach	**Mixed Approach**	**Qualitative Approach**
Scientific Method	Deductive or “top-down” Test hypothesis and theory with data	Deductive and Inductive	Inductive or “bottom-up” Generate new hypotheses and theory from data collected
Most common research objectives	Description Explanation Prediction	Multiple objectives	Description Exploration Discovery
Focus	Narrow-angle lens Testing specific hypotheses	Multi-lens	Wide and Deep-angle lenses Examine the breadth and depth of phenomenon to learn more about them
Nature of study	Study behaviour under artificial, controlled conditions	Study behaviour in more than one context or condition	Study behaviour in its natural environment or context
Form of data collected	Collect numeric data using structured and validated	Multiple forms	Collect narrative data using semi- or unstructured

	instruments (closed-ended survey items, rating scales, measurable behavioural responses)		instruments (open-ended survey items, interviews, observation, focus groups, documents)
Nature of data	Numeric variables	Mixture of numeric variables, words, and images	Words, images, themes, and categories
Data analysis	Identify statistical relationships	Statistical and holistic	Holistically identify patterns, categories, and themes
Results	Generalizable findings. General understanding of respondent's viewpoint. Researcher framed results	Corroborated findings that may be generalizable	Particularistic findings. In-depth understanding of respondent's viewpoint. Respondent framed results
Form of final report	Statistical report including correlations, comparisons of means, and statistically significant findings	Statistical findings with in-depth narrative description and identification of overall themes	Narrative report including contextual description, categories, themes, and supporting respondent quotes

3.4 Selection of Research Strategies

3.4.1 The Case Study Research

A case study research associated with the qualitative research approach is employed in order to be able to study in-depth the AM implementation factors within the supply chain. There are various definitions of case studies as a research strategy in the literature. According to Yin (2014) case study research is a very useful method as it allows expanding and generalizing theories by combining the existing theoretical knowledge with new empirical insights. The author states that this is especially important in studying topics that have not attracted much previous research attention. Robson (2002, p. 45) states that: "Case study research is a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence". Benbasat et al. (1987) identified three outstanding strengths of the case study approach:

1. The phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice;
2. The case method allows the much more meaningful question of why, rather than just what and how, to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon; and
3. The case method lends itself to early, exploratory investigations where the variables are still unknown and the phenomenon not at all understood (Benbasat et al. 1987. p. 370).

Despite the proposed advantages of case studies, are not without their limitations. Fitzgerald (2006) noted that there is little representation of this approach in OM-related academic publications and as a result this approach could be challenged for limited objectivity. Additionally, Silverman (2001) underlined that further criticisms relate to limited generalisability. Here, Flyvbjerg (2006) has argued that case study results through data collection are subjective and cannot be applicable to the broad population.

3.4.2 Case Study Research in Operations Management

In the same manner, Voss et al. (2002) emphasised that when this research approach is applied in operations management (OM) it can develop new theory and increase validity. In particular, in relation to the application of case study research in the field of operations management Meredith (1988) noticed that case and field research studies continue to be rarely published in operations management journals, in spite of increased interest in reporting such types of studies and results. The author in his research argued that these methods are preferred to the more traditional rationalist methods of optimization, simulation, and statistical modelling for building new operations management theories. He concluded that when these methods are combined with traditional rationalist methods can offer greater potential for enhancing new theories than either method alone (Meredith 1988).

Meredith and McCutcheon (1993) in their paper provided an outline of the procedure in relation to case study design, data analysis and the philosophical rationale for the methodology. The authors concluded that case studies in OM have the potential to be used more broadly, within more paradigms and include more forms of data. However, case study needs to be conducted in a manner to assure maximum measurement reliability and theory validity. Only then it can be a true scientific approach (Meredith and McCutcheon 1993).

Fitzgerald and Kiridena (2006) in their paper explore qualitative research and the case study approach as used in OM theory building research. The authors compared qualitative research approaches used in OM research against quantitative methods in relation to their strengths and weaknesses while stressed the need for the adoption of a multiple case study approach as more suitable for investigating contemporary topics and soft issues within the OM field. In their paper, they attempt to underline the importance of case study approach as a credible alternative to traditional positivist approaches currently used in OM research and underlined the need for a holistic approach to research design and methodology (Fitzgerald and Kiridena 2006).

Barratt et al. (2011) in their study examine the state of qualitative case studies in operations management. The authors have recognised that there is an increasing trend toward using more qualitative case studies where contributions in the field of OM can be found particularly in the area of theory building. However, many qualitative case studies lack sufficient details in research design, data collection, and data analysis. Here the researchers have pointed the need for more careful considerations of research protocols for conducting deductive case studies to ensure consistency in the way the case method has been applied (Barratt et al. 2011).

Stuart et al. (2002) in their research proposed a five-step case-based research and dissemination process (Figure 3.5).

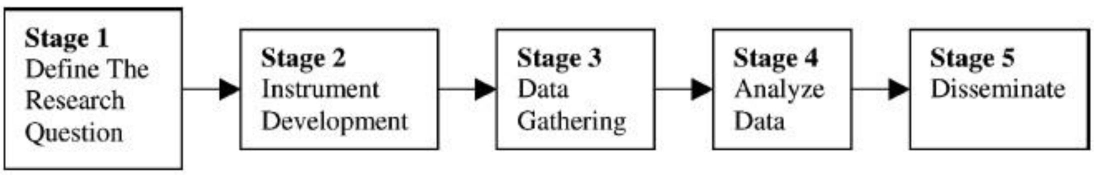


Figure 3.5: The five-stage research process model, proposed by Stuart et al. (2002)

3.4.3 The Case Study Research Design

According to Yin (2014) the case study process is comprised by six interdependent stages: Plan, Design, Prepare, Collect, Analyse and Share (Figure 3.6).

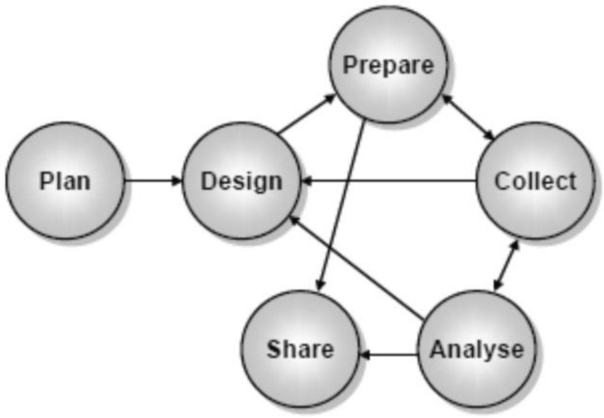


Figure 3.6: The Case Study Process

Source: Yin (2014)

3.4.3.1 Plan

According to Yin (2014) within the first stage, Plan, the researcher needs to identify the research questions or other rationale for conducting case study, decide when to use case study in comparison with other research methods and understand the strengths and weaknesses of the methodology. The author states that there are three factors which will determine whether this type of research is the most appropriate method: a) The types of questions to be answered, b) The extent of control over behavioural events, and c) The degree of focus on contemporary as opposed to historical events. Other methods available to the researcher include surveys, an experiment, a history, a computer-based analysis of archival records. The following Table 3.7 displays these three conditions and shows how each is related to the five major research methods.

Table 3.7: Research Strategies

Source: Yin (2014)

Strategy	Form of research questions	Requires control over behavioural events	Focuses on contemporary events
Experiment	How, Why	Yes	Yes
Survey	Who, What, Where, How many, How much	No	Yes

Archival analysis	Who, What, Where, How many, How much	No	Yes/No
History	How, Why	No	No
Case study	How, Why	No	Yes

Robson (2002) noted that surveys have mainly to do with the collection of small of data in standardized form from a large number of individuals, organizations, department's etc. On the contrary, Yin (2014) underlined that case studies can be very effective when employed to study organisations and institutions. Rowley (2002) highlighted that the number of units involved in a case study is many less than in a survey; however, the information obtained for each case is usually greater. Saunders et al. (2009) pointed out that the survey strategy is usually associated with the deductive approach and Collis and Hussey (2003**)** noted that this strategy is usually employed when positivist philosophical positioning is adapted. As mentioned previously, this research inclined towards interpretivism and undertook a more inductive approach, thus, survey strategy was deemed inapplicable to this research. Additionally, Rowley (2002) highlighted that when a case is compared with an experiment the researcher has much less control over the variables if for example an experiment had been employed to investigate a phenomenon. Schell (1992) compared case studies with histories and emphasized that histories as strategy are preferred when the researcher has no practical form of control and the event or phenomenon has occurred in the past. On the contrary when a contemporary even is examined then the case study is preferred. The researcher here has also the additional advantage to employ in his study research instruments such as direct observation and systematic interviewing including also the historian's primary and secondary documentation as resources.

There are different types of case studies which can be used in accordance with the qualitative case study guided by the overall study purpose. If for example the researcher is looking to describe a case, explore a case or compare between cases. Yin (2014) classifies case studies as explanatory, exploratory, or descriptive (Table 3.8).

Table 3. 8: Definitions of Different Types of Case Studies

Source: Yin (2014)

Case Study	Definition
Explanatory	This type of case study would be used if you were seeking to answer a question that sought to explain the presumed causal links in real-life interventions that are too complex for the survey or experimental strategies. In evaluation language, the explanations would link program implementation with program effects (Yin, 2003).
Exploratory	This type of case study is used to explore those situations in which the intervention being evaluated has no clear, single set of outcomes (Yin, 2003).
Descriptive	This type of case study is used to describe an intervention or phenomenon and the real-life context in which it occurred (Yin, 2003).

Examining the two previous tables, Schell (1992) suggests that 'What' questions usually indicate exploratory research, ‘Who' and 'where' questions (or the derivative 'how many', 'how much') usually employed in survey or archival research with the aim to describe an incident or a phenomenon and predict outcomes and finally 'How' and 'why' questions are usually utilized in experiments, histories and case studies as they tend to be more explanatory by nature. According to the author these types of questions examine best operational links which occur during a span of time, rather than the incidents or phenomena which occur at intervals over time (Schell 1992).

3.4.3.1.1 Justification of the case study approach for this study

As mentioned previously, when the researcher is called to investigate a phenomenon where there is little theoretical background and might not know which conditions are relevant or important, then under these circumstances the case study approach may be the only available means of investigating the problem (Yin 2014; Meredith and McCutcheon 1993). In relation to the first criterion as set by Yin (2014) which is the ‘types of questions to be answered’, as mentioned before, when the research questions take the form of “how” and “why” then case study is preferred. This research was developed to answer the following research questions:

The central research question of this study is the following:

- How do organisations implement Additive Manufacturing as an operational process from a supply chain perspective?

From this central question, the following research sub-questions were produced.

- How does AM technology impact the supply chain?
- What are the key factors affecting implementation of AM on supply chain?
- How do those factors impact implementation of AM on supply chain?

Therefore, by looking at the research questions it can be noted that they mainly consist of 'how' type of research questions, favouring a case study research. Examining the second criterion proposed by Yin (2014) which is the extent of control the researcher has over behavioural events, for this study the researcher did not have any control over the behaviour of medical device manufacturers. Additionally, the researcher could not possible manipulate the behaviour of medical device manufacturers in relation to the implementation of AM technology in contrast with action research (Meredith and McCutcheon 1993) where the researcher is involved as participant and director of events in a natural setting.

In relation to the third criterion proposed by Yin (2014) the issues being investigated were contemporary and about how medical device manufacturers implement AM technology from a supply chain perspective. Finally, the researcher, due to the nature of topic, is called to explore on the issues emerged from the implementation process of AM within the supply chain and therefore this research is exploratory. The literature has also indicated the lack of implementation studies in the field of AM particularly from a supply chain perspective which also strengthens the exploratory nature of this research.

3.4.3.2 Design

According to Yin (2014) within the second stage, 'Design', the researcher needs to focus on defining the unit of analysis and the likely cases to be studied, developing theory/propositions and identifying issues underlying the anticipated study, identifying the case study design (single, multiple, holistic, embedded), and defining procedures to maintain case study quality.

3.4.3.2.1 Developing the research framework, constructs and questions

The particular study has not included any propositions as the topic is subject of "exploration". According to Rowley (2002) propositions are necessary for descriptive and explanatory studies, where research questions need to be translated into propositions. The reason is that the researcher needs to use the existing literature and any other earlier evidence in order to make a speculation as to what they expect the findings of the research to be. Then the data collection and analysis can be structured in order to support or refute the research propositions (Rowley 2002). The overall purpose of this study is to develop an AM implementation framework from a supply chain perspective. The following research objectives were developed to answer the research questions posed in this study:

- To investigate the impact of AM process on supply chain.
- To develop a conceptual framework for implementation of AM on supply chain.
- To examine and enhance the proposed implementation factors on supply chain using real case studies.

There is general acceptance that the researcher must develop a prior view of the general constructs or categories that are to be studied, and their relationships. This is often provided in the form of a conceptual framework. According to Yin (2014) such a framework explains, either graphically or in narrative form, the main things that are to be studied. The research framework of this study graphically explains the factors influencing the success of AM implementation within the supply chain. It suggests that when examining the AM implementation from a supply chain perspective the factors which will influence this process may be grouped into five constructs: Procurement, Design, Production, Distribution/Logistics, and Customers. Details on the development of the implementation framework based on analysis of the literature and initial informal data collection are provided in chapter 5 (Development of the Implementation Framework). The framework is of a closed loop nature, illustrating the interactions and dependencies between each construct and the individual factors within these constructs. The AM implementation framework put forward by the researcher (Chapter 5) is presented for reference in the following Figure 3.7:

Figure 3.7: Additive Manufacturing Implementation Framework

3.4.3.2.2 Defining the unit of analysis

According to Rowley (2002, p.19**)** the unit of analysis is the basis for the case. The author states that the unit of analysis may be an individual person (such as a business leader, or someone who has had an experience of interest), or an event, (such as a decision, a programme, an implementation process or organisational change), or an organisation or team or department within the organisation. Therefore, selecting the unit of analysis, or the case is crucial. Yin (2014) states that as a general rule in order to define the unit of analysis the researcher needs to look back at the initial research questions which will provide guidance for selecting the appropriate unit. The central research question of this study is the following: 'How do organisations implement Additive Manufacturing as an operational process from a supply chain perspective?' Therefore, the researcher has focused within the organisations on people who were leading the AM implementation process. It was found that in most cases it was a single person who managed the AM implementation process; however, where required the study has selected data from multiple informants to further explain the process and satisfy the requirements of the research questions. For this purpose, the researcher has based the unit of analysis for this study on the experience of the product or operational manager for each organisations process of implementing AM technology.

3.4.3.2.3 Sampling - Choosing cases.

In accordance with several authors when researchers employ a case study approach they utilise a theoretical or biased sampling approach where cases are chosen for theoretical reasons instead of statistical sampling (Glaser and Strauss, 1967; Meredith, 1998; Eisenhardt, 1989; Yin, 2003). Eisenhardt and Graebner (2007) state that researchers need to justify the rationale for undertaking theory building case studies. This can be found when there is a gap in the existing theory which does not provide adequate explanation for the phenomenon and when the nature of the research is exploratory and therefore case study research is required to build theories. Curtis et al. (2000) noted that when examining theory building in case studies there are mainly two contrasting perspectives in terms of generating the relevant theory. There are those who generate theory which is derived strictly from the data (Glaser and Strauss 1967) as oppose to those who believe that a prior body of existing social theory, on which research questions may be based, must be utilised to generate the new theory e.g. Miles and Huberman (1994). Thus, an important question arises as to the role of existing theories in this theory-building process. Yin (2003) pointed out that cases can be selected at the beginning of the research study for example in the design phase, based upon the theoretical framework and expected results. The author adopts a replication logic according to which a previously developed theory is used as a template with which to compare the empirical results of the case study. Thus, cases are chosen that either predict similar results or contrary results. However, the use of polar extreme-types has also been suggested where cases have sharply contrasting characteristics (Miles and Huberman, 1994;

Yin, 2003). Thus, Yin's (2003) approach is based on theory development at the beginning of the research and subsequently tested in case settings. This validation process can lead to new insights as well but it is primarily driven by pre-existing theoretical notions, concepts, or codes. In contrast to Yin (2003) in grounded theory there is no initial preconceived framework of concepts and hypotheses but the theory is generated from data. Eisenhardt (1989) argues that the grounded theory selection can be impractical since the study's purpose, site selection, and data gathering require some rationale or preconceived ideas. The author follows a middle road approach somewhere in-between Yin's approach and the grounded theory approach. She adopts the inductive approach of grounded theory; however, a more planned approach should be adopted where selecting cases should be deployed early in the research design or before entering the field. Hence based on the above, Benbasat et al. (1987) emphasised that when building theory from case studies, the selection of cases should be carefully thought out rather than opportunistically derived.

An important question here concerns the number of cases that researchers should select. Baxter and Jack (2008) highlight that researchers in addition to identifying the "case" and the specific "type" of case study to be conducted, they must decide whether a single case study or a multi-case study will be selected in order to develop a better understanding of the phenomenon. Yin (2003) differentiates between single, holistic case studies and multiple-case studies. Single case study can be more appropriate when the researcher is called to investigate an unusual or unique phenomenon. On the contrary multiple case studies, which are especially useful if topics are too complex, tend to be more compelling and provide the potential for generalizability of findings as they may be used to achieve replication of a single type of incident in different settings, or to compare and contrast different cases (Collis and Hussey 2003; Saunders et al. 2003). Voss et al. (2002) suggest that when the number of cases is limited then there is a greater opportunity for depth of observation. However, for theory building purposes when multiple cases are utilised are likely to create more robust and testable theory than single case research (Eisenhardt and Graebner, 2007).

This study is an example of multiple case study research in which an exploratory, qualitative approach is predominantly employed to promote depth of understanding in an emergent research area. The researcher has initially formulated a research problem and some potentially important variables with some reference to extant literature but at this point avoided thinking about specific relationships between variables and theories. Here, only a few focused cases were selected early in the research design based on a planned approach and therefore data collection required some preconceived ideas (Eisenhardt and Graebner 2007). In that respect this research has employed principles of the theory building process.

The researcher has focused on the medical sector. This particular sector has been chosen for two reasons: a) The medical sector in the UK is the largest adopter of AM. b) Applications in the medical sector have moved from prototyping to finished products (Penny et al. 2013, PwC 2014).

The sample for the study for this research consisted of three medical device manufacturers (Table 3.9) the names of which cannot be disclosed but their main characteristics are discussed below:

- They were all based in UK and specialized in prosthetics-orthopaedics.
- In terms of size, small or medium sized enterprise (SMEs) were selected.
- All medical device manufacturers have employed the AM technology in order to deliver customised products to meet particular customer needs.
- Those companies have recognised the potential of this technology to simplify their supply chain and they have been examining new models or further improvements of implementing AM within their supply chain.

Each medical device manufacturing company has been assigned an alternative name for anonymity:

1. Company A is a leading UK manufacturer of orthopaedic medical devices and powder bed fusion processes, providing services to UK hospitals and international markets. The company specialises in the production of joint replacement parts and reconstruction.
2. Company B is an innovative UK manufacturer of orthopaedic medical devices. The company specialises in the production of high quality prefabricated and custom foot orthoses and is committed to research and innovation to offer value and service to health professionals and their patients.
3. Company C is an innovative start up UK social enterprise of orthopaedic medical devices which specialises in the production of parts for wheelchair users. The company has utilised the skills of highly qualified engineers, designers, researchers and wheelchair users in an attempt to design the world’s first open source wheelchair and close the gap between designers and wheelchair users.

Table 3.9 Classification of cases

Company name	Company Case	Company Type	Company Size	Products	Informants/ position
Company A	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive, Joint replacement, repair and reconstruction	AM Production Manager
Company B	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive Insoles	AM Operations Manager
Company C	Medical Device Manufacturer	Orthopaedics	SME – Social Enterprise < 50 employees	Additive Wheelchair parts	Company Director

3.4.3.3 Prepare

According to Yin (2014) the prepare stage focuses on developing skills as a case study investigator, training for a specific case study, developing a case study protocol, conducting a pilot case, and gaining any relevant approvals.

3.4.3.3.1 Developing the Research Instrument and Protocols

This stage involves the development of measurement instruments to capture the data for future analysis. For this research a case study protocol (CSP) has been employed to structure and govern the case research project. The case study protocol encompasses the principal documentation needed to provide the researcher with the necessary focus, organize the visits and ensure that the trail of evidence is thoroughly documented. The research protocol and research instrument were developed based on Yin's (2003) proposed guidance:

• An overview of the case study project (project objectives and auspices, case study issues, and relevant readings about the topic being investigated).
• Field procedures (presentation of credentials, access to the case study "sites", general sources of information, and procedural reminders).
• Case study questions (the specific questions that the case study investigator must keep in mind in collecting data, "table shells" for specific arrays of data, and the potential sources of information for answering each question).

• A guide for the case study report (outline, format for the data, use and presentation of other documentation, and bibliographical information).

3.4.3.3.2 Gaining site access

Voss et al. (2002) state that when researching case-based data, the researcher should seek out for the person, also known as the principle informant, who can provide the most relevant information in relation to the phenomenon being investigated. Thus, gaining access involves a series of steps where the first step usually requires writing or calling a potential prime contact. The researcher has invested a considerable time and resource in order to gain access to case study sites. For this purpose, a number of company conducts have been identified which could potentially contribute to the outcome of this research. Then an initial email was sent out to each contact outlining the research study, pointing out the mutual benefits to the participants and requesting to meet with the person directly involved with the AM implementation process. When required the researcher has forwarded the interview questions in advance in order to familiarize the participants with the areas that are being investigated and also provide them with sufficient time to prepare themselves for when a site visit would take place to the case organisation. Where no response was received, the researcher followed up each email with a second email to gently remind the participants of the purpose of this research which contributed to establishing a visit to the case organisation.

3.4.3.4 Collect

The collect stage involves following the case study protocol, using multiple sources of evidence, creating a case study database, and maintaining a chain of evidence (Yin 2014).

3.4.3.4.1 Sources of evidence

There are a number of sources of evidence available to the researcher as methods of data collection when the case research is employed. Yin (2003) presents six sources of evidence along with their respective strengths and weaknesses in his seminal work on case research strategy (Table 3.10).

Table 3.10: Six Sources of Evidence: Strengths and Weaknesses

Source: Yin (2003)

Source of Evidence	Strengths	Weaknesses
Documentation	Stable, can be reviewed repeatedly Unobtrusive, not created as a result of the case study Exact, contains exact names, references, and details of an event broad coverage, long span of time, many events, and many settings	Retrievability, can be low biased selectivity, if collection is incomplete reporting bias, reflects (unknown) bias of author access, may be deliberately blocked
Archival Records	[Same as above for documentation] precise and quantitative	[Same as above for documentation] accessibility due to privacy reasons
Interviews	targeted, focuses directly on case study topic insightful, provides perceived causal inferences	bias due to poorly constructed questions response bias inaccuracies due to poor recall reflexivity, interviewee gives what interviewer wants to hear
Direct Observations	reality, covers events in real time contextual, covers context of event	time consuming selectivity, unless broad coverage reflexivity, event may proceed differently because it is being observed cost, hours needed by human observers
Participant Observation	[same as above for direct observations] insightful into interpersonal behaviour and motives	[same as above for direct observations] bias due to investigator's manipulation of events
Physical Artefacts	insightful into cultural features insightful into technical operations	selectivity availability

Yin (2003, pp.83, 97-105) contends that the benefits from these six sources can be maximized if three principles are followed:

- Use of multiple sources of evidence;

- creation of a case study database;
- maintaining a chain of evidence.

3.4.3.4.2 Interviews

According to Kvale (1996, p. 174) an interview is "a conversation, whose purpose is to gather descriptions of the [life-world] of the interviewee" with respect to interpretation of the meanings of the 'described phenomena'. In accordance with Kvale (1996), Schostak (2006) points out that an interview is an extendable conversation between partners and provides the opportunity to have an in-depth information about a certain topic. Robson (2002), states that interviews can range from loose and unstructured to tight and heavily pre-structured. Patton (2005) presents the different types of interviews (Table 3.11).

Table 3.11 Types of Interviews

Source: Patton (2005)

Types of Interviews	
Structured	Standardised set of questions Same set of questions for everyone
Semi-structured	Qualitative research interviews Questions can be changed/omitted The interviewee interacts more with the respondent
Unstructured interviews	In-depth interviews Informal

This study has employed semi-structured interviews to provide the researcher the opportunity to obtain relevant information and the informants to express their views. The researcher by adapting this approach administered questions aiming to address the topics directly which can assist in developing new ideas and concepts and also to support the exploratory nature of research (Alvesson and Deetz 2000). Lewis et al. (2009, p. 320) noted that "in semi-structured interviews the researcher will have a list of themes and questions to be covered, although these may vary from interview to interview". The interview process was based on the proposed AM implementation framework and covered themes on supply chain, procurement and logistics and operational management. The interviewees were asked some open-ended questions and they were given the flexibility to elaborate on their own thoughts. Occasionally the researcher has expressed his own views and the interviewee was asked to comment on it. This helped to direct the conversation on certain themes which the researcher identified as particularly important and also to investigate in depth specific topics which would further enhance the exploratory nature of the research. The interviews were tape recorded and once the recordings have been transcribed and analysed then when required, follow – up discussions conducted to explore on the key points. Before the interviews, background research took place to enhance the quality of the interview. To enhance 'data triangulation' (Eisenhardt 2007) and increase validity, a number of tools has been employed along with the semi-structured interviews. The tools employed in this study are listed below:

- Review of documents
- Direct Observation

3.4.3.4.3 Review of Documents

Yin (2014) has stressed the importance of documents within the data collection process and the case study approach. Documents can be a very important source of information to help researchers understand the roots of a specific issue which investigate and draw conclusions on the conditions which have an effect on the research topic which is currently under investigation (Glenn 2009). Furthermore, as Merriam (1988, p.118) pointed out, 'Documents of all types can help the researcher uncover meaning, develop understanding, and discover insights relevant to the research problem'. The researcher has requested various documents from the medical device manufacturers in relation to the implementation of AM within the various stages of the supply chain such as: purchasing of the AM machines and materials, production performance measures - inventory reports and service levels reports in association with the healthcare centres. This method of data collection assisted the researcher to understand first of all the rationale for companies employing AM in the first place and then the implementation process associated with the different stages of their supply chain in terms of potential value when compared with traditional manufacturing methods. By examining information collected through different methods, the researcher aimed to provide further support to findings across data sets and reduce the impact of potential biases that can take place when a case study approach is utilised.

3.4.3.4.4 Direct Observation

To ensure further verification of the information collected from interviews and documentation, observation was undertaken. Marshall and Rossman (1999) highlighted that observation can assist the researcher to obtain great experience about the phenomenon by learning from the behaviours observed and the meaning attached to those behaviours. The direct observations were conducted through a field visit at the same time when other evidence of data was collected such as from interviews and documentation. The researcher has visited on that day the production line of the companies in order to see their AM facilities and make important field notes in relation to manufacturing applications of the AM technology within the context of supply chain management. The purpose was to collect any physical evidence of information and relate that back to the collected data. Yin (2014) states that observations can be particular important when the case study involves a new technology as they can provide the opportunity for the researcher to understand the actual uses of the technology and at the same time any potential problems associated with it. Thus, for the researcher observations have been valuable as the research topic examines the implementation of AM technology, which is an emerging technology in the field of operations and supply chain management.

3.4.3.4.5 Triangulation

Rowley (2002) states that triangulation is a powerful tool that enables researchers to use evidence from different sources to corroborate the same fact or finding. The researcher in order to increase validity and reliability as the criteria to judge quality of the research has followed Yin's (2014) proposed guidelines in relation to construct, internal and external validity and reliability (Table 3.12).

Table 3.12: Case Study Tactics for Four Design Tests, Source: Yin (2014).

TESTS	Case Study Tactic	Phase of research in Which tactic occurs
Construct validity	• use multiple sources of evidence • establish chain of evidence • have key informants review draft • case study report	• data collection • data collection • composition
Internal validity	• do pattern matching • do explanation building • address rival explanations • use logic models	• data analysis • data analysis • data analysis • data analysis
External validity	• use theory in single-case studies • use replication logic in multiple-case • studies	• research design • research design
Reliability	• use case study protocol • develop case study database	• data collection • data collection

3.4.3.4.6 Construct validity

Construct validity ensures that the correct operational measures for the concepts being studied are in place. Sekaran (1992, p. 173) states that the purpose of construct validity is to "testify how well the results obtained from the use of the measure fit the theories around which the test is designed". Construct validity was achieved through the triangulation of multiple sources of evidence such as interviews, documentation and direct observation. This resulted in the development of a 'chain of evidence' where interviews collected the data for the research topic, then documentation was employed to provide further support to findings across data sets and finally direct observation to ensure further verification of the information collected. Thus, this can assist other researchers to obtain the same results based on the same data collected. Finally, the results from the case study report were reviewed and verified by the key informants.

3.4.3.4.7 Internal validity

Internal validity examines the extent to which researchers can establish a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships (Yin, 1994, p. 35). In case study research, there are different techniques to establish this criterion including the use of case analysis, cross case analysis, pattern matching to establish the internal consistency of the information collected. The author states that internal validity can be found mainly in explanatory and casual studies rather than in descriptive or exploratory studies. However, as Stuart et al. (2002) noted still some principles of the internal validity can be applied to exploratory case studies when for example different case studies in nature are utilised to establish if the same phenomenon exists at some sites but not at others. For the particular study, it was noted that a variety of products can be produced when AM technology is employed which all have a range of applications. Additionally, within - case analysis and cross - case analysis was employed to investigate the extent to which the phenomenon (AM implementation) exists at different sites and examine similarities and differences between the case studies.

3.4.3.4.8 External validity / Generalisability

This criterion examines whether a study's findings are generalizable beyond the immediate case study. The case study strategy unlike the survey strategy, relies on analytic generalisation, and the researcher tries to generalise particular finding to wider theories. Thus, a multiple case study approach is required to enhance external validity (Yin 2014). This study has employed principles of the theory building process, and therefore for theory building purposes the use of multiple cases can augment external validity and help guard against observer bias (Eisenhardt and Graebner, 2007). Additionally, the higher the level of consistency between the emergent theory and existing theory, the higher the external validity achieved (Barratt et al. 2011). The researcher when conducted the analysis of the results has focused on identifying factors which may be common characteristic when organisations implementing AM within their supply chain in order to provide a more generic solution and enhance external validity.

3.4.3.4.9 Reliability

Reliability deals with the ability of other researchers to carry out the same study and achieve similar results (Miles and Huberman 1994). Therefore, the steps followed by the researcher during the data analysis should be based on a clear process that another person could adopt.

The aim is to reduce the mistakes and bias in the research (Yin 2014). The researcher during this study have employed reliability techniques including the case study protocol during data collection, and the establishment of a case study data base (Eisenhardt 1989) in order to allow other researchers to repeat the analytical procedures, beginning with the raw data (Yin 2014).

3.4.3.5 Analyse

The analysis of the data collected was carried out on two levels: a) Within - case analysis, b) Cross - case analysis.

3.4.3.5.1 Within-case analysis

Phase 1: Open Coding

Within - case analysis took place immediately after each of the case studies. The proposed implementation framework developed from the existing literature on AM and pilot case results was used as a guidance to provide focus on the relevant factors identified. The purpose was to proceed to the next case study with enhanced knowledge on implementation within the supply chain. At the same time the researcher had to constantly refer back to the proposed framework to ensure that the identified factors have been included and if not to incorporate them when required. The aim of this analysis was to reach a comprehensive knowledge in relation to the main AM implementation factors with considerable effect on supply chain. The first stage of the within-case analysis followed an open coding process in order to transcript the results and identify the initial implementation factors of importance within the supply chain of the examined case study. Here, the interview transcripts were broken down into codes. Miles et al. (2013) highlighted that it is important for the transcripts to be completely broken down into codes since the code is considered as the smallest unit of data in thematic analysis.

Phase 2: Axial Coding

Once all the transcripts were broken down into codes, the next stage of analysis that was conducted was axial coding. This coding was employed to identify groups based on similarities of the implementation factors identified. Miles et al. (2013), noted that in this phase, each code was considered and then categorized into an axis. For example, supplier selection, vendor supply chain, supplier acquisition/integration and in-house AM Co-development factors, were grouped together in a main category under the name

‘Procurement’. While the researcher already had an initial idea of what the categories can contain before reviewing the codes, as the proposed framework was used to guide the process, they were not pre-determined in order to allow flexibility in the analysis. As more codes were considered, some fell into existing categories while others may were used to form new categories. Once all the codes have been categorized, then the codes within each category were further reviewed to ensure that the data was properly analysed. The researcher repeated this analysis process several times until ‘saturation’ was reached, i.e. no new categories from the analysis were identified. At this point the researcher did not contact any further interviews as the analysis of any new data would add limited value to the implementation framework. Once all categories have been identified (Procurement, Design, Production, Distribution/Logistics, Customers) the researcher initially looked at the relationships between the categories and how they connect to each other, as previously no implementation framework of the technology has been developed form a supply chain perspective. Then the factors within the categories had to be examined to identify how they influence each other. For example, for the previous mentioned category ‘Procurement’ and the factors identified - supplier selection, vendor supply chain, supplier acquisition/integration and in-house AM co-development, - it was clear that supplier selection and vendor supply chain would have an impact on the other factors e.g. supplier acquisition/integration would require a strong relation of the examined case study with its suppliers. Consequently, similar connections were identified for the issues/activities which formed the factors.

Phase 3: Selective Coding

The final phase of within-case analysis, was conducted to examine if a core (or main) category or key concepts could be selected (Bohm 2004). The researcher so far through open/ axial coding had identified the categories (constructs), implementation factors within the categories and issues/ activities, which formed the factors. The relations between categories, and connections between the factors - issues/activities accordingly, have also been reported. Through this analysis, a key category emerged which was further discussed on the cross-case analysis. The following Figure 3.8 presents the within-case analysis of the data collected for this thesis.

Open/Axial /Selective coding for the research study

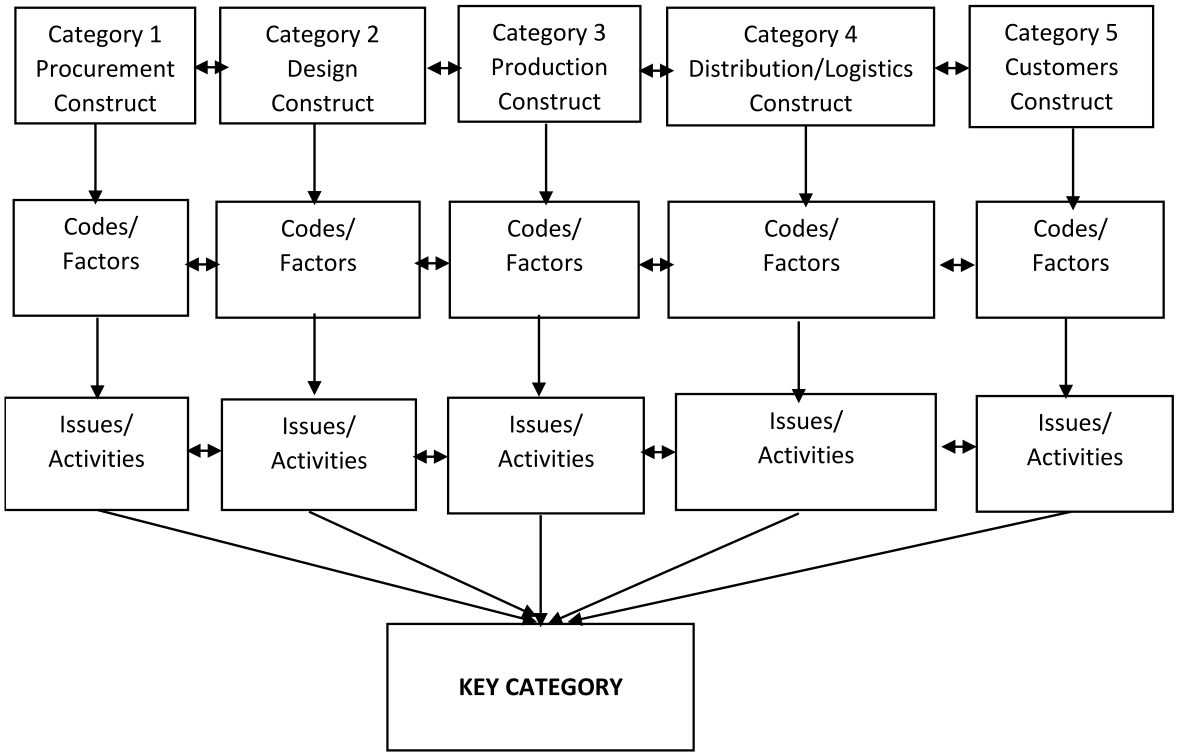


Figure 3.8: Open/Axial /Selective coding for the research study

Source: The author

3.4.3.5.2 Cross - case analysis

The researcher has employed cross - case analysis in order to examine similarities and differences between the case studies in terms of their implementation process. For this purpose, the issues/activities, identified in the implementation process for each case study in relation to proposed factors were compared and provided a further insight to implementation of technology from a supply chain perspective. The purpose of the analysis was to reinforce the conclusions drawn so far and to further discuss the key category emerged in the within -case analysis. The final implementation framework based on the key category was proposed. The multi-case research approach, enabled the researcher to compare if all or most of the case studies provided support for the proposed implementation factors. Thus, if all or most of the case studies provided similar results, there could be substantial support for the development of a fundamental theory that describes the research topic (Yin 2014, Eisenhardt, 2007).

3.4.3.6 Share

During the conduction of this thesis, the researcher has been in communication with peers who had relevant subject matter expertise as well as with industry participants. In particular, when the results of the study were produced, the researcher has been in conduct with the participant case studies in order to review and confirm the results.

3.5 Summary of the Chapter

The third chapter presented the overall research approach adopted in the current study to answer the proposed research questions and achieve the research objectives. First it provided an overview of the philosophical underpinnings of the research in accordance with the qualitative research approach. Then the research design was explained including the case study approach and the data collection tools. Finally, the chapter concluded with the presentation of the methodology used for analysing the data collected. The research design employed for this study is presented on the following Figure 3.9.

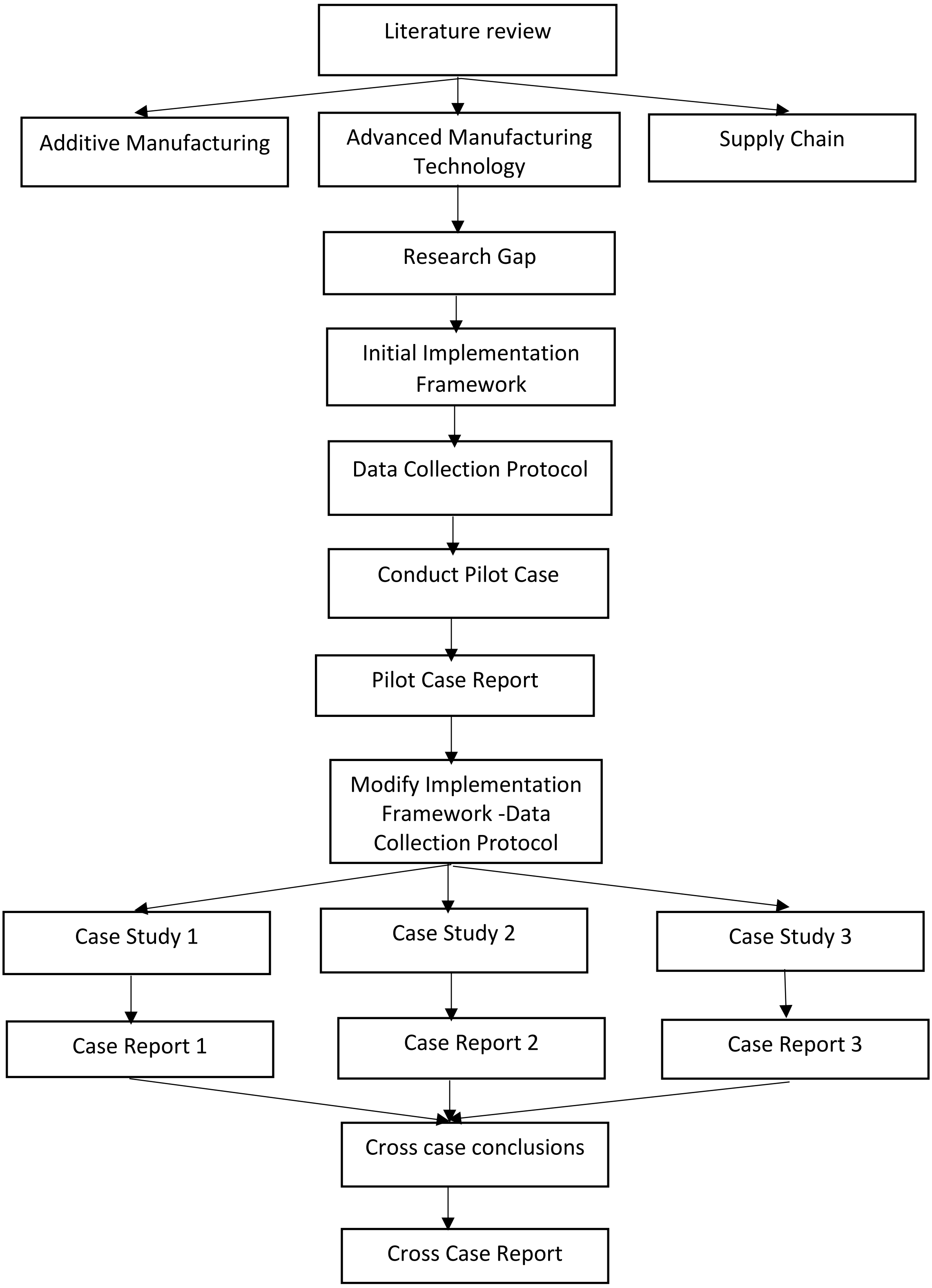


Figure 3.9: The Research methodology employed in this study

Source: The Author

CHAPTER 4

THE PILOT STUDY

4.0 Introduction

Yin (1994) states that a pilot case study, based on an ongoing review of relevant literature and a set of empirical observations, can provide considerable insight into the basic issues being studied and inform the final research design. A pilot case study, as the first stage of the data collection process, was conducted to assist the researcher to gain an insight into the basic issues being investigated and at the same time to become familiar with the AM implementation process when examined from a supply chain perspective. This study, which was based on an ongoing literature review and a first set of empirical findings, has enabled the researcher to further enhance the AM implementation factors identified in the initial research framework based on the review of the literature.

4.1 Background information of the company and informants

The pilot case study was conducted at a UK manufacturer of orthopaedic medical devices which has employed AM methods and specializes in the fabrication of custom - made foot orthoses. The technology assisted the company to alter the shape of insoles and material properties to exactly match the needs of a patient's foot and introduce a lean supply chain business model into the orthotics sector which could potentially revolutionise the way the healthcare centres buys orthotics and other products. The informant was directly involved in the AM implementation process within the supply chain of the company and emphasised that orthotics which are printed by AM methods allow for total design freedom which cannot be found in traditional hand- made techniques. The researcher has employed open - ended questions based on the constructs of the initial AM implementation framework and covered themes on supply chain, procurement and logistics and operational management. The initial AM implementation framework based on the review of the literature is presented in the following Figure 4.1:

Figure 4.1. The proposed framework of AM implementation (initial)

4.2 Pilot Case Study Results

A summary of the results of the pilot case study in relation to each construct of the AM implementation framework is presented as follows: When examining procurement implementation factors, it was found that the medical device industry is highly regulated and therefore the supplier needs to have a comprehensive knowledge of the equipment and materials to be able to deliver a product when it is required and in accordance with the standards of the medical device industry. It is important for suppliers to involve with the company's implementation process through support and back - up services and share their technical knowledge to enhance on materials availability and reduce restrictive practices. In relation to design implementation factors and software considerations it was emphasised that the company needs to choose first the right AM technology and equipment before deciding on the appropriate software application and file exchange. Here, the successful integration of software and technology plays a significant role for producing more customized products as it will ultimately affect the end products and therefore the supply chain. In terms of production implementation factors the technology can assist the company to design products which would not be possible through traditional manufacture and thus flexibility of manufacture is one of the main advantages of the AM process; however, the key constraint remains the technology readiness level of the materials and the whole process. Therefore, further improvements of the technology are required to validate the process for medical applications and enhance on the evolution of the supply chain. When examining implementation factors related to distribution/logistics and in particular location of manufacture it was stressed that companies currently tend to follow an in-house centralised approach to AM as it allows them to develop a better understanding of the process. Although the idea of distributed manufacturing can be appealing, the AM supply chain is not as established as it is for the traditional manufacturing process. Therefore, it is important for a company to carry on investing in both technologies where AM is more innovative but offers less security compared to traditional methods and always within the context of distributed manufacturing. In relation to customers and healthcare centres it was noted that most barriers involve attitude to risk and safety which has to do with every new technology and therefore an early adoption into clinical practice is required to then establish a proper feedback loop. Thus, the extent to which healthcare centres utilise the technology propositions will play a predominant role in the evolution of the supply chain. The pilot case company has provided support for the initial research framework in relation to its constructs and implementation factors and contributed to a further insight into the relationships between the variables. Table 4.1 presents the key implementation issues and activities at the pilot case study.

Table 4.1: Summary of AM issues and activities at Pilot Study

Source: The Author

Factor	AM Issues/Activities
Procurement	• The medical device industry is highly regulated. • Supplier needs to have a comprehensive knowledge of the equipment and materials. • Suppliers need to involve with the company's implementation process through support and back -up services.
Design	• The company needs to choose first the right AM technology and equipment before deciding on the appropriate software application and file exchange. • The successful integration of software and technology plays a significant role for producing more customized products.
Production	• The technology can assist the company to design products which would not be possible through traditional manufacture. • Flexibility of manufacture is one of the main advantages of the AM process. • The key constraint remains the technology readiness level of the materials and the whole process. • Further improvements of the technology are required to validate the process for medical applications and enhance on the evolution of the supply chain
Distribution/Logistics	• Companies tend to follow an in-house centralised approach to AM as it allows them to develop a better understanding of the process. • The AM supply chain is not as established as it is for the traditional manufacturing process. • Companies need to invest in both technologies where AM is more innovative but offers less security compared to traditional methods.
Customers	• Most barriers involve attitude to risk and safety which has to do with every new technology.

	• Early adoption into clinical practice is required to then establish a proper feedback loop.

4.3 Framework refinement based on pilot study

Based on the pilot study a number of factors have been added to the initial research framework.

In relation to the first construct and procurement factors the case study research has stressed the importance of supplier acquisition/integration with machine vendors and material suppliers which can eventually lead to development of new materials and process efficiencies and reduce restrictive practices. In the second construct and design factors the implementation could be enhanced by the development of new software solutions and tailored software tools that the company can use for healthcare – manufacturing services. Referring to the third construct and production factors emphasis was placed on the various costs which can make AM more expensive as traditional methods have become very efficient in terms of saving, including labour and other costs. When the fourth construct distribution/logistics factors examined, it was pointed out that a distributed manufacturing approach for this sector is difficult to be achieved as it involves critical safety components and still post – processing and supporting equipment will be required based on traditional manufacturing methods. Finally, in relation to customers and healthcare centres a very interesting case was found to be the possibility of allocating machines to the hospitals; however, for this scenario to be implemented a clear allocation of responsibilities to the different parts such as hospitals, suppliers and manufacturers needs to be established. The refined framework is presented as follows (Figure 4.2).

Figure 4.2. The refined AM implementation framework

4.4 Summary of the chapter

This chapter has presented the pilot cate study, as the first stage of the data collection process, and enabled the researcher to gain an understanding of the AM implementation process when examined from a supply chain perspective. This first set of empirical findings has enabled the researcher to further enhance the AM implementation factors identified in the initial research framework based on literature review and therefore can now use the refined AM implementation framework as the research instrument for the primary data collection.

CHAPTER 5

DEVELOPMENT OF THE IMPLEMENTATION FRAMEWORK

5.0 Introduction

This chapter describes the implementation framework. It first explains how the framework is developed and then presents the background of the development of the implementation factors within each construct. The proposed framework has included the results from the pilot case study, presented in the previous chapter, which were utilised to enhance the initial AM framework. The aim of this chapter is to provide answers for the second research question. The research question - objective is the following:

Research question:

- What are the key factors affecting implementation of AM on supply chain?

Research Objective:

- To develop a conceptual framework for implementation of AM on supply chain.

5.1. The Proposed Research Framework

The framework suggests that when examining the AM implementation from a supply chain perspective the factors which will influence this process may be grouped into five constructs: Procurement, Design, Production, Distribution/Logistics, and Customers. The above constructs have been proposed in accordance with the background theory on supply chain management and the classical definitions which define the concept of supply chain. Appropriate modifications have been produced to fulfil the requirements of the technology in accordance with the central question of the study which investigates the implementation of the technology as an operational process from a supply chain perspective. Each construct includes the implementation factors that medical device manufacturers need to consider to further improve their implementation process on the supply chain, which can lead to improved service capabilities and increased customer value. Those factors were developed based on a comprehensive review of Advanced Manufacturing Technology (AMT) implementation and existing theory on AM implementation. Within each implementation factor the issues/activities, which formed the factors have also been included. The framework has not included implementation factors for the end users, although that many issues/activities have been considered in the customers (healthcare centres) construct. As it was mentioned previously (3.4.3.2.1 Developing the research framework, constructs and questions), the framework is of a closed loop nature, illustrating the interactions and dependencies between each construct and the individual factors within these constructs. The proposed framework has included the results from the pilot case study, presented in the previous chapter, which were utilised to enhance the initial AM framework. The AM implementation framework put forward by the researcher is presented in the following Figure 5.1.

Figure 5.1: Additive Manufacturing Implementation Framework

5.1.1 Procurement Factors

The first construct of the framework examines the procurement implementation factors in relation to purchasing of AM equipment and materials. Therefore, selecting the right supplier plays a vital part within the supply chain as it is expected to impact the rest of the process. Choosing the right supplier is interrelated with the selection of AM process. However, process considerations will be examined in depth in the third construct of the framework (Production), as here the researcher identifies the criteria in relation to suppliers which can have an impact on the AM manufacturer's supply chain with emphasis on the collaboration between the adopting organisation and the equipment suppliers. Recent studies have involved qualitative and quantitative factors to rank the relative importance of the key attributes in selection of suppliers (Abbasi et al. 2013; Galankashi et al. 2013; Eshtehardian et al. 2013; Deshmukh and Vasudevan 2014). Based on these studies, Hemalatha et al. (2015**)** suggested that the most important criteria for supplier evaluation can be found in quality, cost, service, business performance, technical capability, delivery performance, and environmental performance. Abdolshah (2013) concluded that quality is the most important criterion to support supplier selection. Another very important factor in selecting the right supplier concerns the material availability. Hague et al. (2003**)** stated that it has become more difficult to justify development of new materials in AM as the quantity sold is low compared to conventional manufacturing methods. This results in very high production costs and is also reflected in the sale price. Therefore, for AM to be developed in a widely-used process further research is required to address material challenges. A key issue in AM implementation can be found in vendor restrictive practices. Deradjat and Minshall (2015) noted that machine suppliers limit attempts to scale up production through controlling what materials can be processed and restricting adjustability of machine parameters. Rahman and Bennett (2009) underlined that developing close relationships with technology suppliers is imperative in AM implementation. Chen and Small (1994) found that many users choose to deal directly with the suppliers or hiring a consultant, as their technical knowledge is insufficient to identify the most appropriate system for their situation and to operate and maintain the system after installation. Zairi (1998**)** identified that the level of success of AMT implementation is strongly connected with suppliers' technical knowledge to solve problems and provide efficient support and back-up services throughout the implementation process. Hence, increased collaboration and relationship with equipment suppliers is required in AM implementation as they are expected to affect the rest of the supply chain (Mellor, 2014).

Examining the procurement implementation factors in the healthcare sector, which is a highly regulated industry concerning standards and patient safety, medical device manufacturers face various challenges from understanding the needs of patients to launching their products globally. It is proposed that partnering with a reliable supplier with expertise in medical device and AM process can provide them with services and solutions to address those challenges and minimise risks associated with AM. Specialised suppliers can transfer their knowledge to address design considerations and ensure quality of end products. Medical device manufacturers can also benefit from suppliers' experience of working with hospitals, surgeons, and clinical laboratories to gain a better understanding of patient requirements (Kulpip and Ankur 2014). Hence, as the research framework proposes, when studying procurement implementation factors strong collaboration with suppliers can assist medical device manufacturers in service, experience, solutions and knowledge. This collaboration with suppliers can have the potential to eventually reduce restrictive practices through acquisition and vertical integration of machine-material suppliers. In addition, medical manufacturers can consider the possibility of co-development of their own materials and process efficiencies to better address the various customer requirements. Table 5.1 presents the AM implementation factors – key issues and activities within the procurement construct including related references.

Table 5.1: Summary of Research Framework: Procurement Construct and Implementation Factors - AM Key Issues/Activities

Source: The Author

Construct	**Implementation Factor**	**References**	**AM Key Issues/Activities**
Procurement	**Supplier Selection**	Hague et al. (2003), Deradjat, and Minshall, (2015)	• Difficult to justify development of new materials as the quantity sold is low compared to conventional manufacturing method. • Machine suppliers limit attempts to scale up production through controlling what materials can be processed and restricting

			adjustability of machine parameters.
	Vendor Supply Chain	Rahman and Bennett (2009), Zairi (1998)	• The level of success of AMT implementation is strongly connected with suppliers' technical knowledge to solve problems and provide efficient support and back-up services.
	Supplier Acquisition /Integration	Pilot Case Study	• Collaboration with suppliers could reduce restrictive practices through acquisition and vertical integration of machine-material suppliers.
	In-House AM Co-Development	Pilot Case Study	• Medical manufacturers can consider the possibility of co-development of its own materials and process efficiencies.

5.1.2 Design Factors

The next two constructs examine operational implementation issues within the supply chain in relation to the development of a final AM product. However, in order to gain an in-depth insight in relation to AM implementation factors within the supply chain context, the researcher examines separately software considerations (Design) and technology process considerations (Production). Design for Manufacture and assembly (DFM), traditionally referred to the process where designers aimed to eliminate manufacturing difficulties and minimize manufacturing, assembly and logistics costs (Susman 1992). In order for manufacturers to build on the concept of DFM and design for AM, (DFAM) they need to improve the manufacturability of a part from its CAD model for a given AM process (Ponche et al. 2012). The literature underlines that AM has the potential to transform supply chains as the technology is based on digital data and thus it can assist organisations to be more responsive and achieve agility (e.g. Waller and Fawcett 2014). Therefore, manufacturers need to address challenges associated with CAD systems to capture the full benefits of AM and renovate their supply chains. Selecting the appropriate software can be a very important element for the implementation process within the supply chain. Janssen et al. (2014) underlines that manufacturers need to decide first if the firm has the right capabilities to design new products in-house or to outsource the 3-D design to available service providers offering their expertise within this field. Petrick and Simpson (2013) noted that in any AM process, computer- aided design (CAD) and computer-aided engineering (CAE) software will be employed to create and analyse a digital solid model respectively. However, complex product geometries and material combinations often require further support by high-performance computing resources. Vinodh et al. (2010) highlighted that the integration of CAD and AM technology allow traditional organizations to design and model new concepts quickly and achieve agility, which can assist them to be more competitive and sustainable in a global environment. Weinberg (2010) indicated that reverse engineering can also be used to capture both internal and external features of digital models, where a 3D scanner can produce a CAD design by scanning an existing object. This creates new challenges for intellectual property which need to be addressed. Gibson et al. (2015) pointed out, in all the above pre-processing considerations, where software may require repair, are of importance, and process planners should have in place decision support software and allocate resources appropriately. However, there are a few limitations associated with CAD issues, which constrain the AM implementation process and ultimately affect supply chains. Hague et al. (2003) emphasised that limitation of existing CAD modelling systems including software and hardware compatibility issues, will be one of the main future challenges. Hahn et al. (2014) stressed that existing computer-aided design (CAD) systems are not at all suited for exploring the design freedom of AM processes and when a 3D print file is developed for one printer is not necessarily viable for use on a different printer. Further software challenges are concerned with data management issues and the need to increase memory storage capacity. According to the Royal Academy of Engineering (2013) it will be the software developments that will drive the industry forward and not the technology itself.

In the healthcare sector software design is critically important to the entire AM implementation process. Designing a medical device can be a complex process, where step-by-step design interventions result in increased cost and time (Lantada and Morgado 2012). However, improvements in medical systems with the combined use of medical imaging tools, CAD and CAE software and AM technologies, enable the cost-effective with minimum lead times development of customised biomedical devices (Crabtree et al. 2009). Medical device manufacturers need to develop new methods for integrating personalized customer data into their designs to automate the processes from patient data acquisition to part production (Diegel et al. 2010). Hence, as the research framework proposes, when examining design implementation factors an integrated software solution, which involves software developments and scanning technologies to fully address the design elements including data capture, product design and process planning, is required. This will ultimately enable medical manufacturers to develop more customised devices in a cost-effective and time-efficient manner and thus be more responsive and renovate their supply chain. Here, medical manufactures depending on their in-house capability, can also consider the possibility of developing their own tailored software and thus offer software solutions in the healthcare market. Table 5.2 presents the AM implementation factors – key issues and activities within the design construct including related references.

Table 5.2: Summary of Research Framework: Design Construct and Implementation Factors - AM Key Issues/Activities

Source: The Author

Construct	**Implementation Factor**	**References**	**AM Key Issues/Activities**
Design	**In House/Outsourced**	Janssen et al. (2014)	• Design new products in-house or outsource the AM 3D design to service providers depending on the firm's in-house capabilities.
	Software Selection	Ponche et al. (2012)	• Improve the manufacturability of a part from its CAD model for a given AM process to build on the concept of DFM and design for AM, (DFAM).
	Software Integrated Solution	Vinodh et al. (2010), Weinberg (2010)	• Integration of CAD and AM technology to allow organizations to design and model new concepts quickly and achieve agility. • Reverse engineering to capture both internal and external features of digital models.
	Pre-Processing	Gibson et al. (2015)	• Decision support software and

			appropriate allocation of resources.
	Software Development	Haque (2003), Hahn et al. (2014), Royal Academy of Engineering (2013)	• Software and hardware compatibility issues. • Computer-aided design (CAD) systems are not at all suited for exploring the design freedom of AM processes. • Data management issues - increase memory storage capacity.
	Software Solutions	Pilot Case Study	• Medical manufactures depending on their in-house capability, can consider the possibility of developing their own tailored software.

5.1.3 Production Factors

AM manufacturers need to address the implementation factors associated with AM processes to achieve higher accuracy of finished products in less time and in a more cost-effective manner to transform their supply chains. The literature proposes that AM can assist organisations to reduce overall cost of production and total lead times and therefore the utilisation of an appropriate AM technology can lead to more customised products with immediate effect on their supply chains (e.g. Hopkinson and Dickens 2001; Ruffo et al. 2006). Several AM processes are currently available, some of the more widely used can be found in Stereolithography (SLA), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM) and 3-D Printing (3DP) (Kulkarni et al. 2010). Selecting the appropriate AM process is an essential component of the implementation process within the supply chain. It was emphasised in the previous construct (Design) that the integration of CAD and AM technology will allow manufacturers to design for AM (DFAM) within their supply chain. Their aim is to utilize the AM technology and produce or manufacture end use components (Vinodh et al. 2010). Therefore, they need to use the technology to move towards Direct Digital Manufacturing (DDM), which allows the automatic production of objects from CAD design files without shape-defining tooling. Byun and Lee (2005) and Brajlih et al. (2011) stressed that when deciding on an appropriate process, a comprehensive knowledge of the interrelations between the part quality, part properties and fabrication time becomes necessary. Borille et al. (2010) noted that a combination of the right selection of the process along with the accurate description of user requirements can lead to successful applications of the technology. Borille and Gomes (2011) suggested that decision models should be utilised not only to address the technical limits of each technology but also to evaluate the capabilities of each process in relation to product requirements. Thus, it is clear from the above that each process has its own applications, advantages and limitations which need to be considered when implementing the AM technology within the supply chain. Limitations of technology can be found on capital costs, build time for high volume production, demand for better materials, post processing requirements in relation to accuracy improvements, and technical standards to assure that AM processes are safe and reliable (Royal Academy of Engineering 2013). In relation to post processing requirements, Hopkinson and Dickens (2003) noted that many AM processes require the building of support material which results in additional time and resources especially when volumes increase. The authors also pointed out that high costs associated with machines, maintenance and materials still oppose as the biggest constraint to the AM development. Therefore, further adoption of technology and increased competition between suppliers will lead to a reduction in costs. Here, many authors have stressed the need for the development of comprehensive cost models for AM. Existing research up to now has focused on the comparisons of two AM production technologies. Nevertheless, Ruffo et al. (2006) and Hopkinson and Dickens (2001) have produced more in-depth cost models to address particular processes. Ruffo et al. (2006) developed a costing model to compare laser sintering (LS) with conventional manufacturing process. Hopkinson and Dickens (2001) investigated manufacturing cost of stereolithography (SL) in comparison with equivalent parts of injection moulding. Lindemann et al. (2012) expanded on Hopkinson and Dickens' research and provided a life cycle analysis to enhance on further AM cost reduction activities such as weight reduction. However, the authors addressed the need for a comprehensive supply chain cost model to incorporate production costs within the total cost of the supply chain. In relation to machine and material costs, Diegel et al. (2010) noted that when employing AM, the ratio of the value of the product versus the manufacturing quantity of the product needs to be considered. Here, usually the more expensive the AM machine is, the cheaper the manufacturing material. Ruffo et al. (2007) outlined some of the key criteria when considering the make or buy decision, based on several factors such as cost, capacity, knowledge, response and quality. The authors concluded that the make option appears to be preferable, when analysis is based entirely on costs.

In the healthcare sector technology considerations play a predominant role when examining the AM implementation process. Here, established AM processes include Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Laminated Object Manufacturing (LOM), and Inkjet printing (Ruiwale and Sambhe, 2015). However, there are several limitations of AM technologies, which apply to AM in general. Rengier et al. (2010) noted that further limitations of the AM technology when applied in medical can be found in time and cost for complicated cases where extra costs occur; however, the application of AM results in reduced operating times and higher success rate of the surgical procedure, which compensate for the additional costs. The authors concluded that there are significant opportunities when AM applied in specialized surgical planning and prosthetics applications and a great potential for development of new medical applications. Hence, as the research framework proposes, when investigating production implementation factors medical device manufactures need to address the challenges associated with the selection of an appropriate AM technology, which can reduce the cost of production and total lead times and assist them to overcome some of the barriers connected with the applications of the technology. They can also utilise comprehensive cost models to address some of the challenges related with machines, maintenance and materials. Thus, medical device manufacturers will be able to optimise product design and development and meet patient needs on time and reconfigure their supply chain. Table 5.3 presents the AM implementation factors – key issues and activities within the production construct including related references.

Table 5.3: Summary of Research Framework: Production Construct and Implementation Factors - AM Key Issues/Activities

Source: The Author

Construct	**Implementation Factor**	**References**	**AM Key Issues/Activities**
	Process Selection	Hopkinson and Dickens (2001), Ruffo et al. (2006), Byun and Lee (2005) and Brajlih et al. (2011),	• AM can reduce overall cost of production and total lead times and deliver more customised products. • Comprehensive knowledge of the interrelations between the

Production		Borille and Gomes (2011)	part quality, part properties and fabrication time. • Decision models to address not only the technical limits of each technology but also to evaluate the capabilities of each process in relation to product requirements.
	Process Limitation	Royal Academy of Engineering (2013)	• Capital costs, build time for high volume production, demand for better materials, post processing requirements in relation to accuracy improvements, and technical standards to assure that AM processes are safe and reliable.
	Post-Processing	Royal Academy of Engineering (2013), Hopkinson and Dickens (2003)	• Accuracy improvements - surface finish. • Building of support material which results in additional time and resources when volumes increase.
	Process Cost	Ruffo et al. (2006) and Hopkinson and Dickens (2001), Lindemann et al. (2012), Diegel et al. (2010), Pilot case study	• Reduction in costs will be achieved through further adoption of technology and increased competition between suppliers. • Development of comprehensive cost models and supply chain cost models to incorporate production costs within the total cost of the supply chain.

5.1.4 Distribution/Logistics Factors

Location of manufacturing can have a significant impact on the AM implementation process. There are two extreme types of AM positioning models which companies can choose from. First the centralized model in which production facilities are concentrated in a particular location and serve the world market from that location. The other option is decentralizing production, where production facilities distribute in various regional or national locations close to the major markets (Holmström et al. 2010). The literature compares the two approaches and investigates the potential of distributed manufacturing mainly on the spare parts supply chain. Distributed deployment of AM can be very interesting for spare parts supply as it has the potential to improve service and reduce inventory. It is predicted that local manufacturing can lead to a reduction in transport costs (Tuck and Hague 2006). The potential of distributed manufacturing will be found only if demand is sufficient enough at a given location (Walter et al. 2004). It is found that in order for the distributed scenario to be more feasible AM machines must become less capital intensive, more autonomous and offer shorter production cycles (Khajavi et al. 2014). It is suggested that a centralised approach is always more likely to take place first as a fully functional supply chain is an essential requirement before companies explore their capabilities on distributed manufacturing (Hasan et al. 2013; Hasan and Rennie, 2008). Hence, considering the trade-offs affecting AM, centralised production of spare parts of AM is the most likely approach to succeed (Holmström et al. 2010). Thus, centralised AM will likely be the first to be used due to the level of demand and capacity utilisation. In order for distributed manufacturing to be more feasible demand must be sufficient enough at a given location, which requires an established customer base, or at least an understanding of the demand for products according to location. However, even if companies achieve this, they still need to reduce all costs across their supply chain including personnel and overhead costs especially in relation to AM machines.

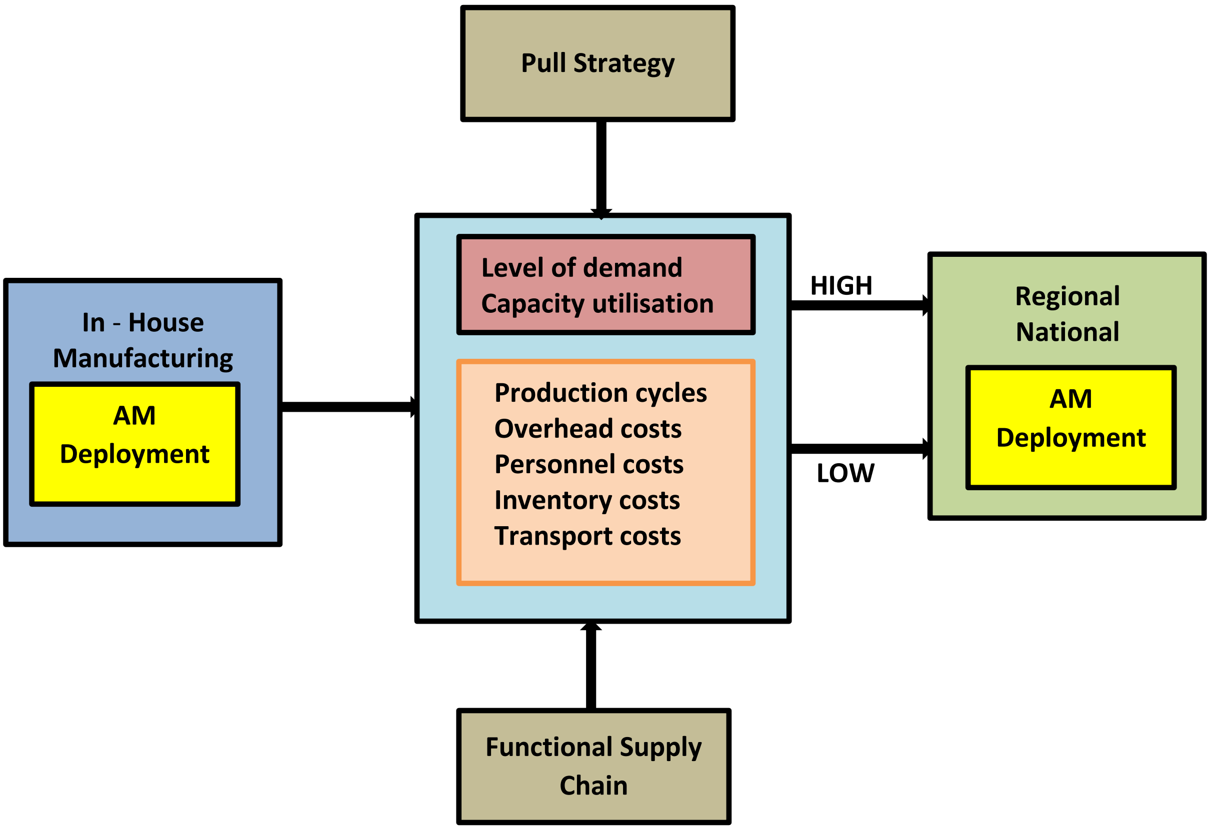


Figure 5.2: Theoretical framework: - AM factors to support the case of Distributed Manufacturing. Source: The Author

AM can have an impact on inventory and logistics, where production based on demand can be placed close to the customer (Manners-Bell and Lyon, 2012). The volume of inventory and the inventory mix could also be affected, and inventory is likely to shift towards the form of raw materials replacing semi-finished parts and components. In particular the physical inventory for technically complex products could be replaced by digital inventory and as a result the number of stored parts could be further reduced. This will ultimately eliminate the need for transportation of parts and goods and decrease delivery times (Sebastian and Omera, 2015).

Medical Device Manufacturers are usually equipped with high levels of stock in order to respond to all types of sizes needed. AM allows products to be manufactured on demand and therefore it can assist them to move towards a 'just –in-time' system. This make- to order model can help medical device manufacturers to significantly reduce inventory waste and risk in relation to unsold finished goods (Jungling et al. 2013). Manufacturing usually takes place in-house as they want to maintain control of the process in a highly-regulated environment involving safety critical components. However, they should also examine opportunities for manufacturing to be outsourced or even to be distributed near to the patient site to serve patients need more effectively. In this case, issues regarding post –processing and support equipment need to be considered such as CNC and also a functional supply chain is required to manage all costs across their supply chain along with an increased demand in a particular location. Table 5.4 presents the AM implementation factors – key issues and activities within the distribution/logistics construct including related references.

Table 5.4: Summary of Research Framework: Distribution/Logistics Construct and Implementation Factors - AM Key Issues/Activities

Source: The Author

Construct	Implementation Factor	References	AM Key Issues /Activities
Distribution/Logistics	**Centralized Manufacturing**	Holmström et al. (2010).	• Centralised production of spare parts of AM is the most likely approach to succeed.
	Distributed Manufacturing	Tuck and Hague (2006), Walter et al. (2004), (Khajavi et al. 2014), Hasan et al. (2013), Hasan and Rennie, (2008), Pilot case study	• Potential to improve service and reduce inventory for spare parts supply. • Possibility for reduction in transport costs. • Sufficient demand at a given location. • AM machines must become less capital intensive, more autonomous and offer shorter production cycles. • Fully functional supply chain before exploring capabilities on distributed manufacturing. • Issues regarding post – processing and support equipment such as CNC.
	Logistics	Sebastian and Omera, (2015)	• Inventory is likely to shift towards the form of raw materials replacing semi-finished parts and components.

			• Physical inventory for technically complex products could be replaced by digital inventory and as a result the number of stored parts could be further reduced.

5.1.5 Customers Factors

AM manufacturers need to address the implementation factors associated with the extent to which healthcare centres and practitioners utilise the technology propositions. AM models have been known to assist surgeons to better plan and understand the situation of the procedure involved in the surgery particularly in complex cases (Gibson et al. 2015). Thus, the application of the technology can lead to improved patient care and cost-effectiveness for the healthcare centre by reducing the duration of the surgical procedure and thus increase capacity (Khanna and Balaji, 2015). According to Bota et al. (2015) there are two likely scenarios for healthcare centres to engage more actively in relation to AM process. According to the first scenario healthcare centres and practitioners can backward integrate the technology into their services offered. However, this scenario can be quite complicated to be implemented as it will require new departments and practices within healthcare centres to serve the technology in terms of scanning and production. On the other hand, in the second scenario, medical device manufacturers could collaborate with local healthcare centres to create per-patient implants. Examining both scenarios there is a strong possibility for a third scenario which involves a combination of the previous two, where some AM services can be outsourced to contractors while others could be developed in-house.

Other factors which can enhance the AM implementation process can be found when medical device manufacturers utilize Web 2.0 technologies to engage with healthcare centres to a much greater extent, which in return will allow knowledge to spread more effectively and bring patients together to discuss their health and healthcare. Moreover, web tools associated with Web 2.0 have all the necessary elements to enhance on product ideas and component designs that can be produced through AM. Going beyond Web 2.0 technologies, the ‘cloud –based design and manufacturing concept’ (CBDM) can be leveraged for both generic and patient specific devices to assist in product development and medical device manufacturers can use this data to create parts or sub-assemblies for the device and ship them to the point of use. Online training tools and portals can also be utilised to assist in improving patient care (Gibson et al. 2015). Medical device manufacturers can also be part of the open source software, which has been used effectively for product development and has provided clinicians, which are non-engineering users, with the necessary skills to actively participate in the creation of designs and architectures. Here, manufacturers can share their knowledge with doctors to use the technology to quickly demonstrate the validity of the process and thus increase the possibility of the product passing clinical trials. In addition, the open source software can be utilised along the 'Maker culture', which involves the combination of traditional mechanical skills to create new devices for increased design participation and is an essential ingredient to invention (Gibson and Srinathb, 2015). Hence, as the research framework proposes, medical device manufacturers need to work in close collaboration with healthcare centres to scale up the AM technology which will lead to the evolution of the supply chain. This will assist in validating the manufacturing process within a highly-regulated environment, where further approvals are constantly required, and lead to the path to commercialization for AM medical devices. Table 5.5 presents the AM implementation factors – key issues and activities within the customers construct including related references.

Table 5.5: Summary of Research Framework: Customers Construct and Implementation Factors - AM Key Issues/Activities

Source: The Author

Construct	**Implementation Factor**	**References**	**AM Key Issues/Activities**
	Collaboration of Medical Manufacturers and Healthcare Centres	Bota et al. (2015)	• Collaborate with local healthcare centres to create per-patient implants.
	Integration of AM within Healthcare Centres	Bota et al. (2015), Pilot case study	• Healthcare centres and practitioners can backward integrate the technology into their services offered. • New departments and practices within healthcare centres to serve the technology in terms of scanning and production.

			• Hybrid Scenario: Outsource some AM services to contractors while develop others in-house.
	Web 2.0 Technologies	Gibson et al. (2015), Pilot Case Study	• Web tools associated with Web 2.0 to enhance on product ideas and component designs that can be produced through AM.
	Cloud- Based Design and Manufacturing (CBDM)	Gibson et al. (2015)	• CBDM for both generic and patient specific devices to assist in product development.
Customers	**Open Source Software and Maker Culture**	Gibson and Srinathb, (2015)	• Open Source Software to demonstrate the validity of the process and increase the possibility of the product passing clinical trials. • 'Maker culture', to create new devices for increased design participation.

5.2 Summary of the Chapter

This chapter has described the implementation framework. It first explained how the framework was produced and then presented the background of the development of the implementation factors within each construct. The proposed framework has included the results from the pilot case study, presented in the previous chapter, which were utilised to enhance the initial AM framework. The research framework will be employed as the research instrument for the case studies examined in the next chapter.

CHAPTER 6

THE MULTI-CASE STUDY: AM IMPLEMENTATION FOR MEDICAL DEVICE MANUFACTURERS

6.0 Introduction

The implementation framework is examined on three medical device manufacturers, based on within-case analysis. The purpose is to examine and further enhance the proposed implementation factors and reach a comprehensive knowledge in relation to the implementation of technology when it is examined from a supply chain perspective. Therefore, this chapter will provide answers for the third research question which is the following:

Research question:

- How do those factors impact implementation of AM on supply chain?

Research objective:

- To examine and enhance the proposed implementation factors on supply chain using real case studies.

The cases are classified in following table 6.1:

Table 6.1: Classification of cases

Source: The Author

Company name	**Company Case**	**Company Type**	**Company Size**	**Products**	**Informants/ position**
Company A	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive, Joint replacement, repair and reconstruction	AM Production Manager
Company B	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive Insoles	AM Operations Manager
Company C	Medical Device Manufacturer	Orthopaedics	SME – Social Enterprise < 50 employees	Additive Wheelchair parts	Company Director

6.1 AM Implementation at Company A

Company A is a leading UK manufacturer of orthopaedic medical devices and powder bed fusion processes, providing services to UK hospitals and international markets. The company specialises in the production of uncemented stem, but the last years have expanded its portfolio to other products including cemented stem, acetabular and revision products. The company as an innovative manufacturer has recognised the need for new technologies and developments and employed AM methods. The technology assisted the company to achieve product modifications which will not be possible through traditional subtractive machining methods particularly around porous net structures, cancellous bone-type structures, surface treatment, surface engineering, and shapes of constructs. The technology ultimately provided the company the ability to offer better solutions for patients, particularly in revision cases and more complex primary anatomy cases that could not be achieved by other means.

- The interviewee was the AM Production Manager of the company.
- The interviewee was directly involved in the implementation of AM technology and powder bed fusion process.
- The interviewee emphasised that improvements to the technology for volume manufacture need to be addressed.

6.1.1 Procurement Factors

Examining the AM implementation process of the case study in relation to procurement factors, the case study operates within the medical device industry, which is highly regulated, including standards relating to patient and device safety. The informant has stressed that when introducing a new device in accordance with the parameters of the new technology (AM), the relevant steps followed are quite tightly controlled and very demanding. Thus, suppliers must be very experienced with specific knowledge of the medical device industry. In particular, within this industry there are certain materials and AM metals, which are biocompatible and relatively new in their use in medical devices and compared with the evolution of AM. Consequently, the supplier must have the expertise to operate with the right materials and also to validate their process related to the required standards in medical devices. As a result, this will disqualify many potential suppliers who have the equipment and materials but they do not have the awareness of how the medical device industry works. Hence, the right supplier needs to have a comprehensive understanding of the medical device industry in relation to equipment and materials in order to use the right equipment and produce the product when is needed with the validation of the appropriate materials.

‘‘We need a supplier who knows medical devices, who has got the right equipment to produce the product that we need, who can operate with the right materials and know how to operate those materials, how to validate and source those materials’’.

In conjunction with those specific implementation factors regarding the selection of the appropriate supplier, suppliers in general need to have the criteria which apply to any manufacturing business, such as a strong presence in the market, to be established and reliable and have an adequate level of expertise.

‘‘We need a company who is established, who has a level of expertise, who knows what they’re doing, who are financially stable, who don’t have bad debts, who’ve been around long enough, they have some liability’’.

One of the challenging areas in AM involves the volume manufacturing and therefore when examining production-type volumes the supplier must be able to have the capacity to guarantee this point of supply and manage the process. Hence, when examining suppliers there are those factors which apply in general to manufacturing business where some of those are specific to AM. Suppliers play a significant part in the company’s implementation process as through their expertise will assist the company to produce and deliver a product when it is required and in accordance with the standards of the medical device industry. Table 6.2 presents the procurement implementation issues and activities at company A.

Table 6.2: Summary of AM Procurement issues and activities at Company A

Source: The Author

Factor	**AM Procurement Issues/Activities**
Supplier Selection	• Highly regulated industry - standards relating to patient and device safety. • New biocompatible AM metals and materials. • Suppliers have limited knowledge of medical industry. • Supplier selection: Expertise on equipment, materials and process.
Vendor Supply Chain	• Support the company to produce and deliver a product when it is required. • Volume manufacturing remains a challenging area for suppliers.
Supplier Acquisition/Integration	• Potential partnership with suppliers could enhance the AM implementation process.
In – House AM Co - Development	• Not proceeded in the development of its own materials and processes as further knowledge is required.

The key issues/activities identified in the implementation process of the case study in relation to procurement factors show that the case study has chosen to deal directly with the suppliers (Chen and Small 1994) to identify the most appropriate system for their situation. It was highlighted that the case study uses certain materials and AM metals, which are biocompatible and relatively new in their use in medical devices and therefore the level of success of AM implementation is strongly connected with suppliers' knowledge in relation to those materials (Zairi 1998). It was noted that it has become more difficult to justify development of new materials in AM as the quantity sold is low compared to conventional manufacturing methods (Hague et al. 2003) which results in high production costs. Consequently, volume manufacturing remains a challenging area for the case study where its suppliers in terms of the capacity will need to guarantee this point of supply and manage the process. Hence, for the case study a potential partnership with suppliers could provide with services and solutions to address the above challenges and further develop materials and process efficiencies.

The case study has shown support for the framework factors included in the procurement construct and provided further insight to relationships between the technology and procurement factors when examined from a supply chain perspective. The case study has found interesting the possibility of a partnership with its suppliers and development of its own materials and processes, as currently a strong vendor supply chain is in place.

6.1.2 Design Factors

Examining the AM implementation process of the case study in relation to design factors, the case study implements software platform issues in-house. The case study designs customs for patient-specific solutions and regular products, non-patient specific. 3D CAD software and in particular SolidWorks, is often employed in medical applications. It is emphasised that the integration of software platform is largely dictated by the technology itself.

‘‘And what we have found in our work so far to date is the software platform and how you integrate with that is, certainly for us anyway, is largely dictated by the technology manufacturer’’.

The case study after examining the particularities in the industry and the different types of process, in order to gain the maximum benefits of powder bed AM employed the Magic software platform, which is also widely used in medical device industry. This task is quite complicated and involves integrating the company’s part files with Magic’s build files. This process involves exchange of knowledge and information and includes details from the design of the product to the end result. Once the product is designed, then the appropriate software platform is selected to deliver the final product. Hence, once the company has identified the right technology and platform as well as the right equipment then a decision is made on the software application and the software file exchange.

‘‘Once we’ve found the right technology and the right platform, the right capital equipment, and then perhaps identify the right supplier, we’ll look at, “Okay, how do we establish data transfer? What do we do?”

In relation to customs and patient specific, the case study relies on the patient’s consultant or hospital to obtain the relevant data. In particular, the case study depends on CT files to acquire 3D information about a patient's anatomy to make custom implants. Then the data is translated into 3D CAD, and through reversed engineering is transferred into Magic software in order to produce patient-specific custom implants. On the other hand, for standard products, which are not patient specific, scanning is not required as the product is designed to a generic shape, design, geometry, and anatomy. Hence, when examining software considerations, the integration of software and technology remains a challenging area and will affect the end products. Medical device manufacturers aim to renovate their supply chains through producing more customised devices and therefore the extent to which this integration is successful, will ultimately impact the supply chain. Table 6.3 presents the design implementation issues and activities at company A.

Table 6.3: Summary of AM Design issues and activities at Company A

Source: The Author

Factor	**AM Design Issues/Activities**
In House/Outsourced	• In-house
Software Selection	• Designs customs and regular products. • Selects its software platform after a decision is made for product, technology, and equipment.
Software Integrated Solution	• Customs and patient specific: Relies on the patient's consultant or hospital to obtain the relevant data. ➢ The data is translated into 3D CAD, and through reversed engineering is transferred into Magic software to produce patient-specific custom implants. • Standard products: Not patient specific, scanning is not required as the product is designed to a generic shape, design, geometry, and anatomy.
Pre - Processing	• File repair software in place - no issues have been reported.
Software Development	• Software serves the company's needs in a satisfactory manner. • Particularities in the industry and different types of AM process constantly call for more customized software. • Integration of software and AM technology remains a challenging area.
Software Solutions	• Recognised the potential benefits of developing its own software.

The key issues/activities identified in the implementation process of the case study in relation to design factors show that the case study currently implements software platform issues and develops new products in-house (Janssen et al. 2014). It was stressed that the case study in relation to software selection and as part of the DFAM (Design for Additive Manufacturing) concept which places emphasis on improving the manufacturability of a part from its CAD model for a given AM process (Ponche et al. 2012), selects its software platform after a decision is made in relation to the product, technology, and equipment. Based on the above the case study has proceeded in the implementation of a software integrated solution (Vinodh et al. 2010) which allows to design and model new concepts quickly and achieve agility for patient – specific custom implants. In relation to software challenges, the case study has recognised the need for more customized software solutions to address the particularities within the industry as it was noted that existing computer-aided design (CAD) systems are not at all suited for exploring the design freedom of AM processes (Hahn et al. 2014).

The case study has shown support for the framework factors included in the design construct and provided further insight to relationships between the technology and design factors when examined from a supply chain perspective. The case study has not mentioned any significant issues in relation to its current software; however, it was recognised that particularities in the industry and different types of AM process constantly call for more customized software and would like to develop its own software.

6.1.3 Production Factors

Examining the AM implementation process of the case study in relation to production factors, the case study by using AM methods and powder bed processes can create a porous net structure that is similar to cancellous bone which would be impossible with traditional manufacturing methods. In addition to the main advantages, the utilisation of AM technology can assist the case study to integrate that porous net structure to a solid structure in one process. It is highlighted that products of different volumes and densities can be built at one. Therefore, a product can be built which can be solid in one area or hollow in another area and thus AM can assist the company to achieve those different types of structure in one product.

‘‘So, it removes problems of how do you achieve those different types of structure on one product? Do you bolt them together? Do you coat them? It removes any of that’’.

It is recognised, that in orthopaedics in general, that porous net structure is much better than other more traditional types of devices with sprayed coatings and as a result it integrates into the body extremely well. Therefore, once the orthopaedic device is implanted into the bone of the patient, which initially needs to stay steady, so the patient can recover and become active, the employment of AM can assist to apply surface treatment and specifications, which cannot be achieved through traditional manufacturing methods. In addition, the technology enables the case study to design products and forms which again would not be possible through traditional manufacture. Hence, flexibility of manufacture is one of the main advantages of the AM process, which enables to build a combination of different products at the same time.

‘‘So, if we want five of one product and three of another product and 10 of a third product and one of a fourth product, we can build those all in one go without having to swap out tooling or machine time or, processes and become very efficient’’.

Limitations of the technology concerning AM powder bed processes can be found in residual powder, where devices need to be made free from residual organics and inorganics when are placed into the patient’s body. This presents a big challenge in the industry at the moment and further research needs to take place to prove that this can be achieved. Each product in the industry is different and therefore when a process works for one product does not necessarily mean that it can work for every product. On the other hand, a limitation can be found on the validity and quality check of solid structures build from AM and particularly powder. Additionally, in relation to process cost issues, it was noted that when considering volume manufacturing AM process can be expensive as the cost associated with running the machine are high.

‘‘It’s an expensive process, it’s an expensive machine, it costs a lot to run, it takes up a lot of space for a build platform that’s actually very small relative to the size of the machine, so that’s definitely a limitation, particularly when you come to volume manufacture’’.

When examining post-processing requirements, the case study acknowledged that different processes produce different results and surface finishes. In general, industries aim to produce a finish, which is equally good to a machined product. However, for the particular case study and for orthopaedics in general this is not a limitation as a rough surface is preferred for the specific applications. Hence, the advantages of the technology are matched by some disadvantages, which are both inherent in the process; however, the industry is moving forward with some of the technology constraints. Improvements to the technology to validate the process for medical applications are key in growing the supply chain. Table 6.4 presents the production implementation issues and activities at company A.

Table 6.4: Summary of AM Production issues and activities at Company A

Source: The Author

Factor	**AM Production Issues/Activities**
Process Selection	• In-house, AM Powder Bed Processes. • Design products and forms which would not be possible through traditional manufacture. • Build a combination of different products at the same time without having to change tooling or stop the machine. • Achieve different types of structure in one product. • Apply surface treatment and specifications, which cannot be achieved through traditional manufacturing methods. • Flexibility of manufacture.
Process Limitation	• Different AM processes produce different results and surface finishes. • A process can work for one product but not necessarily for every product. • Technology improvements to validate the process are key in growing the supply chain.
Post – Processing	• Various stages involved till the product is ready. • Post machining - traditional machining function is required for most products. • Cleaning, packaging, laser marking and sterilising.
Process Cost	• Can be expensive for volume manufacturing as the cost associated with running the machine are high.

The key issues/activities identified in the implementation process of the case study in relation to production factors show that the case study has employed AM Powder Bed Processes, which assisted to reduce overall cost of production and total lead times and deliver more customised products (e.g. Hopkinson and Dickens, 2001; Ruffo et al. 2006). On the other hand, the case study has underlined that limitations of technology can be found on high costs associated with machines, maintenance and materials and build time for high volume production (Royal Academy of Engineering 2013). Furthermore, the AM process for the case study involves various stages till the product is ready and requires the building of support material which results in additional time and resources especially when volumes increase (Hopkinson and Dickens 2003).

The case study has shown support for the framework factors included in the production construct and provided further insight to relationships between the technology and production factors when examined from a supply chain perspective.

6.1.4 Distribution/Logistics Factors

Examining the AM implementation process of the case study in relation to distribution/logistics factors, the case study follows an in/house-centralised approach to AM. The informant has noted that in-house manufacturing offers advantages that cannot be replicated by other means such as distributed manufacturing. In particular, when a product is manufactured in-house to a high standard, the company develops an in-depth knowledge and understanding, which would not be acquired if it was developed outsourced by different manufacturers.

‘‘Manufacturing your own product to a high standard gives you a level of knowledge and understanding that you will miss if you have other people do it for you. So, I think there’s always merit in doing these things in-house’’.

On the other hand, it was stressed that currently with the emerging technologies and markets, there are many opportunities for manufacturing to be outsourced. Companies can choose from a wider specialist supplier base and take advantage of the emerging economies to produce in a more-cost effective manner. However, companies need to consider the cultural differences along with the technical aspects when using outsource suppliers. Additionally, safety critical components are a very important element in the medical industry and one of the main barriers when considering outsourcing this type of technology. Therefore, although the idea of an outsource supplier can be very promising, companies tend to focus on how to overcome the daily problems, rather than introducing new technologies. Nevertheless, companies will probably look of ways to outsource their technology if treatment becomes more patient-specific. A very interesting case is found to be the possibility of distributed manufacturing near to the hospital or to the patient. It was highlighted**,** that the process to manufacture custom-made devices for patients must be planned in advance as it involves preoperative planning, and therefore the advantages of manufacturing on-site, next to the patient can be overrated. In particular, the time taken to manufacture a custom device from the point of CT scan to the manufacturer and back to the patient can be a matter of days or a week. In that respect, for the case study, there is no urgent need to manufacture devices in close proximity to the hospital or patient, as the product can be delivered in short times anyway.

''And that's to make it all the way through the process from the point of CT scan all the way through manufacturer's and back again back to the patient. It can be done in a week or something if need be''.

However, as technologies develop this is likely to change. Technologies and materials need to grow with the patient in order to be applied in a more effective way and therefore in emergency cases, manufacturing next to the patient will be more applicable.

''Now there may be technologies and materials available in the future that are better applied or made maybe even in the theatre or with the patient. So, I don't think there's a lot of need for distributed manufacture at the point of treatment at the moment, but I think it will probably go that way''.

In relation to inventory levels there are two categories of products within the case study; customs and standard-regular products, which require different strategies respectively. Examining the custom products, they do not need any stock as they are based on demand. However, when it comes to standard products, which are additive manufactured products, then the same rules of stock and inventory apply as for normal products. Therefore, there are certain lead times based on how many units are shipped out in a year.

''Standard products made of additive manufacture doesn't make as much difference because we'll need to stock everything, we'll still need to stock the whole size range of a range of products, and there is still a lead time associated''.

In orthopaedics, the AM process is quite complicated and it involves various stages till the product is ready. Most of the products require some other post machining- traditional machining function. It also involves other processes such as cleaning, packaging, laser marking and sterilising. Hence, although the process provides with an advantage in the creation of the initial part, when it comes to volume manufacture the advantages in terms of inventory and stocking are limited. Thus, usually it is required to keep stock longer, although the lead times based on a certain turn rate are shorter, to ensure efficient stock all times.

''There's a lot more to producing a medical device using additive manufacture than nearly the additive manufacture process itself. So, it's not…in volume manufacture it doesn't give you as much advantage in terms of inventory and stocking as you might think''.

One important factor which needs to be considered, is that traditional machining methods are also advancing in terms of speed and they can also be used for custom products. In particular, as it is already mentioned, when considering volume manufacturing, traditional methods still seem to be more appropriate. Hence, companies currently tend to follow an in-house approach to AM as they can acquire a better knowledge of the process. On the other hand, the idea of outsource manufacturing seems quite appealing; however, there is a number of constrains cultural and technical which restricts the implementation of this concept. In relation to inventory levels standard additive manufacture products still follow the same rules for stock and inventory as for normal products. Although the technology can be advantageous in the creation of the initial part, at the moment its contribution is quite limited when examining volume manufacture, where traditional manufacturing methods still seem to be the preferred choice. Table 6.5 presents the distribution/logistics implementation issues and activities at company A.

Table 6.5: Summary of AM Distribution/Logistics issues and activities at Company A

Source: The Author

Factor	AM Distribution/Logistics Issues/Activities
Centralized Manufacturing	• In/house-centralised approach to AM. • Develop an in-depth knowledge and understanding.
Distributed Manufacturing	• Opportunities for manufacturing to be outsourced due to emerging technologies and markets. • Cultural differences and technical aspects. • Safety critical components. • Probably outsource its technology if treatment becomes more patient-specific.

	• No need to manufacture devices in close proximity to the hospital or patient, as the product can be delivered in short times anyway.
Logistics	• Inventory: Customized products and standard-regular products. • Customized products: No stock as they are based on demand. • Standard products: AM manufactured products - same rules of stock and inventory as for normal products.

The key issues/activities identified in the implementation process of the case study in relation to distribution/logistics factors show that the case study follows a centralised approach to AM which is always more likely to take place first due to the level of demand and capacity utilisation (Walter et al. 2004). This allows the case study to maintain control of the process and acquire further knowledge in relation to the implementation of the technology. The research framework suggests when investigating the location of manufacturing medical device manufacturers should also examine opportunities for manufacturing to be outsourced or even to be distributed near to the patient site to serve patients need more effectively. The case study has not yet considered a distributed manufacturing approach to AM due to cultural differences along with technical aspects and critical safety components which need to be considered particularly in the medical industry which is a highly-regulated environment. Nevertheless, the case study will consider the implementation of this scenario if treatment becomes more patient-specific. Furthermore, for the case study there is not urgent need to examine opportunities for manufacturing in close proximity to the hospital or patient as products can be delivered in short times anyway. The case study manufactures both customized and standard products where in relation to the first no stock is required as customized products based on a make- to order model which helps to significantly reduce inventory waste and risk in relation to unsold finished goods (Jungling et al. 2013).

The case study has shown support for the framework factors included in the distribution/logistics construct and provided further insight to relationships between the technology and distribution/logistics factors when examined from a supply chain perspective. The case study has found interesting the scenario of distributed manufacturing and will consider it if treatment becomes more patient-specific.

6.1.5 Customers Factors

Examining the AM implementation process of the case study in relation to customers factors, the case study in terms of the extent to which hospitals utilise the technology propositions has emphasised that in the healthcare sector the decision-making process regarding the appropriate technology for treatment is a quite complex process as at the moment there is a lot of pressure on hospitals and the NHS budget. Therefore, although surgeons have a direct interest in the technology of the product, they are not involved in the decision-making process. As a result, decisions on choosing a technology are based mainly on the cost rather than the technology itself. Hence, the extent to which hospitals utilise or even be part of the company's process and technology proposition is quite limited. It is highlighted that in the medical device industry is quite difficult to justify that a device that uses a better technology produces better long-term results. Therefore, when a new technology is introduced with the potential to produce better results over a long period cannot easily be accepted especially when it is more expensive.

''However, if you start to understand the technology of how those technologies are appropriate for different patients of different ages and different conditions, there are much better reasons for choosing one or the other''.

A very interesting case is found to be the possibility of allocating machines to the hospitals. However, a number of considerations were proposed which make this case not easy to be implemented. In particular, decisions need to be made regarding the validation of the process. A clear allocation of responsibilities to the different parts such as hospitals, suppliers and manufacturers for the different parts of the process needs to be established including the liability, the training and the skill level.

''It's not an easy thing to do because, some of these machines have to be run in a controlled environment. The process has to be validated. Who's going to do that? Is it the hospital or is it the supplier or is it the manufacturer?''

Additionally, companies can already achieve to deliver the products within very short times and therefore in real terms the advantages of having a machine on-site in the hospital could be overestimated. The company is currently serving a large number of hospitals. Thus, if this case was to be implemented then it could only assist companies to serve that particular hospital or if they are part of a group then a few more. However, it is a very interesting case but companies need to consider it in depth in terms of the implementation and the costs of the machines which are quite expensive. Hence, the extent to which hospitals utilise the technology propositions will play a predominant role in the evolution of the supply chain. Table 6.6 presents the customers implementation issues and activities at company A.

Table 6.6: Summary of AM Customers issues and activities at Company A.

Source: The Author

Factor	**AM Customers Issues/Activities**
Collaboration of Medical Manufacturers and Hospitals	• The extent to which hospitals utilise or even be part of the company's process and technology proposition is quite limited. • Technology decisions are based mainly on the cost rather than the technology itself. • When a new technology is introduced with the potential to produce better results over a long period cannot easily be accepted especially when it is more expensive. • Surgeons have a direct interest in the technology of the product, but they are not involved in the decision- making process.
Integration of AM within Hospitals	• Allocation of machines can be difficult to be implemented. ➢ Decisions regarding the validation of the process. ➢ Allocation of responsibilities to hospitals, suppliers and manufacturers including the liability, the training and the skill level. ➢ Products can be delivered within very short times.
Web 2.0 Technologies	• Not proceeded in the development of online training tools-portals for knowledge sharing.
Cloud – Based Design and Manufacturing (CBDM)	• Not implemented CBDM for both generic and patient specific devices. ➢ Use this data to create parts or sub-assemblies for the device and ship them to the point of use.
Open Source Software and Maker Culture	• The company has not been part of the open source software. ➢ Share knowledge with doctors and use the technology to quickly demonstrate the validity of the process.

	➢ Increase the possibility of the product passing clinical trials.

The key issues/activities identified in the implementation process of the case study in relation to customers factors show that the extent to which hospitals utilise or even be part of the company's process and technology propositions is quite limited. Although surgeons have a direct interest in the technology of the product as AM models have been known to assist them to better plan and understand the situation of the procedure involved in the surgery (Gibson et al. 2015), they are not involved in the decision-making process. In relation to the scenarios according to which healthcare centres can engage more actively in relation to AM process, the case study has found interesting the possibility of healthcare centres to backward integrate the technology into their services offered (Bota et al. 2015). However, it was noted that allocating AM machines within hospitals can be difficult to be implemented as it will require a clear allocation of responsibilities for the different parties involved. The case study has recognised that the AM implementation process could be enhanced if they developed Web 2.0 technologies and be part of the open software to engage with healthcare centres to demonstrate the validity of the process (Gibson and Srinathb, 2015).

The case study has shown support for the framework factors included in the customers construct and provided further insight to relationships between the technology and customers factors when examined from a supply chain perspective. It was strongly highlighted that medical device manufacturers need to work in close collaboration with healthcare centres to scale up the AM technology which will lead to the evolution of the supply chain. It also appears that a key category begins to emerge in accordance with the selective coding followed for this study; however, this category needs to be examined on the other case studies.

6.1.6 Summary of the case study

The first case study has presented the implementation process within the supply chain of a leading UK manufacturer of orthopaedic medical devices, specialising in the production of joint replacement parts and reconstruction. The case study has also shown how the technology has assisted to offer better solutions for patients, particularly in revision cases and more complex primary anatomy cases that could not be achieved by other means. A key category began to emerge, which needs to be further examined in the other two case studies. In summary, the case study has shown support for the framework implementation factors and provided further insights to implementation of technology on supply chain.

6.2 AM Implementation at Company B

Company B is an innovative UK manufacturer of orthopaedic medical devices. The company specialises in the production of high quality prefabricated and custom foot orthoses and is committed to research and innovation to offer value and service to health professionals and their patients. Their quality on foot orthotics is built on sound scientific and clinical understanding of foot biomechanics and foot health. The company is focusing on developing new orthotic materials, advanced orthotic designs and development of evidence supporting advances in orthotic practice. The company as an innovative manufacturer has recognised the need for new technologies and developments and employed AM methods to enhance its digital supply chain and offer added value to healthcare sector.

- The interviewee was the AM Operations Manager of the company.
- The interviewee was directly involved in the implementation of AM technology and fused deposition modelling process.
- The interviewee emphasised that further improvements to the technology for production applications are required.

6.2.1 Procurement Factors

Examining the AM implementation process of the case study in relation to procurement factors, the informant has stressed that when the company started, the most important issue for them was to focus on the most innovative process. The rationale was that through this innovative process would be able to offer the most innovative service. In relation to the AM printers, the technical capabilities were taken into consideration in terms of delivering the maximum value; however, they needed to be tested further to ensure that the range of materials and AM processes would provide something which did more than current products actually do. It was clearly found out that some printing processes or some families of materials are just not fit for purpose at the moment. As a result, although the initial focus was on producing innovation, the case study now focuses on where the material and processes can provide them deliverable opportunities. Once this has been fully realised then they can try and work out whether the final product is sufficiently innovative to make that initial investment worthwhile.

''I think that's now turned around, and what we're now focusing on, what we've learnt is that we need to understand what is actually the range of materials and AM processes which will give us something which does more than current products actually do''.

The informant pointed out when it comes to this emerging technology the traditional supply chain relationship needs to be re-examined, as it is not just about supplying materials or supplying printers but also supplying of knowhow which is a two-way flow of information. In particular, the case study has been very interested in getting strategically embed with the supplier in order to have the supplier create new materials for their exclusive use. Therefore, supply of materials and knowledge need to evolve together to provide a sustainable competitive advantage.

''So, they were supplying on the one hand, but it was a supply of materials and a supply of knowledge. And, so actually, both of those things were kind of quite important. One for the short term and one for the long term''.

The case study has invested in a highly innovative AM machine which could only deliver very few things. It was found later that the machine was very good for producing prototypes but was not suitable for industrial – manufacturing applications. The informant has emphasised that it is very important before a company investing in a highly innovative machine to examine if production is ready, in other words to produce things on a sufficient scale to make it commercially viable. Therefore, the concept of AM which can deliver design freedom needs to be examined in collaboration with traditional manufacturing processes as some of the materials are so far away from being ready. Hence, companies need to re-consider the capabilities of the technology as certain production can still be better delivered with traditional manufacturing methods. Table 6.7 presents the procurement implementation issues and activities at company B.

Table 6.7: Summary of AM Procurement issues and activities at Company B

Source: The Author

Factor	AM Procurement Issues/Activities
Supplier Selection	• Initially focused on the most innovative process to offer the most innovative service. • Not all AM processes and materials are ready for production applications. • Currently focuses on where the material and processes can provide deliverable opportunities.
Vendor Supply Chain	• Supply of materials and knowledge need to evolve together. • The traditional supply chain relationship needs to be re-examined.
Supplier Acquisition/Integration	• Interested in getting strategically embed with the supplier.
In – House AM Co - Development	• The company would like to have the supplier create new materials for their exclusive use. • Development of its own materials - processes is not an option yet as further knowledge is required.

The key issues/activities identified in the implementation process of the case study in relation to procurements factors show that the case study focus on where material and processes can provide them deliverable opportunities and then selects its suppliers based on the notion that the final product is sufficiently innovative to make that initial investment worthwhile. It was noted here that some printing processes or some families of materials are just not appropriate for this purpose at the moment and therefore a combination of the right selection of the process along with the accurate description of user requirements can lead to successful applications of the technology (Borille et al. 2010). The case study strongly believes that developing close relationships with technology suppliers is imperative in AM implementation (Rahman and Bennett 2009) and will affect the rest of the supply chain (Mellor, 2014); however, it was highlighted that both parties need to further develop their knowledge in terms of materials and processes and therefore a two-way flow of information needs to be established.

The case study has shown support for the implementation factors included in the procurement construct of the framework and provided further insight to relationships between the technology and procurement factors when examined from a supply chain perspective. The case study would also be interested in getting strategically embed with the supplier and have the supplier create new materials for their exclusive use.

6.2.2. Design Factors

Examining the AM implementation process of the case study in relation to design factors the informant pointed out the difference between the traditional manufacturing methods and AM: The traditional manufacturing process is based on taking a plastic cast of someone's foot, including a positive geometric representation of their foot shape, heat mould plastics or rubbers onto that and then manually manufacture it. Here, there is also a digital version of that process which plugs into traditional CNC milling. This process is based on a laser scanner which catches foot shape and by using an appropriate software would then design these sorts of geometric shapes based on the individual patient's foot shape. The model then goes to a CNC milling machine and it is milled from a block of material and then it is finished. This traditional process based on the digital supply chain has been in place for many years. However, when it comes to AM what makes the difference in terms of the digital supply chain is plugging AM onto the end of that instead of milling and substituting the two. The informant noted that there is no difference in terms of the data acquisition foot shape and other clinical information or the prescription the clinician wants to use. The major difference can be found on the model physical geometric designs, which are based on a process of reduction and elimination of waste material compared with the traditional manufacturing methods which are subtractive and there is a need to create cavities and reduce materials.

''The only knock-on for the design stage is that we currently model physical geometric designs based on a process of reduction, getting rid of waste material left with the product. Whereas when you're printing it, you need to create cavities, reduce materials, look at….''

In particular, in relation to software challenges the informant recognised that currently the challenges are related to producing and designing a product which is more durable if for example it is just printed as a solid. For the case study and AM machine that uses, different materials can be placed in different areas. However, the informant underlined that the mechanical integrity of the product in terms of its durability and robustness cannot be supported or informed by any sort of data.

‘‘And how you blend or bleed one material in one area into a different material in another area and how that affects the mechanical integrity of the product and therefore its durability and robustness, that is not a decision which is in any way supported or informed by any sort of data’’.

One of the challenges for the case study was to use different materials which would not have constructing properties and therefore lead to a mechanical weakness in the structure. Here, it was emphasised that the decision process was based initially more on intuition rather than really understanding the material characteristics. The case study has then used computer modelling to try and predict the best blend of materials and bleeding of materials into each other and then utilised a software to support the decision-making process. Other minor software issues had to do with converting something from a mesh which is sufficient for milling into a solid surface base file. Overall the informant did not recognise any significant problems in relation to software issues.

‘‘So, there were some software issues to do with the design decision-making and those could be better supported by knowledge that’s made more explicit’’.

Table 6.8 presents the design implementation issues and activities at company B.

Table 6.8: Summary of AM Design issues and activities at Company B

Source: The Author

Factor	**AM Design Issues/Activities**
In House/Outsourced	• In-house
Software Selection	• Designs customs insoles for patient-specific solutions. • Computer modelling to predict the best blend of materials followed by software to support the decision-making process. • No difference with traditional manufacturing in data acquisition, foot shape and other clinical information. • Differs on the model physical geometric designs - based on a process

	of reduction and elimination of waste material.
Software Integrated Solution	• Laser scanner to catch foot shape – software to design geometric shapes based on the individual patient's foot shape. • Digital supply chain differs only at the end - AM is plugged instead of CNC.
Pre - Processing	• File repair software in place - no issues have been reported.
Software Development	• No data can inform or support the mechanical integrity of a product in terms of its durability and robustness. • Minor software issues: decision-making process and knowledge transparency. • Overall no significant problems in relation to software issues.
Software Solutions	• Recognised the potential benefits of developing its own software.

The key issues/activities identified in the implementation process of the case study in relation to design factors show that the case study implements software related issues in-house. The case study strengthens the proposition that AM has the potential to transform supply chains as the technology is based on digital data and thus it can assist organisations to be more responsive and achieve agility (Waller and Fawcett 2014); however, it was noted that when AM is compared to traditional manufacturing the only difference in terms of the digital supply chain is plugging AM onto the end of that instead of the traditional CNC milling and thus most of the supply chain is already there to deliver the benefits. In relation to software challenges, the case study has recognised that complex product geometries and material combinations often require further support by high-performance computing resources (Petrick and Simpson 2013) and for this reason it has utilised computer modelling to try and predict the best blend of materials and then employed a software to support the decision-making process.

The case study has shown support for the implementation factors included in the design construct of the framework and provided further insight to relationships between the technology and design factors when examined from a supply chain perspective. The case study has not mentioned any significant issues in relation to its current software; however, it was recognised in accordance with the previous case study, that further software developments would be beneficial for the industry and is keen on developing its own software.

6.2.3 Production Factors

Examining the AM implementation process of the case study in relation to production factors, the case study uses Fused Deposition Modelling (FDM) technology. The informant underlined that there is a perception about customised medical products like an insole or something that fits close to the skin surface, that it needs to have a real high fidelity in the kind of design process in order to really subtly vary the geometries and the different properties in different areas. Therefore, it was noted that the ability to finetune the geometry to that sort of degree remains quite challenging in relation to the extent to which the materials which are deposited in different areas can be varied. The traditional manufacturing paradigm is based on the assumption that when designing these, once the material is in place then by changing the geometry the properties will change. However, AM and in particular FDM technology can deliver the potential of having lots of different materials with one geometry. Thus, the technology has the potential to revolutionise the design paradigm.

''Because with traditional paradigm for designing these is that you choose one material and you change the geometry to change the properties. 3D printing and the FDM allow the possibility of reversing that and saying, "Imagine if you had one geometry and lots of different materials".

In relation to disadvantages for the particular technology (FDM) the informant has stated that the key constraint remains the technology readiness level of the materials and the whole process. There is still a lot post processing required and AM still remains more expensive as traditional processes have actually become very efficient in terms of saving including labour and other costs.

''Because the traditional processes have actually got very efficient over 20, 30 years, there's not a lot of saving in terms of labour and other cost compared to the traditional process which makes the AM even more expensive''.

The informant has underlined that the cost for producing insoles by using FDM can be many times higher compared with conventional methods and a lot of the build cost depends on the height of the object which is about to be produced. In particular, based on a cost model for these, a standard rate for access to the printer will be about £50 to £70 per hour and it can take four or five hours to print these. Then material costs and post-production cost also need to be included. In terms of producing this object with traditional methods it would take 40-45 minutes. Therefore, in order to examine the real added value that AM can offer, a comparison needs to take place between the traditional supply chain and manufacture process which is craft base and the digital supply chain. It was pointed out that when examining the digital supply chain the difference can be found at the end of that chain depending if the object is going to be produced by CNC milling or some other traditional production process or by employing AM technology. Thus, a digital supply chain can take place without requiring AM at the end of that chain. In that respect when most of the supply chain is already there, a lot of the advantages are already in place regardless the technology which is going to be used at the end of that chain. Here taking into consideration that traditional methods have been in place for many years and improved a lot, the opportunity for AM to add value to the existing digital supply chain it can be quite limited for the particular sector.

''And if you've got 90% of that supply chain anyway, a lot of the advantages are already in place. So, the opportunity for AM to add value to an existing digital supply chain I think is quite limited''.

However, when examining the possibility of moving from a traditional craft-based manual manufacture process to AM process then the potential can be greater, which is not always the case for the particular sector. Table 6.9 presents the production implementation issues and activities at company B.

Table 6.9: Summary of AM Production issues and activities at Company B

Source: The Author

Factor	**AM Production Issues/Activities**
Process Selection	• In – house, Extrusion - Based Systems – Fused Deposition Modeling (FDM). • Deliver lots of different materials with one geometry. • AM technology could revolutionise the design paradigm.
Process Limitation	• Invested in a highly innovative AM machine which was very good for producing prototypes but was not suitable for industrial – manufacturing applications.

	• Certain production can still be better delivered with traditional manufacturing methods - commercial capabilities of AM need to be re-examined. • Key constraint: technology readiness level of the materials and the whole process. • Remains more expensive as traditional processes have become very efficient in saving labour and other costs. • Volume manufacturing can be possible only when the production involves a lot small items. e.g. hearing aids.
Post – Processing	• Still a lot post processing is required.
Process Cost	• Cost for producing insoles can be many times higher compared with conventional methods. • A lot of the build cost depends on the height of the object. • AM adds limited value to the existing digital supply chain for the particular sector. • The company has employed cost models to measure rates, material costs and post-production cost.

The key issues/activities identified in the implementation process of the case study in relation to production factors show that the case study has initially invested in a highly innovative AM machine which was very good for producing prototypes but was not suitable for industrial – manufacturing applications. The case study has employed Extrusion - Based Systems and in particularly Fused Deposition Modelling (FDM) with the potential to assist the company of having lots of different materials with one geometry. Their aim was to utilize the appropriate AM technology and produce or manufacture end use components for commercial applications (Vinodh et al. 2010). The case study presents an example of the technology constraints in relation to materials and processes and therefore when an AM technology is particularly good for certain applications does not necessary means that it can be beneficial for others. It was highlighted here that when considering the make or buy decision, several factors such as cost, capacity, knowledge, response and quality need to be considered (Ruffo et al. 2007). Additionally, decision models should be utilised not only to address the technical limits of each technology but also to evaluate the capabilities of each process in relation to product requirements (Borille and Gomes 2011).

The case study has shown support for the framework factors included in the production construct and provided further insight to relationships between the technology and production factors when examined from a supply chain perspective. For the case study the production factors are of particular importance, as it has noted many problems in relation to materials and processes of the technology for production applications.

6.2.4 Distribution/Logistics Factors

Examining the AM implementation process of the case study in relation to distribution/logistics factors, the case study follows an in/house-centralised approach to AM. The informant has noted that at the moment, the only 3D printed AM products, insole products which are on the market are a combination of a printed part and a traditional manufactured part using traditional manufacturing processes.

‘‘And, so in that case, wherever you print, you’ve also got to have the other parts that you glue on afterwards. So, for that reason, I think everything I’m aware of is all done in-house. And I don’t see that changing until you can literally just print the item and it’d be kind of ready and need nothing else doing. And I think that’s probably years off’’.

The informant has addressed the possibility of a blended model. Here the consumer buys a 3D printed insole, has his foot scan off and sends the files to a company which designs it digitally and then forward it back to the consumer who can print it himself by using a local printer or through a printing bureau. Then by post the consumer also receives the other pieces of material and has to do the assembly at home. However, this model has its limitations depending if the consumer will be willing to do the assembly on its own.

‘‘So, I can imagine that sort of model working. I’m just not sure that consumers want to do that sort of thing. I don’t want to buy a watch and have to put it together myself ’’.

The informant noted that the possibility of distributed manufacturing is more likely to be found in the aerospace as you have planes moving all over the world. Here a file can be sent and print the spare part locally. In relation to the advantages of in-house manufacturing in terms of developing knowledge of the AM process, the informant has underlined that critical paths could be created as it is a new technology and the supply chain around spare parts and materials is not as established as it is for the traditional milling process. It is important to invest in both technologies, in traditional methods as well as in AM methods which the first one offers more security but is less innovative compared to AM.

‘‘So, if in the milling something goes wrong, we can send that work to somebody else and they’d do it for us. If our supplier of materials got very expensive, there’s a marketplace for those, so you can go and get other supplier, it’s very easy. So, you end up having to sort of invest in both approaches anyway because they offer, one offers a bit more security even if it’s less innovative than the other one’’.

In relation to inventory levels the informant has noticed that in this area companies do not need to have a lot of stock in the first place. The logistics of traditional supply are good enough in the respect that if a clinician wants a pair of items made by a traditional process, they can order it and have it within a few days. It was noted that the supply of traditional processes is efficient enough and therefore there is no really a stock problem to solve. However, it was noticed that the ability of these materials to last on the shelf is quite limited as they change colour and they degrade. In terms of volume manufacturing and AM, it was suggested that this is possible only when the production involves a lot small items like for example in the case of hearing aids. Table 6.10 presents the distribution/logistics implementation issues and activities at company B.

Table 6.10: Summary of AM Distribution/Logistics issues and activities at Company B Source: The Author

Factor	**AM Distribution/Logistics Issues/Activities**
Centralized Manufacturing	• In/house-centralised approach to AM. • 3D printed - AM insole products on the market are a combination of a printed part and a traditional manufactured part. • Critical paths need to be created as the supply chain around spare parts and materials is not established.
Distributed Manufacturing	• Feasible only if an AM product does not require support from traditional methods. • A blended model could be possible.

	➢ The consumer has his foot scan off, sends the files to a company which designs it digitally and then forwards it back to the consumer who can print it himself by using a local printer or through a printing bureau. ➢ By post the consumer also receives the other pieces of material and has to do the assembly at home.
Logistics	• Inventory: Customized products. • Companies, do not need to have a lot of stock in this area. • Logistics of traditional supply are efficient enough. • Items made by a traditional process can be delivered to clinicians within a few days.

The key issues/activities identified in the implementation process of the case study in relation to distribution/logistics factors show that the case study follows an in/house - centralised approach to AM. It was highlighted, that the only 3D printed AM products - insole products - which are on the market are a combination of a printed part and a traditional manufactured part and therefore a fully functional supply chain is an essential requirement before companies explore their capabilities on distributed manufacturing (Hasan et al. 2013; Hasan and Rennie, 2008). The case study has noted that although distributed deployment of AM can be very interesting for spare parts supply as it has the potential to improve service and reduce inventory (Holmström et al. 2010), critical paths need to be created as the AM supply chain around spare parts and materials is not as established as it is for the traditional milling process. The case study has presented a blended model according to which the consumer buys a 3D printed insole, has his foot scan off and sends the files to a company which designs it digitally and then forward it back to the consumer who can print it himself by using a local printer or through a printing bureau. Then by post the consumer also receives the other pieces of material and has to do the assembly at home. However, it was stressed here that this model can only have potential if the consumer will be willing to do the assembly on its own. In terms of inventory the case study produces customized products which keeps stocks at minimum levels (Jungling et al. 2013) and highlights that the logistics of traditional supply are efficient enough to deliver this as it takes only a few days.

The case study has shown support for the implementation factors included in the distribution/logistics construct of the framework and provided further insight to relationships between the technology and distribution/logistics factors when examined from a supply chain perspective. The case study has found interesting the scenario of distributed manufacturing; however, a fully functional supply chain is an essential requirement before companies explore their capabilities on distributed manufacturing.

6.2.5 Customers Factors

Examining the AM implementation process of the case study in relation to customers factors, the informant has emphasised that the extent to which hospitals utilise the technology propositions is quite limited at the moment as the culture within hospitals and healthcare centres is not always innovation 'friendly'. In particular, it was noted that the two organisations; medical device manufacturers and hospitals are working at completely different paces as AM is growing significantly in the market; however, the technology is not utilised accordingly in hospitals. It is recognised that AM can offer a number of benefits but at the moment healthcare centres are used to the traditional supply relationship where they order an object and receive it.

''But they're very used to a sort of a traditional supply relationship so they just want to be able to order it and have it''.

The informant underlined that hospitals need to understand, as with every emerging technology, that they have to engage with it. Therefore, hospitals need to be more innovation oriented rather than focusing on just delivering care. Further barriers within hospitals can be found in other parts of infrastructure such as sharing electronic data, security clearance, which can take months to set up. This can delay the ability of a device manufacturer to work closely with hospitals and further develop the technology. Hence, it was noted that hospitals have quite high expectations in terms of regulation, safety and quality; however, when it comes to a new technology which needs to be tested, they need to participate to develop that relationship which is necessary for the evolution of technology, instead of just expecting the certain products to be supplied.

''So, there's a lot of critical paths that they're there and they're organised because the primary business of hospitals is healthcare. But what they make is a very inhospitable environment for innovation.''

In relation to the possibility of allocating machines to the hospitals the informant has pointed out that there are several examples where hospitals have invested in the digital supply chain, not the AM but the traditional CNC milling. However, it was found that the capacity utilisation was very low for it to be used on an industrial scale and therefore in that respect it could not justify the initial investment.

‘‘And it’s because they believe that if they can produce it on site it’s somehow better. But that is true as long as you’re using it 90% of the time. If it’s operating 24 hours a day and not 10 hours a week’’.

In relation to the propositions that can help the technology to be more widely used for this particular sector and medical device manufacturers, the informant has stated that the biggest barrier is around implementation and adoption in clinical settings as it is essential for this to happen in order to obtain insights which feeds into the beginning of the chain. At the moment, the technology can be found on printing bureaus or people who have the printers and the material manufacturers. They communicate with each other and innovate things; however, they do not have sufficient information from the marketplace and therefore they need to engage more actively with clinicians to support this innovation.

Therefore, the biggest barrier is to initiate some early adoption into clinical practice to then establish a proper feedback loop. More barriers can be found within hospitals and involve attitude to risk and safety which has to do with every new technology. The informant has pointed out that it will take time to overcome those barriers taking into consideration that the digital supply chain independent of AM has been in the industry for 20 years and still, only about 30% of clinicians have access to it after 20 years. Thus, it can be very slow to innovate. Table 6.11 presents the customers implementation issues and activities at company B.

Table 6.11: Summary of AM Customers issues and activities at Company B

Source: The Author

Factor	**AM Customers Issues/Activities**
Collaboration of Medical Manufacturers and Hospitals	• The extent to which hospitals utilise or even be part of the company’s process and technology proposition is quite limited. • Traditional supply relationship: Healthcare centres order an object and receive it.

	• Healthcare centres need to further participate. • Main barrier: Implementation and adoption in clinical settings. • Other barriers: Attitude to risk and safety, sharing electronic data, security and clearance.
Integration of AM within Hospitals	• Can only offer value as long as hospitals use the maximum capacity of it. • Occupy a lot of space considering the capacity utilisation.
Web 2.0 Technologies	• The company has not yet proceeded in the development of online training tools-portals for knowledge sharing.
Cloud – Based Design and Manufacturing (CBDM)	• The company has not implemented CBDM for both generic and patient specific devices. ➢ Use this data to create parts or sub-assemblies for the device and ship them to the point of use.
Open Source Software and Maker Culture	• The company has not been part of the open source software. ➢ Use the technology to quickly demonstrate the validity of the process. ➢ Increase the possibility of the product passing clinical trials.

The key issues/activities identified in the implementation process of the case study in relation to customers factors show that the extent to which hospitals utilise or even be part of the company's process and technology propositions is quite limited. It has been recognised that the application of the technology can lead to improved patient care and cost-effectiveness for the healthcare centres by reducing the duration of the surgical procedure and thus increase capacity (Khanna and Balaji, 2015); however, the culture within healthcare centres is not always innovation 'friendly' as they are used to the traditional supply relationship where they order an object and receive it. Therefore, healthcare centres need to participate to develop that relationship which is necessary for the evolution of the technology, instead of just expecting the certain products to be supplied. In relation to the scenarios according to which healthcare centres can engage more actively with AM process and the possibility of healthcare centres to backward integrate the technology into their services offered (Bota et al. 2015), the case study has noted that this can offer value as long as hospitals use the maximum capacity of it, which has never been the case. Although the case study has not yet implemented Web 2.0 technologies to further collaborate with healthcare centres and enhance on product ideas and component designs that can be produced through AM (Gibson et al. 2015), it has recognised the importance of those tools for improving patient care (Gibson and Srinathb, 2015).

The case study has shown support for the implementation factors included in the customers construct of the framework and provided further insight to relationships between the technology and customers factors when examined from a supply chain perspective. It was strongly highlighted in accordance with the previous case study, that medical device manufacturers need to work in close collaboration with healthcare centres to scale up the AM technology which will lead to the evolution of the supply chain. Therefore, the key category is also evident on this case study.

6.2.6 Summary of the case study

The second case study has presented the implementation process within the supply chain of an innovative UK manufacturer of orthopaedic medical devices specializing in the production of high quality prefabricated and custom foot orthoses. The case study has shown that all AM processes and families of materials are not suitable for industrial – manufacturing applications for this particular sector. The case study now focuses on where the material and processes can provide them deliverable opportunities. The existence of the key category was reinforced but still needs to be examined in the last case study. In summary, the case study has shown support for the framework implementation factors and provided further insights to implementation of technology on supply chain.

6.3 AM Implementation at Company C

Company C is an innovative UK social enterprise of orthopaedic medical devices which specialises in the production of parts for wheelchair users. The idea for working on the development of customised wheelchairs was based on the notion that there is a huge number of people who need to use a wheelchair but do not have access to one that suits their needs. For this purpose, the company has utilised the skills of highly qualified engineers, designers, researchers and wheelchair users in an attempt to design the world's first open source wheelchair and close the gap between designers and wheelchair users. The company is focusing on creating a wheelchair that is affordable and attainable for all the world's disabled population and has been examining at how AM and distribution manufacturing networks could be used in the healthcare sector and enhance its supply chain. For this purpose, it employed AM methods for that particular customer group of wheelchair users.

- The interviewee was the Director of the company.
- The interviewee was directly involved in the implementation of AM technology and production of wheelchair parts.
- The interviewee emphasised that the company is keen on a wider network involving the contribution of the different communities on a local and global scale.

6.3.1 Procurement Factors

Examining the AM implementation process of the case study in relation to procurement factors, the informant has stressed that the case study has received support from suppliers working in AM industry. The case study, which is a social enterprise, by participating in various exhibitions where it run trial on AM objects has attracted attention from different suppliers who were willing to donate their materials as they were interested in that new concept of producing parts for wheelchairs.

The informant has pointed out that there are a lot of materials that are still being developed as it is comparatively a new space. Here, suppliers have provided the case study with different materials to try themselves which are also new for the suppliers and therefore it is a continuing research process for both parties on the development of appropriate products which can be used for the wheelchair sector. Additionally, in order for suppliers to get a better understanding of the process and meet the requirements for this sector, they have asked the collaboration of healthcare professionals. In that respect, everybody in the industry has been very open to the idea of collaborating and working together.

‘‘We found suppliers wanted us to try things for ourselves and have sent us materials that they’re testing and have quite openly said this is new product for us’’.

In particularly in relation to collaboration with suppliers, the informant has noted that within this sector everybody seems to be willing to share their knowledge and expertise and on many occasions, they have been working on the same project with other AM companies also using the same space.

‘‘They have been very happy to come and teach us things or come and share things with us or to facilitate our events and they are happy to work with other companies in the same space, so, it’s much more collaborative than I expected’’.

Thus, taking into consideration this increased collaboration and the interest of so many parties the case study has begun designing the world’s first open source wheelchair comprised of a mix of engineers, designers, researchers, suppliers, healthcare professionals and wheelchair users who shared their ideas and expertise and have been working towards creating a wheelchair that is affordable and attainable for all the world’s disabled population. Table 6.12 presents the procurement implementation issues and activities at company C.

Table 6.12: Summary of AM Procurement issues and activities at Company C

Source: The Author

Factor	**AM Procurement Issues/Activities**
Supplier Selection	• Social enterprise: Collaborates with a number of suppliers. • Suppliers have provided the company with different materials to try themselves. • Comparatively a new space - a lot of materials are still being developed.
Vendor Supply Chain	• Continuing research process for both parties on the development of appropriate products. • Increased collaboration and interest of many parties including healthcare professionals. • The company has begun designing the world’s first open source wheelchair.
Supplier Acquisition/Integration	• Potential partnership with its suppliers could enhance the AM implementation process.
In – House AM Co - Development	• Not proceeded in the development of its own materials and processes as a substantial amount of knowledge is required.

The key issues/activities identified in the implementation process of the case study in relation to procurement factors show that the case study as a social enterprise, collaborates with a number of suppliers who are interested in that new concept of producing parts for wheelchairs. The case study has underlined that there are a lot of materials that are still being developed as it is comparatively a new space and therefore further research is required to address material challenges (Hague et al. 2003). The case study works with suppliers to develop appropriate products for this sector in collaboration with hospitals, surgeons, and clinical laboratories to gain a better understanding of patient requirements (Kulpip and Ankur, 2014). The case study has recognised that a potential partnership with its suppliers could be particularly beneficial in relation to the AM implementation process (Rahman and Bennett 2009) as the case study at the moment has a limited knowledge of materials and processes and therefore relies heavily on the different parties involved.

The case study has shown support for the implementation factors included in the procurement construct of the framework and provided further insight to relationships between the technology and procurement factors when examined from a supply chain perspective. The case study is a new start - up and therefore a vendor supply chain is not established yet as it collaborates with a number of suppliers who also develop knowledge for this concept. The case study has recognised that a potential partnership with its suppliers could be particularly beneficial as at the moment has limited knowledge of materials and processes. The case study has also shown support for the possibility of developing its own materials and processes.

6.3.2 Design Factors

Examining the AM implementation process of the case study in relation to design factors, the informant has stressed that software related issues are implemented in-house. Their principle for designing the right product is based on a compatible solution between AM technology and 3D CAD software, where the end – user is placed at the beginning of the process and therefore once the particular needs of the end – user are identified then a decision is made with regards to an appropriate software solution.

‘‘The thing that got us really interested in the 3D printing and CAD to begin with was the fact that you could put the user or the everyday person or the end-user right at the beginning of that process’’.

The informant has pointed out that this can be an exciting experience where participants who do not have the appropriate knowledge in relation to 3D CAD software and how to customise the product, can learn about the whole AM process, which is based on exchange of knowledge and information and includes details from the design of the product to the end result.

‘‘But it’s very interesting because even if you might not know enough about CAD to be able to customise your wheelchair parts by doing that yourselves you’re learning about the whole process of manufacturing and the whole process of 3D printing’’.

Here, the process is based on generative design to create AM printable designs for the wheelchair parts. In generative design the known forces, such as the weight of the user acting down, are input into a computer program which analyses and designs a structure using the minimum amount of material possible. The resulting shapes are stunning organic forms, a huge contrast to traditional design. Hence, these customisable components can be created by mapping the individual user's biometric information and inputting the data into 3D-printing software. Thus, when examining software solutions particular attention is paid to ensure that the selection of different parts such as frame, seat and basket will fit together and make a usable wheelchair.

The informant has recognised that AM is the most appropriate and powerful technology available to capture each individual's unique body shape and an integrated software solution can only be achieved when within the supply chain, the customer, the designer and the manufacturer work closely together. The case study in terms of their supply chain is working towards this concept aiming to shorten the supply chain process for end-users so that they have more control and choice in the supply chain through more customised products. Table 6.13 presents the design implementation issues and activities at company C.

Table 6.13: Summary of AM Design issues and activities at Company C

Source: The Author

Factor	**AM Design Issues/Activities**
In House/Outsourced	• In-house
Software Selection	• Customs wheelchair parts for patient-specific solutions. • Based on generative design to create AM printable designs for the wheelchair parts. • Create customisable components by mapping the individual user's biometric information and inputting the data into 3D-printing software.
Software Integrated Solution	• Compatible solution between AM technology and 3D CAD software. End – user is placed at the beginning of the process.

	• Decision is made with regards to an appropriate software solution once the particular needs of the end – user are identified. • AM is the most appropriate and powerful technology available to capture each individual's unique body shape. • Integrated software solution: Customer, designer and manufacturer work closely together.
Pre - Processing	• File repair software in place - no issues have been reported.
Software Development	• Minor software issues related with the decision-making process and knowledge transparency. • Overall the company did not recognise any significant problems in relation to software issues.
Software Solutions	• Recognised the potential benefits of developing its own software.

The key issues/activities identified in the implementation process of the case study in relation to design factors show that the case study designs new products in-house (Janssen et al. 2014). It was noted that designing a medical device can be a complex process, including step-by-step design interventions (Lantada and Morgado, 2012) and therefore the case study employs generative design to create AM printable designs for the wheelchair parts by mapping the individual user's biometric information and inputting the data into 3D-printing software. The process is based on exchange of knowledge and information and includes details from the design of the product to the end result and therefore computer- aided design (CAD) and computer-aided engineering (CAE) software are employed to create and analyse a digital solid model respectively (Petrick and Simpson 2013). The case study implements a software integrated solution, where the end – user is placed at the beginning of the process and this can only be achieved when within the supply chain, the customer, the designer and the manufacturer work closely together.

The case study has shown support for the implementation factors included in the design construct of the framework and provided further insight to relationships between the technology and design factors when examined from a supply chain perspective. The case study has not mentioned any significant issues in relation to its current software; however, it was recognised in accordance with the previous case studies, that further software developments would be beneficial for the industry and is keen on developing its own software.

6.3.3 Production Factors

Examining the AM implementation process of the case study in relation to production factors the case study was originally formed as a result of a group of people who were looking at how AM and distribution manufacturing networks could be used in the healthcare sector. Therefore, the case study rather than starting with an existing model and existing product and then trying to adapt that product to meet particular needs in relation to wheelchair users it started at the basis what could AM do for a particular customer group which is wheelchair users.

''We actually started the other way around. So, we are kind of working backwards. So, we are starting at the basis what can additive manufacturing do and can we make that work for a particular customer group which is wheelchair users''.

The informant has stressed that AM methods and fused deposition modelling (FDM) in particular have enabled the company to produce more customised wheelchair parts in less time and in a cost-effective time. The first part that the case study produced was a case support for somebody whose cast support had broken. It was highlighted that if this particular component was outsourced to a manufacturer it would take up to three weeks to be build based on traditional manufacturing methods. However, when AM methods are employed the aforementioned component can be produced within 24 hours which means that the patient can go back straight away to his daily activities. The informant has noted that although this case support is strong enough and meets the specifications further testing is required to ensure that it will survive in the long term and will not break. This has to do with some of the limitations associated with the technology when it comes to processes and strength of materials.

''And their manufacturer gave an estimated delivery time of three weeks in the wheelchair. And in three weeks it would effectively mean that the individual would have been at bed or stuck at home... But we were able to print, 3D print cast support in a day, 24 hours, that was to specification and it was strong enough''.

The informant has highlighted that customisation is probably the greatest advantage that the technology can deliver; however, every single part is completely different and that makes the technology more complex. Additionally, a number of factors need to be considered which can affect the quality of the final product which relate to the inability to really control the environment. Here, the product needs to be tested on proper industrial conditions to ensure that there are no future problems in relation to its attributes. The case study at the moment is working towards this stage where testing can take place on proper industrial conditions to validate the process.

‘‘We had a case where we printed a second cast support and it broke. It was the same filament and the same nozzle’’.

Table 6.14 presents the production implementation issues and activities at company C.

Table 6.14: Summary of AM Production issues and activities at Company C

Source: The Author

Factor	**AM Production Issues/Activities**
Process Selection	• In-house, Extrusion - Based Systems – Fused Deposition Modelling (FDM). • The company started at the basis what could AM do for wheelchair users and how AM and distribution manufacturing networks could be used in the healthcare sector. • Enabled the company to produce more customised wheelchair parts in less time and in a cost-effective time.
Process Limitation	• Every single part is completely different and that makes the technology more complex. • Strength of materials. • Factors which can affect the quality of the final product relate to the inability to really control the environment. • Product needs to be tested on proper industrial conditions to ensure that there are no future problems in relation to its attributes. • The company is working towards this stage where testing can take place on proper industrial conditions to validate the process.
Post – Processing	• Still a lot post processing is required.
Process Cost	• The company has not mentioned any major implications in relation to the cost of the process.

The key issues/activities identified in the implementation process of the case study in relation to production factors show that the case study is a new start - up in terms of implementation and production applications, which designs customs wheelchair parts for patient-specific solutions. The case study has employed Extrusion - Based Systems and in particularly Fused Deposition Modelling (FDM) and begun designing the world's first open source wheelchair comprised of a mix of engineers, designers, researchers, suppliers, healthcare professionals and wheelchair users. The utilisation of the AM technology has led to more customised wheelchair parts in less time and in a cost-effective time with immediate effect on their supply chain (e.g. Hopkinson and Dickens, 2001; Ruffo et al. 2006). The case study has recognised the limitations of the AM technology in relation to the materials and the quality of the final part (Royal Academy of Engineering 2013) and is working towards the stage where testing can take place on proper industrial conditions to validate the process.

The case study has shown support for the framework factors included in the production construct and provided further insight to relationships between the technology and production factors when examined from a supply chain perspective. For the case study, which a new start-up, production factors are priority to address quality issues of the final part.

6.3.4 Distribution/Logistics Factors

Examining the AM implementation process of the case study in relation to logistics/distribution factors, the case study operates in UK; however, it has been working towards developing a global network. The informant has stressed that the case study has an aspiration to be global and the idea of collaborating with different partners around the world and choosing from a wider specialist supplier base is quite appealing; however, issues concerning technical aspects as the technology involves critical safety components cannot be ignored. Additionally, as it is an emerging technology and for the wheelchair sector still testing is taking place, communication between the different parties particularly for more specific medical cases needs to be personal. However; the case study, as a social enterprise, is keen on a wider network involving the contribution of the different communities on a local and global scale. This knowledge exchange and sharing will also help the case study to further develop its in-house capability.

''So there, maybe they have a spinal curvature that means that the seat is the main issue that they need terms of medical and technical design and this person could be

based in London, but if our specialist or the person that we know who specialises in hospital support is based in America, we would still be able to connect them ''.

The informant has pointed out that there are also limitations in terms of regulations. It was noted here that a lot of regulations need to be re-examined in the healthcare sector as they tend to be quite outdated when considering the wheelchair fabrication. Healthcare centres play a predominant role in the evolution of the technology as they can either approve or not when a medical device is produced; however, they need to take into consideration that in terms of AM, the technology is constantly advancing to meet the world's different needs and therefore healthcare services need to constantly work close with regulators to validate AM processes and materials. Additionally, regulations need to be flexible enough to address the above challenges.

''But I think a lot of regulations are quite outdated in the healthcare sector and I'm aware that a lot of the ISO standards are being updated at the moment but I don't know whether or not that is to take account of wheelchair fabrication''.

In relation to inventory levels, the informant has emphasised that the case study only produces customised products based on AM and therefore there is no need to keep any stock as production is based on demand. Table 6.15 presents the distribution/logistics implementation issues and activities at company C.

Table 6.15: Summary of AM Distribution/Logistics issues and activities at Company C Source: The Author

Factor	AM Distribution/Logistics Issues/Activities
Centralized Manufacturing	• In/house-centralised approach to AM. • Social enterprise: Keen on a wider network involving the contribution of the different communities on a local and global scale. • In-house capability can be further developed through knowledge exchange and sharing.
Distributed Manufacturing	• Technical aspects - critical safety components. • Wheelchair sector: Still testing is taking place.

	• Communication between the different parties particularly for more specific medical cases needs to be personal.
Logistics	• Inventory: Only AM customised products - no need to keep stock as production is based on demand.

The key issues/activities identified in the implementation process of the case study in relation to logistics/distribution factors show that the case study follows a centralised approach to AM; however, as a social enterprise, is keen on a wider network involving the contribution of the different communities on a local and global scale. The case study highlighted that aims to further develop its in-house capability based on the knowledge exchange and sharing of the different parties involved. The case study has noted that although distributed deployment of AM can be very interesting for spare parts supply (Holmström et al. 2010), issues concerning technical aspects need to be considered as the technology involves critical safety components. Additionally, AM is an emerging technology and for the wheelchair sector still testing is taking place, and thus communication between the different parties particularly for more specific medical cases needs to be personal. In relation to inventory the case study produces only customs wheelchair parts for patient-specific solutions and therefore no stock is required as the process is based on a make- to order model (Jungling et al. 2013).

The case study has shown support for the implementation factors included in the distribution/logistics construct of the framework and provided further insight to relationships between the technology and distribution/logistics factors when examined from a supply chain perspective. The case study has found interesting the scenario of distributed manufacturing as it is keen on a wider network involving the contribution of the different communities on a local and global scale; however, critical safety components need to be addressed.

6.3.5 Customers

Examining the AM implementation process within the case study in terms of the extent to which hospitals utilise the technology propositions, the informant has pointed that the case study has very limited experience of working with the NHS. It was noted that at the moment it is mainly the heath- tech companies which are assigned to work within the NHS and not so much the medical device manufacturers and filament producing companies. There are maker spaces and innovation sectors in NHS and an interesting shift towards user-center design to personalize services; however, it was suggested that a more holistic approach in terms of services should be undertaken to look at whole communities but for a particular health issue. It was recognised that the NHS is making efforts to get involved in the whole process; however, they need to collaborate more with the community to validate the process.

The informant in relation to possibility of allocating machines to the hospitals has highlighted that there are many constraints in terms of the implementation of this scenario, which include decisions in relation to the allocation of responsibilities between the different parts involved in the validation of the process. It was also stressed that healthcare practitioners need to develop digital and fabrication skills which could potentially lead to the establishment of a department within the hospital run by hospital technicians who have an AM technology experience.

An interesting point was found to be the role of Universities in terms of providing the right skills for potential users of the technology within the healthcare sector. It was noted that currently at Universities digital fabrication learning can be found mainly in design or engineer course which are not suited for medical applications and healthcare centres. Table 6.16 presents the customers implementation issues and activities at company C.

Table 6.16: Summary of AM Customers issues and activities at Company C

Source: The Author

Factor	**AM Customers Issues/Activities**
Collaboration of Medical Manufacturers and Hospitals	• Very limited experience of working with the NHS. • Heath tech companies are mainly assigned to work within the NHS. • Maker spaces and innovation sectors in NHS - an interesting shift towards user-centre design to personalize services. • NHS needs to collaborate more with the community to validate the process • Services should look at whole communities but for a particular health issue. • Regulations tend to be quite outdated when considering the wheelchair fabrication.
Integration of AM within Hospitals	• Allocation of responsibilities between the different parts involved.

	• Healthcare practitioners need to develop digital and fabrication skills.
Web 2.0 Technologies	• The company has not yet proceeded in the development of online training tools-portals for knowledge sharing.
Cloud – Based Design and Manufacturing (CBDM)	• The company has not implemented CBDM for both generic and patient specific devices. ➢ Use this data to create parts or sub-assemblies for the device and ship them to the point of use.
Open Source Software and Maker Culture	• The company as a social enterprise has developed an open source software. ➢ Share and exchange knowledge with the different partners in the network including healthcare professionals.

The key issues/activities identified in the implementation process of the case study in relation to customers factors, show that the case study has very limited experience of working with healthcare centres. It was emphasised that currently it is mainly the heath - tech companies which are assigned to work within the healthcare centres and not so much the medical device manufacturers and filament producing companies. It was underlined that the application of the technology can lead to improved patient care and cost-effectiveness for the healthcare centres by reducing the duration of the surgical procedure and thus increase capacity (Khanna and Balaji, 2015), however healthcare centres need to collaborate more with the community to validate the process. In relation to the scenario of allocating AM machines within hospitals, the case study pointed out that healthcare practitioners need to develop digital and fabrication skills which could potentially lead to the establishment of a department within the hospital run by hospital technicians who have an AM technology experience. The case study, as a social enterprise, has developed an open source software to share and exchange knowledge with the different partners in the network including healthcare professionals to actively participate in the product development which can be used to quickly demonstrate the validity of the process (Gibson and Srinathb, 2015).

The case study has shown support for the implementation factors included in the customers construct of the framework and provided further insight to relationships between the technology and customers factors when examined from a supply chain perspective. It was strongly highlighted in accordance with the previous case studies that medical device manufacturers need to work in close collaboration with healthcare centres to scale up the

AM technology which will lead to the evolution of the supply chain. The key category is now evident in relation to customers factors, which will be further discussed when the cross-case analysis is conducted.

6.3.6 Summary of the case study

The third case study has presented the implementation process within the supply chain of an innovative UK start up social enterprise of orthopaedic medical devices which specialises in the production of parts for wheelchair users. The case study aims to design the world's first open source wheelchair and close the gap between designers and wheelchair users. The case study has confirmed the existence of the key category in relation to customers factors. The case study supports the framework propositions and provides further insights to implementation of technology on supply chain.

6.4 Summary of the Chapter

This chapter has examined the implementation framework on the supply chain of three medical device manufacturers based on within - case analysis. All case studies have strongly highlighted that medical device manufacturers need to work in close collaboration with healthcare centres to scale up the AM technology which will lead to the evolution of the supply chain. A key category in relation to customers factors emerged which would be discussed in the next chapter, cross – case analysis. All case studies have provided support for the proposed implementation factors.

CHAPTER 7

CROSS-CASE ANALYSIS

7.0 Introduction

This chapter following the within case-analysis examines similarities and differences between the case studies in terms of their implementation process. For this purpose, the issues/activities, identified in the implementation process for each case study in relation to proposed factors are compared to provide a further insight to implementation of technology from a supply chain perspective. The purpose of this chapter is to reinforce the conclusions drawn so far and to further discuss the key category identified in the previous chapter. The final implementation framework based on the key category is proposed.

7.1 Cross – Case Analysis

The classification of the main study cases is provided in Table 7.1

Table 7.1. Main study case classification

Source: The Author

Company name	Company Case	Company Type	Company Size	Products	Informants/ position
Company A	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive, Joint replacement, repair and reconstruction	AM Production Manager
Company B	Medical Device Manufacturer	Orthopaedics	SME < 50 employees	Standards and Additive Insoles	AM Operations Manager
Company C	Medical Device Manufacturer	Orthopaedics	SME – Social Enterprise < 50 employees	Additive Wheelchair parts	Company Director

7.1.1 Comparison of Issues/Activities for Procurement Factors

The framework has provided support for the case studies in relation to procurement implementation factors. Based on the issues/activities identified in the implementation process for each case study in relation to procurement factors the following conclusions can be drawn:

Case study A has recognised that within this industry only a few suppliers have an adequate knowledge of how the medical industry works and therefore after a thorough examination has selected the supplier which could assist the company with the right equipment and materials to validate the process. It was highlighted (Zairi 1998) that the level of success of AMT implementation is strongly connected with suppliers' technical knowledge to solve problems and provide efficient support and back-up services throughout the implementation process. Hence, increased collaboration and relationship with equipment suppliers is required in AM implementation as they are expected to affect the rest of the supply chain (Mellor, 2014).

Case study B has initially selected the 'wrong' process for production applications and realised that not all printing processes or some families of materials are appropriate for this purpose at the moment. It was suggested (Borille and Gomes 2011) that decision models should be utilised not only to address the technical limits of each technology but also to evaluate the capabilities of each process in relation to product requirements. As a result, the case study had to re-examine the criteria in relation to selection of equipment – materials and now focuses on where material and processes can provide them deliverable opportunities and thus selects its suppliers based on the notion that the final product is sufficiently innovative to make that initial investment worthwhile. It was noted (Borille et al. 2010) that a combination of the right selection of the process along with the accurate description of user requirements can lead to successful applications of the technology.

Case study C is a new start -up and has not yet developed a vendor supply chain which will ultimately affect the quality of end products and production applications. The case study currently develops knowledge in relation to materials-processes and hence the result is based on trial and error. It was stated (Hague et al. 2003) that it has become more difficult to justify development of new materials in AM as the quantity sold is low compared to conventional manufacturing methods. Therefore, for AM to be developed in a widely-used process further research is required to address material challenges. It was suggested (Kulpip and Ankur,

2014) that medical device manufacturers can benefit from suppliers' experience of working with hospitals, surgeons, and clinical laboratories to gain a better understanding of patient requirements.

The case studies have recognised that a potential partnership with their suppliers could be beneficial to further address limitations of technology and have shown support for the possibility of developing their own materials and processes.

7.1.2 Comparison of Issues/Activities for Design Factors

The framework has provided support for the case studies in relation to design implementation factors. Based on the issues/activities identified in the implementation process for each case study in relation to design factors the following conclusions can be drawn:

The case studies have provided support for the in-house approach to design. It was underlined (Janssen et al. 2014) that manufacturers need to decide first if the firm has the right capabilities to design new products in-house or to outsource the 3-D design to available service providers offering their expertise within this field.

The case studies have noted that software selection needs to be carefully planned as existing computer-aided design (CAD) systems are not at all suited for exploring the design freedom of AM processes and when a 3D print file is developed for one printer is not necessarily viable for use on a different printer (Hahn et al. 2014). When examining software integration, it was highlighted (Vinodh et al. 2010) that the integration of CAD and AM technology allow traditional organizations to design and model new concepts quickly and achieve agility, which can assist them to be more competitive and sustainable in a global environment. Thus, successful implementation depends on the extent to which an organisation can manage existing CAD modelling systems including compatibility issues related to software and hardware (Haque 2003).

The case studies have not proceeded in software development, as they have not mentioned any significant issues in relation to their current software; however, it was noted that further software developments would be beneficial for the industry and they are all keen on developing their own software. According to the Royal Academy of Engineering (2013) it will be the software developments that will drive the industry forward and not the technology itself.

7.1.3 Comparison of Issues/Activities for Production Factors

The framework has provided support for all case studies in relation to production implementation factors. Based on the issues/activities identified in the implementation process for each case study in relation to production factors the following conclusions can be drawn:

Case study A has employed Powder Bed Processes which allowed the company to design products and forms which would not be possible through traditional manufacture. It was proposed that AM can assist organisations to reduce overall cost of production and total lead times and therefore the utilisation of an appropriate AM technology can lead to more customised products with immediate effect on their supply chains (Hopkinson and Dickens, 2001; Ruffo et al. 2006). However, it was stressed that as the volume increases, implementation needs to be further addressed particularly in relation to process cost (Royal Academy of Engineering 2013).

Case study B has employed Extrusion - Based Systems and in particularly Fused Deposition Modeling (FDM) with the potential to achieve production applications. However, their AM machine proved to be very good for producing prototypes but was not suitable for industrial – manufacturing applications. It was highlighted (Hopkinson and Dickens 2003) that high costs and the technology readiness level of the materials and the whole process remain the key constraints of the technology.

Case study C, is a new start-up and therefore, production factors are priority for the case study to address quality issues of the final part. The case study has stressed that a number of factors need to be considered which can affect the quality of the final product and relate to the inability to really control the environment. Hence, products need to be tested on proper industrial conditions to ensure that there are no future problems in relation to its attributes. As case study C is a new start-up is expected to have more problems when compared with the other two case studies in relation to quality of the final product as further testing needs to take place.

In relation to volume manufacturing, the case studies highlighted that it remains a challenging area where traditional manufacturing methods still seem to have an advantage as they have also been advancing and become very efficient in terms of saving including labour and other costs.

Examining post processing requirements, the case studies noted that in orthopaedics, the AM process is quite complicated as it involves various stages till the product is ready. Most of the products require some other post machining - traditional machining function and other processes such as cleaning, packaging, laser marking and sterilising.

The case studies underlined that process cost considerations could be addressed with the utilisation of cost models. It was highlighted (Ruffo et al. 2007) that when considering the make or buy decision, several factors such as cost, capacity, knowledge, response and quality need to be considered.

7.1.4 Comparison of Issues/Activities for Distribution/Logistics Factors

The framework has provided support for the case studies in relation to distribution/logistics implementation factors. Based on the issues/activities identified in the implementation process for each case study in relation to distribution/logistics factors the following conclusions can be drawn:

The case studies follow an in/house-centralised approach to AM, as the medical industry is highly regulated, which enables them to further enhance on the knowledge required in relation to the technology. It was pointed out (Holmström et al. 2010) that there are two extreme types of AM positioning models which companies can choose from. First the centralized model in which production facilities are concentrated in a particular location and serve the world market from that location. The other option is decentralizing production, where production facilities distribute in various regional or national locations close to the major markets.

Case study A has stressed that in-house centralised manufacturing helps to maintain control of the process; however, it will probably look of ways to outsource its technology if treatment becomes more patient-specific. In accordance with case study A, case study B has underlined that the only 3D printed AM products, insole products, which are on the market are a combination of a printed part and a traditional manufactured part. Case study C as a new start-up and social enterprise, is keen on a wider network involving the contribution of the different communities on a local and global scale; however, issues concerning technical aspects as the technology involves critical safety components need to be considered.

The case studies have found the potential of distributed manufacturing quite appealing; however, it was suggested (Hasan et al. 2013; Hasan and Rennie, 2008) that a centralised approach is always more likely to take place first as a fully functional supply chain is an essential requirement before companies explore their capabilities on distributed manufacturing. The proposed framework can provide support for the implementation process of this scenario, as it highlights that in order for distributed manufacturing to be feasible demand must be sufficient enough at a given location, which requires an established customer base, or at least an understanding of the demand for products according to location. In this case, issues regarding capacity utilisation, production cycles as well as all costs across the supply chain need to be considered (Fig.7.1).

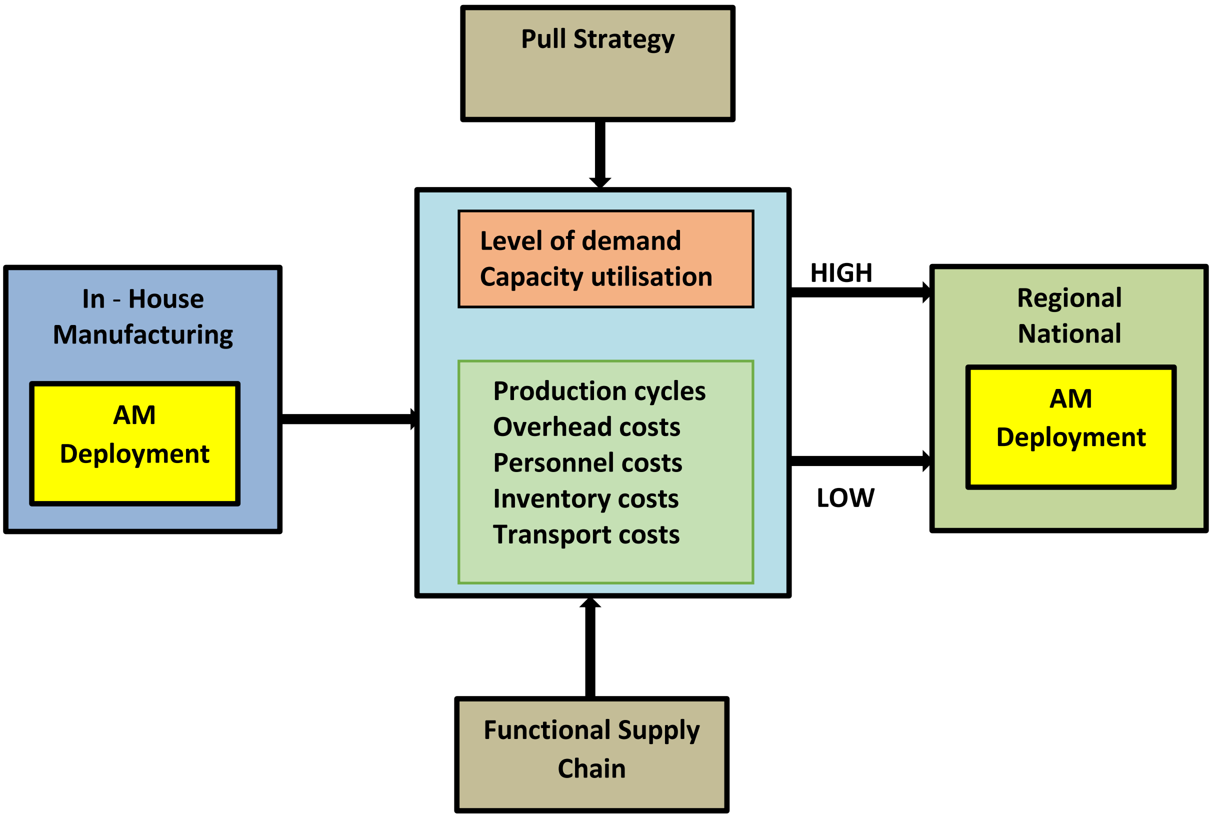


Figure 7.1: Theoretical framework: AM factors to support the case of Distributed Manufacturing. Source: The Author

The case studies in relation to inventory and AM products, have pointed out that no stock is required as the process is based on a make- to order model. It was suggested (Jungling et al. 2013) that this make-to order model can help medical device manufacturers to significantly reduce inventory waste and risk in relation to unsold finished goods. However, the case studies will need to further address issues/activities in relation to logistics as the volume increases.

7.1.5 Comparison of Issues/Activities for Customers Factors

The framework has provided support for the case studies in relation to customers implementation factors. The case studies have strongly highlighted that medical device manufacturers need to work in close collaboration with healthcare centres to scale up the AM technology which will lead to the evolution of the supply chain. It was emerged through the within - case analysis that this is the key category, which will be further discussed.

Based on the issues/activities identified in the implementation process for each case study in relation to customers factors the following conclusions can be drawn:

Case study A has stressed that the extent to which hospitals utilise or even be part of the company's process and technology propositions is quite limited. It was highlighted (Gibson et al. 2015) that AM models have been known to assist surgeons to better plan and understand the situation of the procedure involved in the surgery particularly in complex cases; however, surgeons are not involved in the decision-making process. It was pointed out that in healthcare centres decisions on choosing a technology are based mainly on the cost rather than the technology itself. Consequently, even when a new technology is introduced with the potential to produce better results over a long period cannot easily be accepted especially when it is more expensive.

Case study B has emphasised that the culture within hospitals and healthcare centres is not always innovation 'friendly'. It was underlined that the healthcare centres are used to the traditional supply relationship where they order an object and receive it. It was pointed out that healthcare centres, as with every emerging technology, they need to participate to develop that relationship which is necessary for the evolution of technology. It was stated that the biggest barrier is around implementation and adoption in clinical settings as it is essential for this to happen in order to obtain insights which feeds into the beginning of the chain. It was stressed that hospitals have quite high expectations in terms of regulation, safety and quality; and further barriers can be found in other parts of infrastructure such as sharing electronic data, security clearance, which can take months to set up and delay the ability of a device manufacturer to work closely with hospitals and further develop the technology. It was emphasised that at the moment, the technology can be found on printing bureaus and material manufacturers who communicate with each other and innovate things;

however, they do not have sufficient information from the marketplace and therefore they need to engage more actively with clinicians to support this innovation.

Case study C, has stated that at the moment it is mainly the heath - tech companies which are assigned to work within the healthcare centres and not so much the medical device manufacturers and filament producing companies. It was noted that there are maker spaces and innovation sectors in NHS and an interesting shift towards user- centre design to personalize services; however, it was suggested that a more holistic approach in terms of services should be undertaken to look at whole communities but for a particular health issue. It was recognised that the NHS is making efforts to get involved in the whole process; however, they need to collaborate more with the community to validate the process.

All case studies have recognised that they could be more actively engaged with healthcare centres if they utilised online training tools-portals for knowledge sharing and cloud – based design and manufacturing (CBDM) for both generic and patient specific devices, It was pointed out (Gibson et al. 2015) that the 'cloud –based design and manufacturing concept' (CBDM) can be leveraged for both generic and patient specific devices to assist in product development and medical device manufacturers can use this data to create parts or sub-assemblies for the device and ship them to the point of use.

Examining the issues/activities identified in the in the implementation process of the case studies in relation to open software and maker culture, only case study C, as a social enterprise has developed an open source software to share and exchange knowledge with the different partners in the network. It was suggested (Gibson and Srinathb, 2015) that medical device manufacturers can be part of the open source software to share their knowledge with doctors to use the technology to quickly demonstrate the validity of the process and thus increase the possibility of the product passing clinical trials.

The case studies although have found interesting the possibility of allocating AM machines within healthcare centres, they highlighted that the implementation of this scenario could be quite complicated in terms of a clear allocation of responsibilities to the different parts involved in the process. It was suggested (Bota et al. 2015) that a hybrid scenario could be developed where some AM services outsourced to contractors while others developed in-house.

Based on the above, and in order to address the barriers in relation to the adoption of technology in clinical settings the following process diagram (Figure 7.2) is proposed:

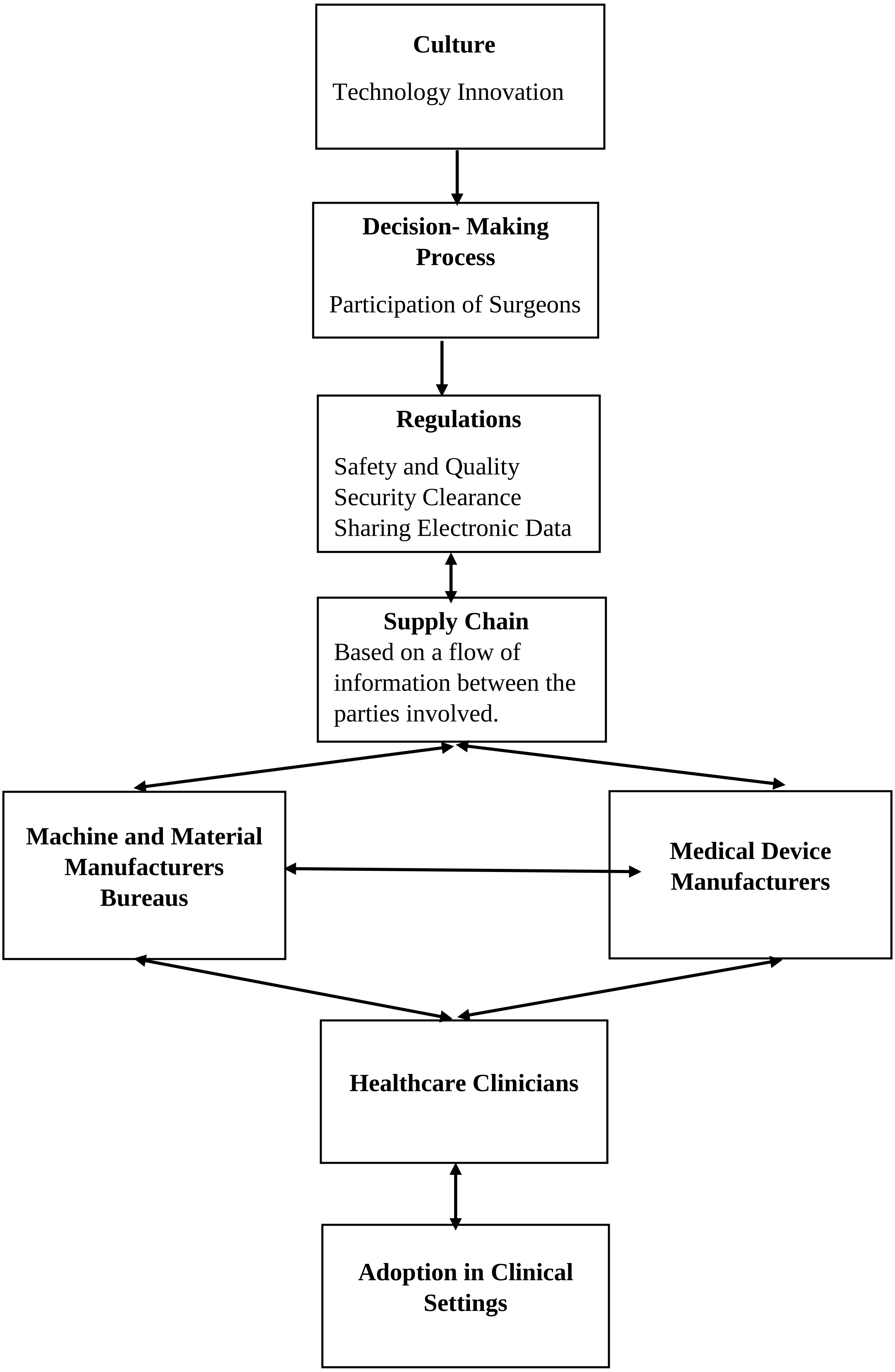


Figure. 7.2: Proposed process diagram for the adoption of technology in clinical settings

Source: The Author

Thus, it clear from the above that a strong collaboration between the healthcare centres and the machine - material manufacturers, bureaus and medical device manufacturers is required to scale up the technology and lead to the evolution of the supply chain as it is shown on the following Figure 7.3.

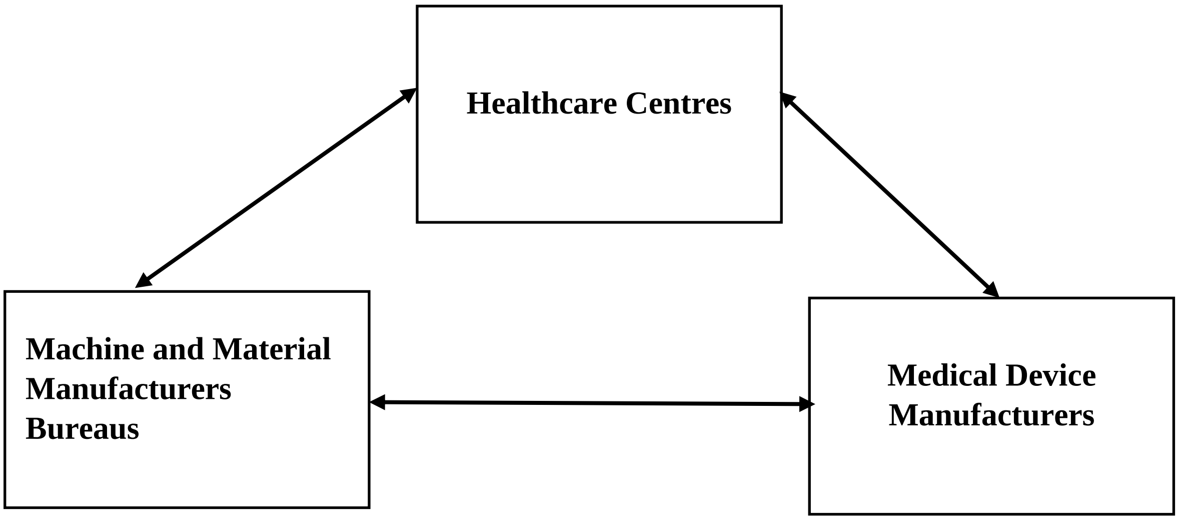


Figure 7.3: Supply Chain based on a flow of information between the parties involved Source: The Author

Referring back to the proposed framework, it can be clearly seen that the different parties involved have been included under the Procurement (Suppliers) and Customers (Healthcare) construct. Thus, the following diagram can be proposed (Figure 7.4):

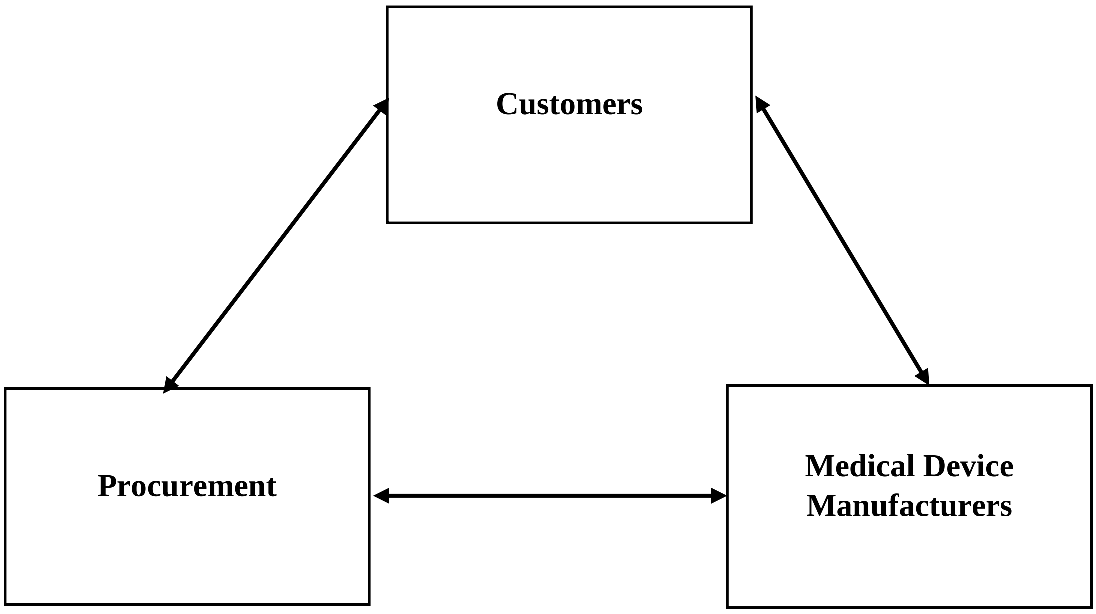


Figure 7.4: Supply Chain based on a flow of information between the parties involved, in accordance with the proposed framework. Source: The Author

The proposed final framework based on the above and in accordance with the key category will be as follows (Figure 7.5).

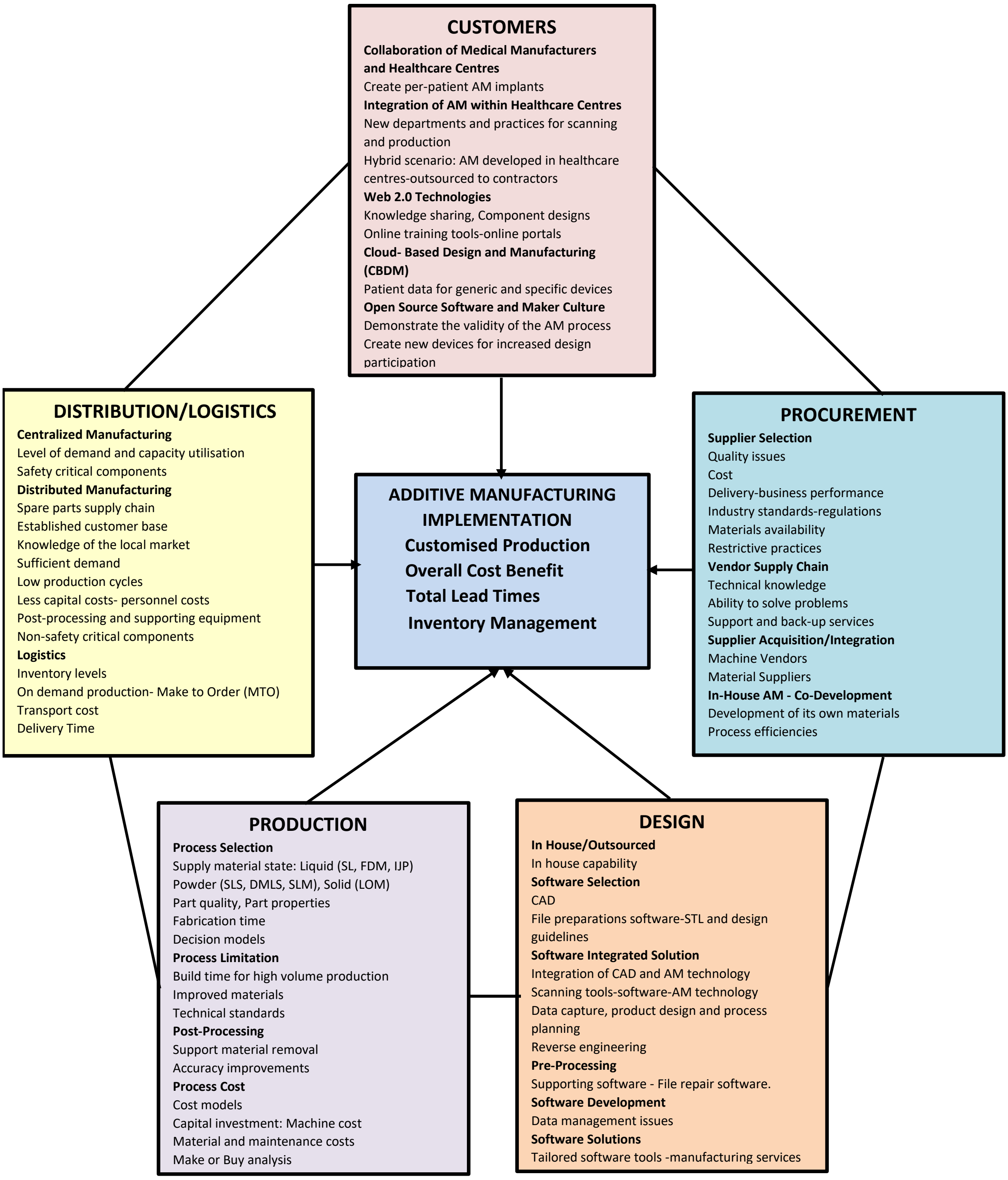


Figure 7.5 The final proposed AM implementation framework

7.2 Summary of the chapter

This chapter has presented the cross-case analysis of the case studies and further discussed the emerged key category. Issues/activities, identified in the implementation process for each case study in relation to proposed factors were compared and provided further insight to the implementation of the technology from a supply chain perspective. The final implementation framework was proposed.

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CHAPTER 8

CONCLUSIONS, CONTRIBUTIONS AND FUTURE RESEARCH

8.0 Conclusions

This final chapter of this thesis will first discuss how the objectives of the study have been fulfilled, followed by implications, contributions, limitations of the study and areas for future research.

The objectives set out for this study have been fulfilled. In relation to the first objective which was to investigate the impact of AM process on supply chain, several studies have been presented as part of the literature review chapter which have clearly shown the potential implications of technology when is examined from a supply chain perspective. The conclusions have suggested that AM technology as a driver of supply chain transformation it can achieve precision, speed, affordability, and materials range. Therefore, it has the potential to redesign products with fewer components and to manufacture products near the customers. The results of the first objective have also shown that studies on AM implementation on supply chain is disappointingly absent, where most studies on supply chain focus mainly on the potential disruptions of AM in distribution/logistics and therefore on location of manufacturing. Hence, an investigation on the key AM implementation factors within the various stages of a supply chain from the selection of raw material-equipment suppliers towards the customers needed to be examined.

The identification of the research gap has led to an investigation of the key factors affecting implementation of AM on supply chain and therefore to the second objective which was to develop a conceptual framework for implementation of AM on supply chain. Here, an AM implementation framework on supply chain was proposed, which included the results from the pilot case study. The proposed framework suggests that when examining the AM implementation from a supply chain perspective the factors which will influence this process may be grouped into five constructs: Procurement, Design, Production, Distribution/Logistics, and Customers. Each construct included the implementation factors that medical device manufacturers need to consider to further improve their implementation process on supply chain, which can lead to improved service capabilities and increased customer value. Within each implementation factor the issues/activities, which formed the factors have also been included.

The third objective was to investigate how those proposed factors impact implementation of AM on supply chain and therefore the implementation framework was examined on three medical device manufacturers, based on within - case analysis. The purpose was to identify and further enhance the proposed implementation factors and reach a comprehensive knowledge in relation to the implementation of technology when it is examined from a supply chain perspective. The case studies have stressed that strong collaboration with healthcare centres are key in growing the supply chain and therefore a key category was emerged. All case studies have shown support for the framework factors included in the constructs and provided further insight to implementation of technology on supply chain.

The third objective was strengthened by the cross - case analysis which examined similarities and differences between the case studies in terms of their implementation process. For this purpose, the issues/activities, identified in the implementation process for each case study in relation to proposed factors were compared to provide a further insight to implementation of technology from a supply chain perspective. The key category was further discussed and the final implementation framework based on the key category was proposed. In that respect the overall aim of the thesis which was to develop an AM implementation framework from a supply chain perspective has been fulfilled.

8.1 Implications of the Study

Some of the key implications based on the AM implementation framework and results can be summarized as follows:

Suppliers need to develop a comprehensive knowledge of how the medical device industry works in relation to AM equipment and materials as there are certain materials which are biocompatible and relatively new in their use in medical devices and compared with the evolution of AM. Collaboration with medical device manufacturers through acquisition and vertical integration could result in co-development of materials and process efficiencies and eventually reduce restrictive practices which constrain the AM implementation process on supply chain.

The choice of appropriate software applications and data transfer depends on decisions on the technology itself. Medical device manufacturers should develop an integrated software solution which involves data capture, product design and process planning. The possibility of tailored software can also be examined depending on their in-house capability to offer software solutions and manufacturing services in the healthcare market.

AM technology enables device manufacturers to build a combination of different products at the same time which would not be possible through traditional manufacture and therefore flexibility of manufacture is one of the main advantages of the AM process. However different processes produce different results and surface finishes and when considering volume manufacturing, AM process can be expensive as the cost associated with running the machine are high. The technology can be advantageous in the creation of the initial part, however when examining volume manufacture its contribution is quite limited at the moment where traditional manufacturing methods are also advancing and still seem to be the preferred choice. Here, comprehensive cost models to address some of the challenges related with machines, maintenance and materials should be utilised.

Medical device manufacturers currently tend to follow an in-house approach to AM as they can acquire a better knowledge of the process. The idea of outsource manufacturing seems quite appealing; however, there are several constrains cultural and technical which restrict the implementation of this concept. In this case, issues regarding post – processing and support equipment need to be considered and a functional supply chain is required to manage all costs across their supply chain along with an increased demand in a particular location. There is no urgent need at the moment for the concept of distributed manufacturing in close proximity to the hospital or patient as the product can be delivered in short times. For this to be feasible technologies and materials need to grow with the patient to be applied in a more effective way and particularly in emergency cases, where manufacturing next to the patient will be more applicable. In relation to the scenario of allocating machines to the hospitals there are several constraints regarding the validation of the process including a clear allocation of responsibilities to the different parts such as hospitals, suppliers and manufacturers for the different parts of the process.

In the healthcare sector the decision - making process regarding AM technology can be quite complex and therefore the extent to which hospitals utilise the technology propositions will play a predominant role in the evolution of the supply chain. Decisions on choosing a technology are based mainly on the cost rather than the technology itself and therefore when a new technology is introduced with the potential to produce better results over a long period cannot easily be accepted especially when it is more expensive. The utilisation of different tools such as Web 2.0 technologies to engage with healthcare, 'cloud – based design and manufacturing' (CBDM) which can be leveraged for both generic and patient specific devices to assist in product development as well as the open source software along the 'Maker culture', which involves the combination of traditional mechanical skills to create new devices for increased design participation, can increase awareness and enhance the implementation process.

The case studies have stressed that strong collaboration with healthcare centres are key in growing the supply chain. They have also reported limitations of the technology and therefore further improvements in relation to AM process are required especially when it comes to volume manufacture. The case studies have not mentioned any major issues in relation to software; however; they recognized that software improvements would be beneficial for the industry. Finally, although they have found interesting the case of distributed manufacturing they have not proceeded to implement this scenario as there is no urgent need at the moment.

8.2 Contributions of the Study

The contributions of this research are several and provide both theoretical and practical insights to the operations and supply chain management field. From a theory - building perspective it constructs an AM implementation framework and provides an insight concerning the AM implementation process of the adopting organisation. At the time of writing is the first study which examines the AM implementation process of medical device manufacturers on supply chain and proposes an implementation framework. Therefore, this research contributes to the body of knowledge by bridging the gap on AM implementation studies from a supply chain perspective.

The research framework focuses on the healthcare sector. The practical insights of the study can be found on medical device manufacturers as well as for healthcare centres and practitioners. Concerning the medical manufacturers, the research provides insight to further assist AM managers with the implementation process throughout their supply chain and thus use this AM implementation framework as a guide to develop their own implementation plans. Examining the practical implications for healthcare centres it has been underlined that the industry is highly complex and regulated when it concerns the adoption of new technologies. Here healthcare centres, by utilising this technology, can plan ahead and better understand the situation of the procedure involved in the surgery, particularly in complex cases, reduce operation times, improve success surgery rates and thus improve significantly patients care. At the same time, as the technology can assist in pre - surgical planning and during the surgery, it can lead to an increased capacity for hospitals and ultimately reduce costs within the healthcare sector.

8.3 Limitations of the Study

Limitations of this study can be found on the fact that although a multi - case approach can increase validity of results (Eisenhardt, 2007), still care is needed in drawing generalizable conclusions. Therefore, further research should examine the application of the AM framework to more case studies to further increase the validity of results. However, taking into consideration that a robust research methodology has been employed and saturation of the implementation factors was reached and most importantly that the framework is the first of its kind, still provides a valuable insight to the AM implementation process from a supply chain perspective.

A significant limitation of this study concerns the amount of time and resource spent gaining access to the case study sites. This limited the researcher from undertaking further work with regards to the implementation framework and further explore on each of the framework constructs and the implementation implications for the adopting organisation. However, the framework has captured the key implementation factors and thus provides a solid foundation for further research.

Another limitation of this study again due to time and resource constraints concerns the fact that the researcher did not include in his study data from the supplier's point of view and procurement construct as well as data for the customers construct and healthcare centers. This study has focused on examining the implementation of the technology for the adopting organisation and thus further data collected from the participant members within the broader supply chain perspective could potentially enhance the implementation framework. However, still the research case studies and the informants have provided a considerable amount of information for the members of the supply chain and the various implications concerning the implementation of the technology.

8.4 Areas for future research

This study has not addressed implications for the end users although that many issues have been examined in the customers (healthcare centres) construct. Thus, further research could take place to integrate end users in the implementation process when examined from a supply chain perspective. Additionally, the potential of distributed manufacturing near to the hospital or to the patient or the possibility of allocating AM machines within healthcare centres should be further examined. The study has proposed a process diagram for the adoption of technology in clinical settings; however further research needs to take place in relation to the barriers of adopting the technology within healthcare centres as it is an essential requirement for the evolution of supply chain.

References

- Abbasi.M., R. Hosnavi, and B. Tabrizi, 2013. An Integrated Structure for Supplier Selection and Configuration of Knowledge-Based Networks Using QFD, ANP and Mixed-Integer Programming Model. *Journal of Industrial Engineering*, pp.1-8. Available from [PDF] hindawi.com.
- Abdolshah, M. 2013. A Review of Quality Criteria Supporting Supplier Selection. *Journal of Quality and Reliability Engineering*, pp.1–9. Available from [PDF] from hindawi.com.
- Afzulpurkar, S., Huq, F., and Kurpad, M. 1993. An alternative framework for design and implementation of cellular manufacturing. *International Journal of Operations and Production Management*, 13 (9), pp. 4-17.
- Aliakbari M. 2012. Additive Manufacturing: State- of-the-Art, Capabilities, and Sample Applications with Cost Analysis. Department of Industrial Production, KTH, Online available from www.diva-portal.org.
- Alverson, C. 2003. Beyond Purchasing Managing Hospital Inventory. Managed Healthcare Executive.
- Alvesson, M. and Deetz, S. 2000. Doing critical management research. London: SAGE Publications.
- AM Platform. 2014. Additive Manufacturing: Strategic Research Agenda. UK: AM Sub-Platform.
- Arcam 2009. EBM Process (Online). http://www.arcam.com/technology/ebm- 71 process.aspx.
- Arya, V., Deshmukh, S. G., and Bhatnagar, N. 2015. High Technology Health Care Supply Chains: Issues in Collaboration. *Procedia - Social and Behavioral Sciences*, 189, 40–47. http://doi.org/10.1016/j.sbspro.2015.03.190
- ASTM Standard F2792 − 12a (2012). Standard terminology for additive manufacturing technologies. ASTM International.
- ASTM, 2009. ASTM Additive Manufacturing Committee Approves Terminology Standard Available from: http://www.astmnewsroom.org/default.aspx?pageid=1944
- Awad, H.A. and Nassar, M.O. 2010. A broader view of the Supply Chain Integration Challenges. *International Journal of Innovation Management and Technology*, 1(1), pp. 51-56.

- Babbar, S. and Rai, A. 1990. Computer integrated flexible manufacturing: an implementation framework. *International Journal of Operations and Production Management*, 10 (1), pp. 42-50.
- Baharanchi, S. H. 2009. Investigation of the Impact of Supply Chain Integration on Product Innovation and Quality. *Transaction E: Industrial Engineering*, 16(1), pp. 81-89.
- Baldwin J, Diverty B. 1995. Advanced technology use in Canadian manufacturing establishments. Micro-Economics Analysis Division, Statistics Canada, No.85.Ottawa.
- Barratt, M, Thomas, Y. Choi, and Mei Li. 2011. Qualitative Case Studies in Operations Management: Trends, Research Outcomes, and Future Research Implications. *Journal of Operations Management* 29(4):329–42.
- Baxter, P., and Jack, S. 2008. Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13(4), 544–559.
- Beamon, BM. 1998. Supply Chain Design and Analysis: Models and Methods. *International Journal of Production Economics*, 55.3: 281-294.
- Beaumont, N., Schroder, R. and Sohal, A. 2002. Do foreign-owned firms manage advanced manufacturing technology better. *International Journal of Operations and Production Management*, Vol. 22 No. 7, pp. 759-71.
- Benbasat, D., Goldstein, and. Mead, M. 1987. The case research strategy in studies of information systems. *MIS Quarterly*, vol. 11, no. 3, pp. 369–386, [PDF] from bath.ac.uk.
- Bhandari, R. 2016. Impact of Technology on Logistics and Supply Chain Management. *IOSR Journal of Business and Management*, 19–24. Retrieved from www.iosrjournals.org.
- Bhasin, V., and Bodla, M., R. 2014. Impact of 3D Printing on Global Supply Chains by 2020. Submitted to the Engineering Systems Division in Partial Fulfilment of the Requirements for the Degree of Master of Engineering in Logistics, [PDF] from mit.edu.
- Boer, H., Hill, M., and Krabbendam K. 1990. FMS implementation management: promise and performance. *International Journal of Operations and Production Management*, 10 (1), pp. 5-20.

- Bohm, A. 2004. Theoretical Coding: Text Analysis in Grounded Theory. *A Companion to Qualitative Research,* (1978), 270–275.
- Borille, A.V. and Gomes, J.D.O, Meyer, R., Grote, K., 2010. Applying decision methods to select rapid prototyping technologies. *Rapid Prototyping Journal,* Vol. 16 Iss 1 pp. 50, Emerald Insight – 62.
- Borille, A.V. and Gomes, J.D.O. 2011. Selection of Additive Manufacturing Technologies Using Decision Methods. Rapid Prototyping Technology - Principles and Functional Requirements Edited, pp.29–54, available from [PDF] from intechweb.org.
- Bota, N., Coppenrtath, E., Li, N., Manning, M. 2015. 3D Printing and The Medical Industry An in- depth analysis of 3DP 'S potential impact on health care.
- Bozarth, C. and Handfield, R.B. 2008. Introduction to Operations and Supply Chain, 2nd ed, Pearsons.
- Brajlih T., Valentan B., Balic J., Drstvensek I., 2011. Speed and accuracy evaluation of additive manufacturing machines. *Rapid Prototyping Journal*, 17 (1), 64 – 75. Available from Emerald Insight, http://dx.doi.org/10.1108/13552541111098644.
- Breir, F. J. 1995. The Management of the Supply Chain for Hospital Pharmacies: A Focus on Inventory Management Practices. *Journal of Business Logistics*, Vol. 16. 2, p. 153-174.
- Brennan, Charles D. 1998. Integrating the Healthcare Supply Chain. *Healthcare Financial Management,* 52(1):31-4.
- Bryman, A., Bell, E., Mills, A. J., and Yue, A. R. 2010. Business Research Methods. Oxford University Press.
- Burcher P, Lee G, Sohal A. 1999. Lessons for implementing AMT: some case experiences with CNC in Australia, Britain and Canada. *International Journal of Operations and Production Management*, 19(5, 6): 515–527.
- Burns, R. Lawton. 2002. The Healthcare Value Chain: Producers, Purchasers, and Providers. Jossey-Bass.
- Burt, D.N., 1989. Managing suppliers up to speed. *Harvard Business Review* 67 (4), 127–135.
- Buruncuk G., and Zarife G., G. 2001. Factors Affecting Implementation of Information Systems' Success and Failure. Boaziçi University Department of Management Information Systems Bebek 34342, Istanbul/Turkey.

- Byun, H. S., and Lee, K. H. 2005. A decision support system for the selection of a rapid prototyping process using the modified topsis method. *The International Journal of Advanced Manufacturing Technology*, 26, 1338-1347, available from http://link.springer.com.
- Campbell, T., Williams, C., Ivanova, O., Banning G., 2011. Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. Strategic Foresight Report, Atlantic Council. Available from [PDF] from aiaa.org.
- Chen I J, Small I J. 1994. Implementing advanced manufacturing technology: an integrated planning model. *International Journal of Management Science*, 22(1): 91–103, http://www.sciencedirect.com/science/article/pii/0305048394900108.
- Chen, I. J. and Paulraj, A. 2004. Towards a theory of supply chain management: the constructs and measurements. *Journal of Operations Management*, 22 (2), pp. 119-150.
- Childerhouse, P. and Towill, D. 2011. Arcs of Supply Chain Integration. *International Journal of Production Research*, 49(24), pp. 7441-7468.
- Chopra, S., and P. Meindl. 2007. Supply Chain Management: Strategy, Planning, and Operation. 3rd ed. New Jersey: Pear- son Prentice Hall.
- Christopher, M. 1992. Logistics and Supply Chain Management: Strategies for Reducing Costs and Improving Service. Pitman Publishing, London, UK.
- Chua, C., Leong, K., and Lim, C. 2003. Rapid prototyping: Principles and applications. World Scientific Publishing Company.
- Chuu SJ (2009) Selecting the advanced manufacturing technology using fuzzy multiple attributes group decision making with multiple fuzzy information. *Computers and Industrial Engineering* 57:1033–1042
- Clark, K.B. 1989. Project scope and project performance: the effect of parts strategy and supplier involvement on product development. *Management Science*, Vol. 35, pp. 1247-63.
- Cohen, L., Manion, L., & Morrison, K. 2007. Research methods in education (6th Edition). London: Routledge.
- Colin, S., Lundgren, H., and Thompson, P. 2011. Guide to Supply Chain Management, Springer, Available from books.google.com.
- Collis, J. and Hussey, R. 2003. Business research: a practical guide for undergraduate and postgraduate students, 2nd Edition, Palgrave Macmillan, Basingstoke.

- Cooper, D., and Schindler, Pamela S. 2002. Business research methods. 8th ed. McGraw-Hill, Boston.
- Cooper, Donald R. and Pamela S. Schindler. 2014. Business Research Methods. 12th ed. McGraw-Hill, Boston.
- Cooper, M. C., Lambert, D. M., and Pagh, J. D. 1997. Supply Chain Management: More Than Just a New Name for Logistics. *International. Journal. of Logistics Management*, 8 (1).
- Cooper, R. B. and Zmud, R. W. 1990. Information technology implementation research: a technological diffusion approach. *Management Science* 36, 123–139.
- Costa S E, Lima E P. 2009. Advanced manufacturing technology adoption: an integrated approach. *Journal of Manufacturing Technology Management*, 20(1): 74–96.
- Cotteleer, M.J. 2014. Deloitte: 3D Opportunity Additive manufacturing paths to performance, innovation and growth. Pp. 3-19. Available from [PDF] cellular3d.com.
- Council of Supply Chain Management Professionals. 2011. Supply Chain Management: http://cscmp.org/aboutcscmp/definitions.asp, Visited: October 21, 2011.
- Crabtree, P. et al. 2009. Manufacturing methodology for personalised symptom-specific sports insoles. *Robotics and Computer-Integrated Manufacturing*, 25(6), pp.972–979, available from [PDF] from bath.ac.uk.
- Creswell, J. W. 2009. Research design: Qualitative and mixed methods approaches. London: SAGE.
- Crotty, M. 1988. The foundations of social research. London: Sage.
- Curtis S, Gesler W, Smith G, Washburn S. 2000. Approaches to Sampling and Case Selection in Qualitative Research: Examples in the Geography of Health. *Social Science and Medicine* 50(7-8):1001–14.
- Custompartnet, 2008. Additive fabrication.
- Damanpour, F. 1991. Organizational innovation: a meta-analysis of effects of determinants and moderators. *Academy of Management Journal* 34 (3), 555–590.
- Danermark, B., Ekstrom, M., Jakobsen, L., and Karlsson, J., C. 1997. Generalization, scientific inference and models for an explanatory social science in Berth Danermark (Eds.) Explaining Society: Critical realism in the social sciences, Ablingdon, Oxon: Routledge.

- Dangayach G S, Deshmukh S G. 2005. Advanced manufacturing technology implementation: evidence from Indian small and medium enterprises (SMEs). *Journal of Manufacturing Technology Management*, 16(5): 483–496.
- De Brito, M. P. and van der Laan, E. A. 2000. Supply chain management and sustainability: Procrastinating research integration in mainstream research. *Sustainability* 2(859-870).
- De Villiers, M.R. 2005. Interpretive Research Models for Informatics: Action Research, Grounded Theory, and the Family of Design- and Development Research. *Alternation* 12(2), 10-52.
- Dean J W Jr, Susman G I, Porter P S. 1990. Technical, economic and political factors in advanced manufacturing technology implementation. *Journal of Engineering and Technology Management*, 7(2): 129–144.
- Decelle, A. F., Young, B. I., Das, B. P., Case, K., Rahimifard, S., Anumba, C. J., and Bouchlaghem, D. M. 2007. A review of approaches to supply chain communications: From manufacturing to construction. *Electronic Journal of Information Technology in Construction*, 12(May 2005), 73–102.
- Deloitte (2014). Supply chain leadership: Distinctive approaches to innovation, collaboration and talent alignment. Available from https://www2.deloitte.com.
- Denzin, N. K., and Lincoln, Y. S. 2000. Handbook of Qualitative Research (2nd ed.). Thousand Oaks: Sage Publications Inc.
- Deradjat, D. and Minshall, T.I.M., 2015. Implementation of Additive Manufacturing Technologies for Mass customisation. International Association for Management of Technology IAMOT. Conference Proceedings, pp.2079–2094, available from [PDF] from iamot2015.com.
- Deshmukh. A. J., Vasudevan H., 2014. Emerging Supplier Selection Criteria in the Context of Traditional Vs Green Supply Chain Management. *International Journal of Managing Value and Supply Chains*, Vol.5, No. 1, pp.19-33. Available from [PDF] semanticscholar.org.
- Despeisse Melanie.and Ford Simon. 2015. The Role of Additive Manufacturing in Improving Resource Efficiency and Sustainability, Centre for Technology Management working paper series ISSN 2058-8887 No. 3. Available from cam.ac.uk [PDF].

- Diegel, O. et al. 2010. Tools for Sustainable Product Design: Additive Manufacturing. *Journal of Sustainable Development*, 3(3), pp.68–75, [PDF] from researchgateway.ac.nz.
- Dimov, S.S., Pham, D.T., Lacan, F., and Dotchev, K.D. 2001. Rapid tooling applications of the selective laser sintering process. *Assembly Automation*, Vol. 21(4), pp.296-302.
- Driscoll, D. L., Salib, P., and Rupert, D. J. 2007. Merging Qualitative and Quantitative Data in Mixed Methods Research: How To and Why Not. *Ecological and Environmental Anthropology*, 3(1), 18–28.
- Dugatkin, L. 2001. Model systems in behavioral ecology: integrating conceptual, theoretical, and empirical approaches. Princeton University Press.
- Durach, C. F., Kurpjuweit, S., Wagner, S. M. 2017. The impact of additive manufacturing on supply chains. *International Journal of Physical Distribution and Logistics Management*, 47(10), 954–971. https://doi.org/10.1108/IJPDLM-11-2016-0332.
- Easterby-Smith, M., Thorpe, R., and Lowe, A. 2002. Management Research: An introduction, 2nd, SAGE publications, London.
- Easterby-Smith, M., Thorpe, R., Jackson, P. and Lowe, A. 2012. Management Research. 4th ed. London: SAGE Publications, London.
- Efstathiades, A., Tassou, S., and Antoniou, A. 2002. Strategic planning, transfer and implementation of Advanced Manufacturing Technologies (AMT). Development of an integrated process plan. *Technovation* 22, pp. 201-212.
- Eisenhardt, K., M. 2007. Theory building from cases: Opportunities and Challenges, *Academy of Management Journal*, Vol 50, No 1 25-32, http://aom.org.
- Eisenhardt, K.M. 1989. Building theories from case study research. *Academy of Management Review*, vol. 14, no. 4, pp. 532-550.
- Eisenhardt, K.M. and Graebner, M.E. 2007. Theory Building from Cases: Opportunities and Challenges. *Academy of Management Journal* 50(1):25–32.
- Eisenhardt, K.M. and Tabrizi, B.N. 1994. "Accelerating adaptive processes: product innovation in the global computer industry", *Administrative Science Quarterly*, Vol. 40 No. 1, pp. 84-110.
- Eshtehardian E., Parviz G., Azadeh B., 2013. Using ANP and AHP for the Supplier Selection in the Construction and Civil Engineering Companies: Case Study of

Iranian Company. KSCE *Journal of Civil Engineering*, Vol.17, No.2, pp.262-270. Available from [PDF] academia.edu.

- Fitzgerald, A., Kiridena, B. 2006. Case study approach in operations management. Social Science Methodology Conference (pp. 1-18). Sydney: ACSPRI.
- Flynn, B., Huo, B. and Zhao, X. 2010. The Impact of Supply Chain Integration on Performance: A Contingency and Configuration Approach. *Journal of Operations Management*, Volume 28, pp. 58-71.
- Flyvbjerg, C. 2006. Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, vol. 12, no. 2, pp. 219–245. [PDF] from arxiv.org.
- Forslund, H and Jonsson, P. 2009. Obstacles to Supply Chain Integration of the Performance Management Process in Buyer-Supplier Dyads. The Buyer's Perspective. *International Journal of Operations and Production Management*, 29(1), pp. 77-95.
- Frohlich M. 1998. How do you successfully adopt an advanced manufacturing technology? *European Management Journal*, 16(2): 151–159.
- Fulton, M. and Hon, B. 2010. Managing advanced manufacturing technology (AMT) implementation in manufacturing SMEs. *International Journal of Productivity and Performance Management* Vol. 59 No. 4, pp. 351-371.
- Galankashi M., Rahiminezhad, A., Moazzami, N., Madadi, A., Haghighian R., Syed A. H., 2013. Supplier Selection for Electrical Manufacturing Companies Based on Different Supply Chain Strategies. *International Journal of Technology Innovations and Research*, pp.1-13. Available from [PDF] academia.edu.
- Ganeshan, R. and Harrison, T. P, 1995. An Introduction to Supply Chain Management. Penn State University.
- García, J., & Alvarado, A. 2012. Problems in the implementation process of advanced manufacturing technologies. *The International Journal of Advanced Manufacturing Technology,* 64(1-4), 123–131.
- Gatto, A., Iuliano, L., and Settineri, L. 1998. Particles’ Formation and Deposition in Sanders RP Process. Proceedings 7th European Conference on Rapid Prototyping and Manufacturing, pp. 211-227.
- Gerwin, D. 1988. A theory of innovation processes for computer-aided manufacturing technology. *IEEE Transactions of Engineering Management* 35, 90–100.

- Gerwin, D. and Tarondeau, J. C. 1982. Case studies of computer integrated manufacturing systems: a view of uncertainty and innovation process. *Journal of Operations Management* 2, 87–99.
- Ghani K A, Jayabalan V, Sugumar M. 2002. Impact of advanced manufacturing technology on organizational structure. *Journal of High Technology Management Research*, 13(2): 157–175.
- Ghani K A, Jayabalan V. 2000. Advanced manufacturing technology and planned organizational change. *The Journal of High Technology Management Research*, 11(1): 1–18.
- Gibson and Srinathb 2015. Simplifying Medical Additive Manufacturing: Making the Surgeon the Designer, The International Design Technology Conference, DesTech, Geelong, Australia. Available from sciencedirect.com [HTML].
- Gibson, I., Rosen, D.W. and Stucker, B. 2015. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. 2nd ed, New York: Springer.
- Gioia, D.A. and Pitre, E. 1990. Multiparadigm Perspectives on Theory Building. *Academy of Management Review*, Vol. 15 No. 4, pp. 584 -602.
- Glaser, B. G. and Strauss, A. 1967. The Discovery of Grounded Theory. Strategies for Qualitative Research. Chicago: Aldine.
- Glenn A. Bowen. 2009. Document Analysis as a Qualitative Research Method. *Qualitative Research Journal*, Vol. 9 Issue: 2, pp.27-40.
- Gomez, B. and Jones, J. 2010. Research Methods in Geography: A Critical Introduction. UK: Blackwell Publishing Ltd.
- Goulding, C. 1998. Grounded theory: the missing methodology on the interpretivist agenda. *Qualitative Marketing Research: An International Journal*, No. 1, pp. 50-57.
- Guba, E. G., and Lincoln, Y. S. 1994. Competing Paradigms in Qualitative Research. Handbook of Qualitative Research 105-117.
- Gunasekaran, A., and Ngai, E. W. T. 2004. Information systems in supply chain integration and management. *European Journal of Operational Research*, 159(2 SPEC. ISS.), 269–295. http://doi.org/10.1016/j.ejor.2003.08.016.
- Gunawardana, Kennedy D. 2006. Introduction of Advanced Manufacturing Technology: a literature review. *Sabaragamuwa University Journal*, vol 6, no.1, pp 116-134.

- Hague, R.J.M., Campbell, R.I. and Dickens, P.M. 2003. Implications on design of rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science*, 217 (1), pp. 25-30, available from [PDF] from lboro.ac.uk
- Hahn, F., Jensen, S. and Tanev, S. 2014. Disruptive Innovation vs Disruptive Technology: The Disruptive Potential of the Value Propositions of 3D Printing Technology Start-ups. *Technology Innovation Management Review*, (December), pp.27–36. Available from **[HTML]** from timreview.ca.
- Hamid Noori. 1997. Implementing Advanced Manufacturing Technology: The Perspective of a Newly Industrialized Country (Malaysia), *The Journal of High Technology Management Research*, 8(1), 1–20.
- Hanemann, T., Bauer, W., Knitter, R. and Woias, P. 2006. Rapid Prototyping and Rapid Tooling Techniques for the Manufacturing of Silicon, Polymer, Metal and Ceramic Micro devices. Chapter 4 in MEMS/NEMS Handbook - Techniques and Applications. Volume 3. Leondes, Cornelius T (eds). Springer.Hanumaiah.
- Hasan, S. and Rennie, A. E. W. 2008. The application of Rapid Manufacturing technologies in the spare parts industry. Nineteenth Annual International Solid Freeform Fabrication (SFF) Symposium, 4-8, August 2008, Austin, TX, USA. Available from open.ac.uk [PDF].
- Hasan, S., Rennie, A. & Hasan, J. 2013. The Business Model for the Functional Rapid Manufacturing Supply Chain. Studia commercialia Bratislavensia, 6(24), pp.536–552. Available at: **[PDF]** from degruyter.com.
- Healy, M. and Perry, C. 2000. Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm. *Qualitative Market Research: An International Journal,* Vol. 3 No. 3, pp. 118-26.
- Heinbuch, E. Susan. 1995. A Case Study of Successful Technology Transfer to Health Care: Total Quality Materials Management and Just-In-Time. *Journal of Management in Medicine.* 9(2):48-56.
- Hemalatha S., Ram Babu, G., Narayana Rao K., and Venkatasubbaiah K. 2015. Supply Chain Strategy based Supplier Evaluation – An Integrated Framework. *International Journal of Managing Value and Supply Chains (IJMVSC)* Vol. 6, No. 2. Available from http://airccse.org/journal/mvsc/papers/6215ijmvsc07.pdf.

- Holmstrom, J., Partanen, J., Tuomi, J., Walter. M., 2010. Rapid manufacturing in the spare parts supply chain. *Journal of Manufacturing Technology Management* 21 (6), 687 – 697, http://www.emeraldinsight.com/doi/abs/10.1108/17410381011063996.
- Hopkinson, N. and Dickens, P. 2003. Analysis of rapid manufacturing — using layer manufacturing processes for production. Science, 217, pp.31–39, available from [PDF] from lboro.ac.uk.
- Hopkinson, N. and Dickens, P. 2001. "Rapid prototyping for direct manufacture", *Rapid Prototyping Journal*, Vol.7 Iss4 pp.197-202, Emerald Insight http://dx.doi.org/10.1108/EUM0000000005753.
- Hopkinson, N., Hague, R., and Dickens, P. 2006. Rapid manufacturing: an industrial revolution for the digital age. Chichester England: John Wiley.
- Huang, S.H. et al.2013. Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, 67, pp.1191–1203, Available at: http://link.springer.com/10.1007/s00170-012-4558-5.
- Hugos, Michael H. 2011. Essentials of supply chain management. Vol. 62. John Wiley and Sons.
- Janssen, G.R., Blankers, I.J., Moolenburgh, E.A., Posthumus, A.L. 2014. TNO: The impact of 3-D printing on supply chain management, *Journal of orthopaedic trauma*, 28(April), p.24. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24922266.
- Johnson and Christensen. (2004). Educational Research: Quantitative, qualitative and mixes approaches, 2nd ed. Boston: Allyn & Bacon.
- Jungling Michael, Wood Patrick, Koike Yukihiro 2013. MedTech: 3D Printing – A Solution for Innovation, Morgan Stanley Research.
- Kagioglou, M., Cooper, R., Aouad, G., Kinks, J., Sexton, M. G., and Shealth, D. M. 1998. A generic guide to the design and construction processes protocol. UK: University of Salford.
- Kakati, M. 1997.Evaluation of Advanced Manufacturing Technology, *International Journal Production Economics*, 53, 141–156.
- Kamaruddin, N. K., and Udin, Z. M. 2009. Supply chain technology adoption in Malaysian automotive suppliers. *Journal of Manufacturing Technology Management*, 20(3), 385–403. http://doi.org/10.1108/17410380910936819.
- Karagol, B. 2014. 3D Printing: What does it offer and for whom? TEKPOL | Science and Technology Policies Research Center.

- Kellens, K., Baumers, M., Gutowski, T. G., Flanagan, W., Lifset, R., & Duflou, J. R. 2017. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. *Journal of Industrial Ecology,* 21, pp.49–68. https://doi.org/10.1111/jiec.12629.
- Kersten, W., Rall, K., Meyer, C., Dalhöfer, J. 2006. Complexity Management in Logistics and ETO-Supply Chains, in Blecker, T., Kersten, W. (Eds.). Complexity Management in Supply Chains, pp. 325–347, Erich Schmidt Verlag GmbH, Berlin.
- Khajavi, Janssen, G.R., Blankers, I.J., Moolenburgh, E.A. and Posthumus, A.L., 2014. TNO: The impact of 3-D printing on supply chain management. *Journal of orthopaedic trauma*, 28(April), p.24.
- Khajavi, S.H., Partanen, J., Holmström, J., 2014. Additive manufacturing in the spare parts supply chain. *Computers in Industry* 65, 50–63.
- Khanna, A., and Balaji, S. 2015. 3D Printing: New Opportunities for the Medical Devices Industry, Tata Consultancy Services (TCS). Available from http://www.tcs.com.
- Kieviet, A. 2014. Implications of Additive Manufacturing on Complexity management within supply chain in a production environment, [PDF] from louisville.edu.
- Kim, D. 2005. An Integrated Supply Chain Management System: A Case Study in Healthcare Sector. https://link.springer.com.
- Kritchanchai, D. 2012. A Framework for Healthcare Supply Chain Improvement in Thailand. *Operations and Supply Chain Management*, 5(2), 103–113.
- Kruth, J.P., Levy, G., Klocke F., and Childs, T.H.C. 2007. Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Annals - Manufacturing Technology*, Vol. 56(2), pp. 730-759.
- Kulkarni, P., Marsan, A., Debasish D. 2000. A review of process planning techniques in layered manufacturing. *Rapid Prototyping Journal*, Vol. 6 Iss 1 pp. 18 – 35, Emerald Insight, http://dx.doi.org/10.1108/13552540010309859.
- Kulpip and Ankur. 2014. Additive Manufacturing for personalized systems. Cyient. Available from www.cyient.com.
- Kvale, S. 1996. Interviews: An introduction to qualitative research interviewing. Thousand Oaks, CA: Sage.

- Lantada and Morgado. 2012. Rapid prototyping for biomedical engineering: Current capabilities and challenges. *Annual Review of Biomedical Engineering*, 14, pp.73–96. Available at HTML] from annualreviews.org.
- Laosirihongthing, T., Paul, H., and Speece M.W. 2001. Evaluation of new manufacturing technology implementation: an empirical study in the Thai automotive industry. *Technovation*, Article in Press.
- Lee, H.L. and Billington, C. 1995. The Evolution of Supply-Chain-Management Models and Practice at Hewlett-Packard. [PDF] iisc.ernet.in.
- Leonard - Barton D. 1988. Implementation as mutual adaptation of technology and organization. *Research Policy* 17, 241–287.
- Levy, G. N., Schindel, R., and Kruth, J. P., 2003. Rapid manufacturing and rapid tooling with layer manufacturing (lm) technologies, state of the art and future perspectives. *CIRP Annals - Manufacturing Technology*, 52 (2), 589-609.
- Lewis, M. W., and Boyer, K. K. 2002. Factors impacting AMT implementation: An integrative and controlled study. *Journal of Engineering and Technology Management* - JET-M, 19(2), 111–130.
- Lewis, P., Saunders, M. N. K., and Thornhill, A. 2009. Research methods for business students. Pearson.
- Lincoln, Y., and Guba, E. 1985. Naturalistic inquiry. Beverly Hills, CA: Sage.
- Lindemann, C. and Jahnke, U., 2012. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. Available from [PDF] from utexas.edu.
- Machuca J A D, Diaz M S, Gil M J. 2004. Adopting and implementing advanced manufacturing technology: new data on key factors from the aeronautical industry. *International Journal of Production Research*, 42(16): 3183–3202.
- Manners-Bell, J. and Lyon, K. 2012. The Implications of 3D Printing for the Global Logistics Industry. Transport Intelligence. Available at [PDF] from johnmannersbell.com.
- Marri H., B., Irani, Z., Gunasekaran, A. 2006. A Framework of Justification Criteria for Advanced Manufacturing Technology Implementation in Small and Medium Enterprises. *European and Mediterranean Conference on Information Systems* (EMCIS), Costa Blanca, Alicante, Spain.
- Marshall, C. and Rossman G.B. 1999. Designing qualitative research, 3rd Edition, Sage Publications, London.

- Mashhadi, A.R., Esmaeilian, B. and Behdad, S. 2015. Impact of Additive Manufacturing Adoption on Future of Supply Chains. Proceedings of the Asme 10Th *International Manufacturing Science and Engineering Conference,* Vol 1, pp.1–10. Available at PDF] from buffalo.edu.
- Mastrocinque, E., Mondragon, A. E. C., and Hogg, P. J. 2016. Manufacturing technology selection in the supply chain context by means of fuzzy-AHP: A case in the high-performance textile industry. ARPN *Journal of Engineering and Applied Sciences,* 11(1), 240–246.
- Mathew, J., John, J. and Kumar, S. 2013. New Trends in Healthcare Supply chain in *POMS 24th Annual Conference* "Integrating Practice in POM Research and Teaching".
- Mehrjerdi, Y., Z. 2009. Excellent Supply Chain Management. *Assembly Automation,* 29.1: 52-60.
- Mellor, S. 2014. "An Implementation Framework for Additive Manufacturing." PhD Thesis, University of Exeter.
- Mellor, S., Hao, L., and Zhang, D. 2014. Additive manufacturing: A framework for implementation. *International Journal Production Economics* 149 (2014) 194–201, http://www.sciencedirect.com/science/article/pii/S0925527313003204.
- Mentzer, John T., et al. 2001. Defining Supply Chain Management. *Journal of Business Logistics*. 22.2, 1-26.
- Meredith, J. 1998. Building Operations Management Theory through Case and Field Research. *Journal of Operations Management* 16(4):441–54. Retrieved (http://linkinghub.elsevier.com/retrieve/pii/S0272696398000230).
- Meredith, Jack R. and M. Mccutcheon. 1993. Conducting Case Study Research in Operations Management. *Journal Of Operations Management,* 11:239–56.
- Merriam, S. B. 1988. Case study research in education: A qualitative approach. San Francisco: Jossey-Bass.
- Miles, M. and Huberman, A., 1994. Qualitative data analysis: An expanded sourcebook. UK: Sage.
- Miles, M., Huberman, M., and Saldaña, J. 2013. Qualitative Data Analysis: A Methods Sourcebook. London: SAGE Publications, Inc.
- Mohajeri, B., Khajavi S. H., Nyberg, T., Khajavi S.H., 2014. Supply chain modifications to improve additive manufacturing cost-benefit balance, pp.1304–1314, available from PDF from utexas.edu.

- Mokasdar, A. 2012. A Quantitative Study of the Impact of Additive Manufacturing in the Aircraft Spare Parts Supply Chain. Masters Thesis, University, Available at [PDF] from ohiolink.edu.
- Morgan Stanley, 2013. Capital Goods: 3D Printing Don't Believe (All) The Hype, http://www.wisburg.com.
- Mumtaz, K.A., and Hopkinson, N. 2009. Selective Laser Melting of thin wall parts using pulse shaping. *Journal of Materials Processing Technology*, Vol. 210, pp. 279-287.
- Munoz, C., Kim, C. & Armstrong, L. 2013. Layer-by-Layer: Opportunities in 3D printing Technology trends, growth drivers and the emergence of innovative applications in 3D printing. MaRS Market Insights.
- Nagar, B., and Raj, T. 2012. Risk mitigation in the implementation of AMTs: A guiding framework for future. *International Journal of Industrial Engineering Computations*, 3(3), 485–498.
- Nair, P. R., Raju, V., and Anbudayashankar, S. P. 2009. Overview of Information Technology tools for Supply Chain Management. *CSI Communications*, 33(9), 20–27.
- Nyman, H.J. and Sarlin, P. 2014. From bits to atoms: 3D printing in the context of supply chain strategies. Proceedings of the Annual Hawaii International Conference on System Sciences, pp.4190–4199, Available at [PDF] from ieee.org.
- Ochi 2014. Investigating present and future interactions between radio frequency identification, additive manufacturing and supply chain. A Thesis presented to the Faculty of California Polytechnic State University.
- Orlikowski, W.J. 1993. CASE Tools as Organizational Change: Investigating Incremental and Radical Changes in Systems Development. *MIS Quarterly*, volume 17, pp. 309-340.
- Orlikowski, W.J. and Baroudi, J. 1991. Studying Information Technology in Organizations: Research Approaches and Assumptions. *Information Systems Research*, Vol. 2 No. 1, pp. 1-28.
- Park, Y.H., Park, E.H., and Ntuen, C.A. 1990. An economic model for cellular manufacturing systems, in Parsaei, H., Ward, T., and Karwoski, W. 1990. Justification Methods for Integrated Manufacturing Systems, Elsvier, Network, NY, pp.176-192.

- Patterson, K., Grimm, C. M., and Corsi, T. M. 2003. Adopting new technologies for supply chain management. *Transportation Research*, 39(2), 95–121.
- Patton, M., 2005. Qualitative research. John Wiley and Sons, Ltd.
- Penny, M., Hellgren, T. and Bassford, M. 2013. Future Technology Landscapes: Insights, analysis and implications for defence (Final Report). Available at: http://www.rand.org/pubs/research_reports/RR478.html.
- Petrick, I.J. and Simpson, T.W. 2013. Point of View: 3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition. *Research-Technology Management*, 56(December), pp.12–16. Available at: [PDF] from psu.edu.
- Phichitchaisopa, N., and Naenna, T. 2013. Factors Affecting the Adoption of *Healthcare. Experimental and Clinical Sciences Journal*, 12(1), 413–436.
- Pinna, R., Pier Paolo Carrus, P., P., and Marras, F. 2015. World's largest Science, Technology & Medicine Open Access book publisher, published by Intech, http://dx.doi.org/10.5772/59748.
- Ponche, R. et al. 2012. A new global approach to design for additive manufacturing. *Virtual and Physical Prototyping*, 7, pp.93–105, available from [PDF] from archives-ouvertes.fr.
- Power, D., and Simon, A. 2004. Adoption and diffusion in technology implementation: a supply chain study. *International Journal of Operations and Production Management*, 24(6), 566–587.
- Prajogo, D., and Sohal, A. 2013. Supply chain professionals. *International Journal of Operations and Production Management*, 33(11/12), 1532–1554. http://doi.org/10.1108/IJOPM-08-2010-0228.
- PwC 2014. The future of 3-D printing: Moving beyond prototyping to finished products. Available from http://www.pwc.com/us/en/technology-forecast/2014/3d-rinting/index.jhtml.
- Ragatz, Gary L., Robert B. Handfield, and Thomas V Scannell. 1997. Success Factors for Integrating Product Development Suppliers into New. *Journal of Production Innovation Management*. 6782(97):190–202.
- Rahman A. 2008. Buyer-supplier relationships in advanced manufacturing technology acquisition and implementation in Malaysia. *International Journal of Economics and Management*, 2(1): 95–126.

- Rahman A., Bennett D. 2009. Advanced manufacturing technology adoption in developing countries. Journal of Manufacturing Technology Management, Vol. 20 Iss 8 pp. 1099 – 1118, Emerald Insight.
- Ramamurthy K. 1995. Influence of planning on implementation success of AMT. IEEE. *Transactions on Engineering Management*, 42 (1): 62–73.
- Rand Europe 2014. Future Technology Landscapes Insights, analysis and implications for defence. Case Study Documentation. https://www.rand.
- Ray, J.T. LT. 2013. The 3D Printed Supply Chain', Defence *Transportation Journal*, pp. 14-24. http://www.ndtahq.com/documents/3DPrintedSupplyChain.pdf.
- Reeves, P. 2014. Building business models in the additive manufacturing and 3d printing ecosystem, www.econolyst.co.uk/resources/documents/files/2014_AM-3DP_business_ecosystems.pdf.
- Reeves, P. 2009. Additive Manufacturing - A supply chain wide response to economic uncertainty and environmental sustainability. [PDF] from econolyst.co.uk.
- Rengier, F. et al. 2010. 3D printing based on imaging data: Review of medical applications. *International Journal of Computer Assisted Radiology and Surgery*, 5(4), pp.335–341. Available from [PDF] from researchgate.net.
- Robson C. 2002. Real world research: a resource for social scientists and practitioner-researchers, 2nd Edition, Blackwell Publishers, Oxford.
- Roland Berger Strategy Consultants. 2013. Additive manufacturing - A game changer for the manufacturing industry? (p. 30). Munich: Roland Berger Strategy Consultants.
- Rowley, J. 2002. Using case studies in research. Management Research News, 25(1), 16-27.
- Royal Academy of Engineering (2013): Additive manufacturing: opportunities and constraints. Published by Royal Academy of Engineering London, http://www.raeng.org.uk/publications/reports/additive-manufacturing.
- Ruffo, M., Tuck, C. and Hague, R., 2007. Make or buy analysis for rapid manufacturing. *Rapid Prototyping Journal*, 13(1), pp.23–29. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/13552540710719181.
- Ruffo, M., Tuck, C., Hague, R. 2006. Cost Estimation for Rapid Manufacturing – Laser Sintering Production for Low to Medium Volumes. Proceedings of the

Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 220 (9), pp. 1417– 1427. Available from [PDF] from lboro.ac.uk.

- Ruiwale V., V., Sambhe, R. U., 2015. Application of Additive Manufacturing Technology for Manufacturing Medical Implants: A Review. *International Journal of Mechanical Engineering and Technology*, 6, 976–6340. Available from http://www.iaeme.com.
- Russell, S. 1997. Supply Chain Management: More than Integrated Logistics. *Air Force Journal of Logistics*, 31 (2), pp. 56.
- Ryan, K. Jennifer. 2005. Systems Engineering: Opportunities for Health Care, Building a Better Delivery System: A New Engineering/ Health Care Partnership. National Academy Press.
- Rylands, B. 2015. 3D Printing – To print or not to print? Aspects to consider before adoption, A supply chain perspective, 22nd EurOMA Conference, http://ro.uow.edu.au/cgi/viewcontent.cgi?article=2763&context=aiimpapers.
- Saberi, S. and Mohd, R. Yusuff 2011. Advanced Manufacturing Technology Implementation Performance: Towards A Strategic Framework., *Proceedings of the 2011 International Conference on Industrial Engineering and Operations Management*, Kuala Lumpur, Malaysia, January 22 – 24, 2011, pp.145–150. Available at [PDF] from iieom.org.
- Saiz. E., Castellano, E. 2006. Global and Flexible Supply Chain Networks Modelling and Simulation in Blecker, T., Kersten, W. (Eds.) "Complexity Management in Supply Chains," pp. 161–189, Erich Schmidt Verlag GmbH, Berlin.
- Sambasiva Rao and Deshmukh S.G. 1994. Strategic Framework for Implementing Flexible Manufacturing Systems in India. *International Journal of Operations and Production Management*, Vol. 14 Iss 4 pp. 50 – 63 Permanent link to this document: http://dx.doi.org/10.1108/01443579410056038.
- Saunders, M., Lewis, P. & Thornhill, A. 2009. Research methods for business students, 5th ed., Harlow, Pearson Education.
- Saunders, M., Lewis, P., and Thornhill, A. 2003. Research methods for business students, 3rd, Pearson Education, England.
- Schell, C. 1992. The Value of the Case Study as a Research Strategy. Available from: www.finance-mba.com/Case%20Method.pdf.

- Schilling, Melissa A. and Charles W. L. Hill. 1998 Managing the New Product Development Process: Strategic Imperatives," *The Academy of Management Executive*, Vol. 12, No. 3, pp. 67-81.
- Schneller, S. Eugene S., Larry R. Smeltzer. 2006. Strategic Management of the Healthcare Supply Chain. Jossey-Bass.
- Schostak, J. 2006. Interviewing and representation in qualitative fieldwork. New York: Open University Press.
- Scotland, J. 2012. Exploring the Philosophical Underpinnings of Research: Relating Ontology and Epistemology to the Methodology and Methods of the Scientific, Interpretive, and Critical Research Paradigms, *5*(9), 9–16. [PDF] ccsenet.org.
- Sealy, W. 2011. Additive Manufacturing as a Disruptive Technology: How to Avoid the Pitfall. *American Journal of Engineering and Technology*, 12(1), pp.86–93, http://www.ajetr.org/vol12/no1/vol12no110.pdf.
- Sebastian, M. and Omera, K. 2015. 3D Printing and Its Disruptive Impacts on Supply Chains of the Future. *Technology Innovation Management Review*, 5(11), pp.20–24. Available at: http://timreview.ca/article/942.
- Sekaran, U. 1992. Research methods for Business, 2nd ed. Wiley, New York, Shapiro.
- Shames, H. 2010. Development of a Selection Program for Additive Manufacturing Systems. *Stellenbosch University*, (March), [PDF] sun.ac.za.
- Shingo, S. 1998. Non-Stock Production. Productivity Press, Cambridge, MA.
- Silverman, D. 2001. Interpreting Qualitative Research: Methods for Analysing Talk Text and Data, Sage Publications.
- Simchi-Levi, D., Kaminsky, P. and Simchi-Levi, E. 2008. Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies. 3rd ed. McGraw Hill and Irwin.
- Singh R K, Garg S K, Deshmukh S G, Kumar M. 2007. Modelling of critical success factors for implementation of AMTs. *Journal of Modelling in Management*, 2(3): 232–250 36.
- Singh, M., Haverinen, H. M., Dhagat, P., and Jabbour, G. E. 2010. Inkjet printing—process and its applications. *Advanced materials*, 22 (6), 673-685.
- Sirichakwal, I., and Conner, B. 2016. Implications of Additive Manufacturing for Spare Parts Inventory. 3D Printing and Additive Manufacturing, 3(1), 56–63. https://doi.org/10.1089/3dp.2015.0035.

- Slack, N., Chambers, S., and Johnston, R. 2007. Operations Management, 3rd Edition, Pearson Education Limited, UK.
- Small M H, Yasin M M. 1997. Advanced manufacturing technology: Implementation policy and performance. *Journal of Operations Management*, 1997, 15(4): 349–370.
- Small M H, Yasin M M. 2003. Advanced manufacturing technology adoption and performance: The role of management information systems departments. *Integrated Manufacturing Systems*, 14 (5):409–422.
- Snape, D. and Spencer, L. 2003. The foundations of qualitative research. In Qualitative research practice – a guide for social science students and researchers, (ed. J. Ritchie and J. Lewis), pp. 1-23. Sage, Publications, London.
- Snyder, G.H., Cotteleer, M., Kotek B 2014. 3D opportunity in medical technology, Deloitte University Press, available from http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech.
- Soe, S. P. 2012. Quantitative analysis on SLS part curling using EOS P700 machine. *Journal of Materials Processing Technology*, 212, 11; 2433-2442.
- Stevens, G. C. 1989. Integrating the Supply Chain. *International Journal of Physical Distribution and Materials Management*, 19 (8), pp. 3–8.
- Stuart et al. 2002. Effective Case Research in Operations Management: A Process Perspective. *Journal of Operations Management* 20(5):419–33.
- Supply Chain Council 2008. SCOR 9.0 Overview Booklet.
- Susman G.I. 1992. Integrating design and manufacturing for competitive advantage. Available from books.google.co.uk.
- Swaminathan, J. M., Smith, S.F. and Sadeh, N. M. 1996. A Multi Agent Framework for Modeling Supply Chain Dynamics. Technical Report, The Robotics Institute, Carnegie Mellon University.
- Teigen, R. 1997. Information flow in a supply chain management system. Ph.D. Thesis, Dept. of Industrial Economics and Technology Management, Trondheim University, Sweden.
- The Economist, April 2012. A third industrial revolution, Special Report: Manufacturing and Innovation, http://web.mit.edu/pie/news/Economist.pdf.
- Thomas, A.J., Barton, R. and John, E.G. 2008. Advanced manufacturing technology implementation: a review of benefits and a model for change. *International Journal of Productivity and Performance Management*, Vol. 57 No. 2, pp. 156-76.

- Thomas, D. J. and Griffin P.M., 1996. Coordinated supply chain management. *European Journal of Operational Research*, 94 (1), pp. 1-15.
- Thomas, D.R. 2006. A General Inductive Approach for Analysing Qualitative Evaluation Data. *American Journal of Evaluation*, 27, pp.237–246. [PDF] from auckland.ac.nz.
- Tuck C, Hague R, Burns N. 2007. Rapid manufacturing – impact on supply chain methodologies and practice. *International Journal of Services and Operations Management*, 3(1), pp.1-22, https://dspace.lboro.ac.uk/2134/5657.
- Tuck, C. and. Hague, R. 2006. The pivotal role of rapid manufacturing in the production of cost effective customised products. *International Journal of Mass Customisation*, vol.1, no. 2–3, pp. 360–373, https://dspace.lboro.ac.uk/2134/5653.
- Tyre, M. J. and Hauptman, O. 1992. Effectiveness of organizational responses to technological change in the production process. *Organization Science* 3, 301–320.
- Tyre, M. J. and Orlikowski, W. J. 1993. Exploiting opportunities for technological improvement in organizations. *Sloan Management Review* 40, 13–25.
- Udo G J, Ehie I C. 1996. Advanced manufacturing technologies: determinants of implementation success. *International Journal of Operations and Production Management*, 16(12): 6–26.
- Van der Veen, J., and Robben, H. 1997. Supply Chain Management: [PDF] researchgate.net.
- Van West, A. 2011. The History of 3D Printing, 3D printer and 3D printing news, Retrieved November 27, 2013, from http://www.3ders.org/3d-printing/3d-printing-history.html.
- Ventola, C.L. 2014. Medical Applications for 3D Printing: Current and Projected Uses., 39(10), pp.704–711. Available from [HTML] from nih.gov.
- Vinodh, S., Devadasan, S., Maheshkumar, S., Aravindakshan, M., Arumugam, M., and Balakrishnan, K. 2010. Agile product development through CAD and rapid prototyping technologies: An examination in a traditional pump-manufacturing company. *International Journal of Advanced Manufacturing Technology*, 46(1), 663-679, http://link.springer.com/,doi:10.1007/s00170-009-2142-4.
- Voss C A. 1988. Implementation: a key issue in manufacturing technology: The need for a field of study. *Research Policy*, 17(2): 55–63.

- Voss C., Tsikriktsis N, and Frohlich, M. 2002. Case research in operations management. *International Journal of Operations & Production Management*, vol. 22, no. 2, pp.195–219.
- Voss, C. 1985. Success and Failure in Advanced Manufacturing Technology. In B. Hundy (Ed.), Proceedings of the 3rd European Conference on Automated Manufacturing. Kempston, UK.
- Voss, C.A. 1986. Implementing manufacturing technology: A manufacturing strategy approach. *International Journal of Operations and Production Management*, 6 (5), pp. 17-25.
- Vrijhoef, R and Koskela, LJ 2000. The four roles of supply chain management in construction. *European Journal of Purchasing and Supply Management*, 6 (3-4).
- Wallenius, V., and Decade, N. 2014. 3D Printing and Retail. Thesis, Helsinki Metropolia University of Applied Sciences.
- Waller, M.A., Fawcett, S.E., 2014. Click here to print a maker movement supply chain: How invention and entrepreneurship will disrupt supply chain design. *Journal of Business Logistics* 35(2), 99-102.
- Walsham, G. 1995. The Emergence of Interpretevism in IS Research. *Information Systems Research*, Vol. 6 No. 4, pp. 376 -394.
- Walter, M., Jan, H., Hannu, Y. 2004. Rapid manufacturing and its impact on supply chain management. *Logistics Research Network Annual Conference*, Dublin, Ireland, http://legacy-tuta.hut.fi.
- Weinberg, M., 2010. It will be awesome if they don't screw it up: 3D printing, intellectual property and the fight over the next great disruptive technology. Public Knowledge, (November), p.16. Available at: [PDF] from dyndns.org.
- White, G. and Lynskey, D. 2013. Economic Analysis of Additive Manufacturing for Final Products: An Industrial Approach, pp.1-11. [PDF] from 136.142.82.187.
- Wholer, T. and Caffrey, T. 2013. Wohlers Report 2013: Additive Manufacturing and 3D Printing State of the Industry – Annual Worldwide Progress Report, Wohlers Associates. Fort Collins, CO.
- Wigan, M. 2014. Transport Replacement and Sustainability aspects associated with Additive manufacturing. Available at: http://works.bepress.com/mwigan/6.
- Wirth M. 2014. Shapeways and 3D Printing Revolution, Thesis, University of Wuerzburg, pp 1-14.

- Wisner, J., Tan, K.C. and Leong, G.K. 2012. Principles of Supply Chain Management: A Balanced Approach. 3rd edition. Mason: South-Western Cengage Learning.
- Wohlers Associates, 2013.Wohlers Report 2013.
- Wohlers Report 2011. Additive Manufacturing and 3D Printing State of the Industry. Annual Worldwide Progress Report. Wohlers Associates, 2011.
- Wohlers Associates, 2018.Wohlers Report 2018.
- Yasinshaikh, G., Marri, H. B., Sohag, R. A., Aslamuqaili, M., and Aziz, S. 2012. Implementation of Advanced Manufacturing Technology as Tool for Manufacturing Industries, *Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management,* Istanbul, Turkey.
- Ye, M. 2015. The Impact of 3D Printing on the World Container Transport. Master of Transport, Infrastructure and Logistics Delft University of Technology, Available at: [PDF] from tudelft.nl.
- Yin R. 2014. Case study research: design and methods, 5th ed. Sage Publications, London UK. books.google.com.
- Yin R. K. 2003. Case study research: design and methods, 3rd Edition, Sage, London.
- Yin, R.K. 1994. Case study research: design and methods. Second edition. Thousand Oaks: Sage Publications.
- Yusuff R M, Yee K P, Hashmi M S J. 2001. A preliminary study on the potential use of the analytical hierarchical process (AHP) to predict advanced manufacturing technology (AMT) implementation. *Robotics and Computer-Integrated Manufacturing*, 17(5): 421–427.
- Zäh, Michael, and Florian Hagemann. 2006. "WirtschaftlicheFertigungmit Rapid-Technologien." Anwender-LeitfadenzurAuswahlgeeigneterVerfahren. München: Hanser.
- Zairi, M. 1992. Measuring success in AMT implementation using customer-supplier interaction criteria. *International Journal of Operations and Production Management* 12:34–55.
- Zairi, M., 1998. Supplier partnerships for effective advanced manufacturing technology implementation: a proposed model. *Integrated Manufacturing Systems* 9 (2), 109–119.

- Zammuto R F, O'Connor E J. 1992. Gaining advanced manufacturing technologies' benefits: the roles of organization design and culture. *The Academy of Management Review*, 17(4): 701–728.
- Zhao H X, Co H C. 1997. Adoption and implementation of advanced manufacturing technology in Singapore. *International Journal of Production Economics*, 48(1): 7–19.
- Zhou H, Keong LG, Jonsson P, Sum CC. 2008. A comparative study of advanced manufacturing technology and manufacturing infrastructure investments in Singapore and Sweden. *International Journal of Production Economics* 120:42–53.

APPENDIX A

INTERVIEW QUESTIONNAIRE

The following interview-questionnaire will examine the implementation process for the Company A from a supply chain perspective within the following stages: Procurement, Design, Production, Distribution/Logistics and Customers. The interview will take place with Mr ……. who is the Production Manager of the Company A.

INTRODUCTION:

First before proceeding with the questions a description of the company will be given. Mr …., could you please provide us with a general background of Company A?

INTERVIEW:

A) Procurement-Suppliers.

QUESTION 1: In depth information of Supplier Selection

1) What are the criteria for selecting your suppliers? (Machine-material suppliers: In depth details in relation to criteria, the support you receive from suppliers and also the problems you come across - e.g. materials availability, quality issues, technical knowledge, support and back-up services etc).

QUESTION 2: AM Supplier Implementation- Actions to overcome the problems

2) What actions have you undertaken in order to achieve higher level of co-ordination with your suppliers? (e.g. have you considered the possibility of supplier acquisition or even in house AM co-development of your own material and process efficiencies?).

Sub question: How do you collaborate with your Suppliers in order to achieve agility? (Print and deliver e.g. orthotics to Hospitals on time).

B) Design

QUESTION 1: In depth information of Software Selection

3) How does this particular software you use ensure design customization? (In depth details in relation to software selection-scanning tools, software problems. Data capture, product design and process planning).

QUESTION 2: AM Software Implementation- Actions to overcome the problems

4) What actions have you undertaken in order to maximise design optimisation? (Integration of 3D Model Scanning and CAD Package) - (e.g. have you considered the possibility of developing your own software which can be used in a variety of medical applications in order to eliminate problems relating with the software?).

Sub question: How do you maximize efficiency of scanning tools and software in order to design on time?

C) Production

QUESTION 1: In depth information of Process Selection

5) Which AM technology you use in order to achieve higher accuracy of finished product? (In depth details in relation to AM technology including benefits and limitations).

QUESTION 2: AM Process Implementation- Actions to overcome the problems

6) How do you overcome the limitations of this process in order to achieve specialist production and reduce cost and total lead times? (Process constraints and costs - Post Processing).

Sub question: Why this particular AM technology can achieve specialist production and reduce overall cost of production and total lead times?

D) Distribution/Logistics

QUESTION 1: In depth information of Distribution (Centralised/Decentralised manufacturing).

7) What are the reasons for following a centralised manufacturing approach? (In depth analysis and also explain if the potential of distributed approach has been considered).

QUESTION 2: AM Centralised Manufacturing Implementation - Actions to overcome the problems.

8) How do you maximize the benefits of Centralised Manufacturing? (e.g. How do you ensure sufficient level of demand and capacity utilisation?).

Sub question: How does this particular approach (in – house manufacturing) assist the company to reduce delivery time and transport costs?

E) Customers (Healthcare centres)

QUESTION 1: In depth information of on demand production- make to order (MTO)

9) Could you please explain in detail how do healthcare centres use your technology and then in return you deliver the customised product? (Make to order for specialist production).

QUESTION 2: Future plans to improve service in the medical sector

10) What actions have you taken to improve your service to the healthcare centres? (e.g. have you considered the possibility of developing online training tools-portals or even a web-based customisation software in order to train doctors use your technology?).

Sub question: How can healthcare centres benefit more from your technology? (Future plans)