The Flexibility of Industrial Additive Manufacturing Systems

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A thesis submitted in fulfilment for the requirements of the degree of
Doctor of Philosophy of Cardiff University

Logistics Systems Dynamics Group
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2015

DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed ………………………………… (candidate) Date 22 June 2015

STATEMENT 1

This thesis is being submitted in fulfilment of the requirements for the degree of PhD.

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STATEMENT 2

This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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Abstract

The overall aim of this study is to explore the nature of Industrial Additive Manufacturing Systems as implemented by commercial practitioners, with a specific focus on flexibility within the system and wider supply chain. This study is conducted from an Operations Management perspective to identify management implications arising from the application of contemporary Industrial Additive Manufacturing in the fulfilment of demand.

The generation of the theoretical constructs and their evaluation is achieved through an abductive approach. The concept of an Industrial Additive Manufacturing System is developed, through which activities, enabling mechanisms, and control architectures are demonstrated. This is complimented by the proposal of a typology of flexibilities both for the manufacturing system and its supply chain. Twelve case studies are examined through practitioner interviews, observation, and mapping of the production processes at three Industrial Additive Manufacturing companies. These explorations are complimented by interviews with customers downstream of the Additive Manufacturer, and with interviews and a survey of principal upstream machine and material suppliers.

This study identifies and classifies types of flexibility relevant to Industrial Additive Manufacturing Systems. It is shown that to achieve requisite flexibilities, it is necessary to manage the whole manufacturing system, not just individual machines. By extension, the internal manufacturing systems' ability to achieve flexibility is shown to be both facilitated and constrained by the environment in which it operates. In particular, inadequacies in the supply of materials are shown to result in suboptimal practices within the manufacturing system.

The principal contribution of this thesis is therefore the development of Industrial Additive Manufacturing from a manufacturing systems perspective, and an evaluation of its implications for flexibility.

Acknowledgements

Whilst this thesis is the result of my own independent study, it would not have been possible without the support of a multitude of companies, colleagues, and friends. I am particularly indebted to:

- Dr Andrew Potter, Professor Mohamed Naim, and Dr Jonathan Gosling who have been my academic supervisors and provided support and guidance in the conduct of this study.

- The anonymous Industrial Additive Manufacturing companies and their customers, who have hosted me at site visits, answered my interview questions, completed my questionnaires, and helped me explore the ideas developed in this study.

- EPSRC who provided financial support in the early stages of this research, and Cardiff Business School who supported the completion of this work.

- The former staff of Cardiff University's EPSRC Innovative Manufacturing Research Centre, and my current colleagues within the Logistics and Operations Management Section of Cardiff Business School.

- The old friends at Cardiff School of Engineering who have mentored me since my arrival as a nervous undergraduate student some fifteen years ago, and continue to inspire and motivate me today. I will always be thankful to Dr Roger Grosvenor, Mr Paul Prickett, and Dr Mehrdad Ghassempoory for the continual kindness and support they have shown over the years.

- James Levine and the Vienna Philharmonic Orchestra for providing the soundtrack that has played continually whilst I wrote this thesis, and to Mr Mozart for his creation.

My greatest thanks are extended to my wife Hannah, who has endured yet another six years of lost evenings, weekends, and holidays, and without whose support this research would not have been possible.

Daniel Eyers
Cardiff, June 2015

Dedication

This thesis is dedicated to my wife Hannah, and to my parents Roy and Lydia in recognition of the support and encouragement they have provided in all aspects of my life.

Contents

List of tables

List of figures

Table of abbreviations

Abbreviation	Description
3DP / 3D Printing	3 Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ATO	Assemble To Order
CAD	Computer Aided Design
CMM	Coordinate Measurement Machine
DFM	Design For Manufacture
DIY	Do It Yourself
DSP	Digital Signal Processor
E-COMMERCE	Electronic Commerce
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
EUROMA	EURopean Operations Management Association
GIS	Geographic Information System
FDM	Fused Deposition Modelling
FFF	Fit, Form, Function
FMS	Flexible Manufacturing System
IJOPM	International Journal of Operations and Production Management
ITE	In The Ear (Hearing Aid)
JOM	Journal of Operations Management
LS	Laser Sintering
MFG	Manufacturing
MFR	Manufacturer
MTO	Make To Order
MTS	Make To Stock
NHS	National Health Service
OEM	Original Equipment Manufacturer
OR	Operations Research
OM	Operations Management
POC	Penalty Of Change
PLC	Programmable Logic Controller
RE	Reverse Engineering
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
RSM	Rapid Shell Modelling
SL	Stereolithography
SLS	Selective Laser Sintering
SOHOD	Small Office, Home Office, and Desktop
STS	Ship To Stock
UK	United Kingdom
UOA	Unit Of Analysis
WWW	World Wide Web

Chapter 1 Introduction

Chapter Aims

1. Introduce and justify the topic of this doctoral research.
2. Present the principal research questions tackled in this study.
3. Summarize the structure of this thesis.

1.1 Chapter overview

The purpose of this chapter is to provide an introduction to the topic of "The Flexibility of Industrial Additive Manufacturing Systems" that is investigated in this doctoral study. It presents the main concepts considered in this research, and provides a discussion on the context and motivations for the study. The four research questions examined in this research are introduced, and the structure of the thesis is explained.

1.2 Context for the study

The term "*Additive Manufacturing*" is defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM International 2009). A wide range of Additive Manufacturing technologies have been developed, however all share a common approach to fabrication through an incremental layer-wise approach to the formation of parts. In the current study, specific focus is given to the larger industrial-grade Additive Manufacturing machines that are termed as "*Industrial Additive Manufacturing*". These technologies enjoy adequate maturity to be employed in real-world manufacturing environments (rather than lab-based experimental machines or hobbyist devices), and may therefore be considered to be in competition with 'conventional' approaches to manufacturing. As described fully in Appendix C, Industrial Additive Manufacturing includes the most popular Additive Manufacturing technologies such as Laser Sintering/Selective Laser Sintering, Stereolithography, and Fused Deposition Modelling.

Compared to other approaches to production, a number of advantages have been identified to arise from the application of Additive Manufacturing. Whilst subtractive approaches remove materials from a larger billet, and formative approaches mould materials to form geometries, by depositing material layers incrementally Additive Manufacturing technologies are able to produce highly complex parts without many of the design-for-manufacturing constraints that are inherent in many ‘conventional’ subtractive or formative approaches to production (Hopkinson et al. 2006b). Some of the perceived advantages of the additive approach have been identified as reducing waste, improving responsiveness, making low-volume production viable, promoting customization, and supporting innovation in design. As a result of such capabilities, since inception there has been much enthusiasm for Additive Manufacturing technologies to produce a wide range of different parts for a variety of applications, with Wohlers (2014) identifying the total industry size as growing from $295m in 1995 to $3.07bn in 2013.

As the technologies have matured, the way in which they are utilized in industry has changed. The first Additive Manufacturing technology (Stereolithography) was patented almost thirty years ago (Hull 1986), and since this time many different Additive Manufacturing technologies have been developed. Originally employed in the production of one-off prototypes in laboratory-like environments, some Additive Manufacturing technologies are today finding increased application in the direct manufacture of end-use goods, particularly in highly customized or complex geometrical applications. In 2003 3.9% of all Additive Manufacturing was in the production of end-use parts; by 2013 this had risen to over 34% (Wohlers 2014). At the same time, whilst the ability to viably produce one-off parts has remained an important characteristic of the technologies, increasingly higher volume production has been evidenced in recent years, particularly for applications where Additive Manufacturing has displaced other techniques.

This progression from prototyping, to single unit customization, to higher volume production is an important acknowledgement for the context of this work. In ‘prototyping’, emphasis typically focuses on the achievement of individual, accurate one-off models that can be used for product development (e.g. Nyaluke et al. 1995). By contrast, when employed in ‘manufacturing’ the technologies may be producing a range of different products at different volumes, within a range of competitive priorities (e.g. cost, quality, speed, dependability, flexibility). As Additive Manufacturing technologies become employed in ‘manufacturing’, rather than merely ‘prototyping’, implementation requires a range of different resources to fulfil demand. For conventional manufacturing, the marshalling and controlling of a multitude of related resources is often considered a fundamental tenet of a ‘manufacturing system’ (Hitomi 1996), whereby emphasis is placed on the integrated whole, rather than the individual components (Parnaby 1979). As a result, it becomes increasingly important and relevant for both academia and practice to understand how to manage Additive Manufacturing from a *systems* perspective, rather than the individual *technologies*.

This ability to manufacture has led to increasing interest in the opportunities afforded by Additive Manufacturing (and also the related, but not synonymous concept of 3D Printing) from both media and academia, with some authors suggesting the technologies will bring about a revolution in manufacturing (Anonymous 2008, 2011a; Barnatt 2013; Berman 2012; Bogue 2013; Jinks 2013; Manyika et al. 2013; Peels 2013; Potstada and Zybura 2014). In terms of government policy, Additive Manufacturing has recently been identified as a significant contributor to competitive strategies for a number of governments (e.g. European Commission 2014; Foresight 2013; Obama 2013; TSB 2012), highlighting its importance and relevance for manufacturing. For some, Additive Manufacturing is a disruptive technology, which in time will serve to fully displace ‘conventional’ approaches to manufacturing (Anonymous 2011a; CSC 2012). Although such prophesies may be considered sensationalist, as recognized by Holmström and Romme (2012) it is apparent that Additive Manufacturing does have the potential to radically change operations practice, for which research is needed to understand this impact.

However, whilst the technologies offer much potential for manufacturing applications, it is acknowledged that much hype surrounds them (Taylor et al. 2013), and many of the practical implications are often overlooked. For example, when referring to the ‘Dirty Secrets’ of Additive Manufacturing in a call for research, Wilson spoke of the disjunction between some perceptions of Additive Manufacturing and the practical realities:

> "You press a button and it comes out, doesn’t it? Rubbish! It’s not true is it?"
>
> *Robert Wilson 11 December 2012*
> *Lead Technologist, Technology Strategy Board*

Additive Manufacturing and the related concept of 3D printing are still evolutionary, and whilst they are increasing in commercial prevalence there are still many challenges in terms of perfecting both the machines and support processes. Acknowledging the imperfect state of existing machines and the requirement for additional activities in the manufacture of parts, Peels (2013, p. 15) identified that “if 3D printing is the future, the future is going to suck and have a lot of sandpaper in it”. These two observations are important, since they support a perspective that to understand that application of Additive Manufacturing in manufacturing environments, it is necessary to look beyond some of the simplistic evaluations of the technologies and instead appreciate the practical constraints that may be readily observed in a manufacturing system.

Despite the potential commercial applications, the accelerating rate of technological improvement and commercial adoption has not been matched in research that considers the consequences for the management of Additive Manufacturing technologies. Whilst Additive Manufacturing has been identified as an important enabler for concepts such as Mass Customization (Reeves et al. 2011; Tuck and Hague 2006), the implications for businesses that arise has only recently begun to receive research attention (Fogliatto et al. 2012). There are few scholarly Operations Management studies for Additive Manufacturing (Bianchi and Åhlström 2014), and Taylor et al. (2013) have highlighted that technological developments are "out pacing" the development of complementary business knowledge. Of the few studies that exist, many are theoretical and lack empirical evidence, whilst others have been conducted in somewhat idealized laboratory conditions, for which the ability to generalize to the demands and challenges of practical manufacturing environments is constrained. In particular, the emphasis on the practicalities of manufacturing has received scant attention. Whilst there is much evidence in the literature on the capabilities of individual technologies to produce parts, there has been little emphasis on how these machines are employed as commercial manufacturing systems. Recent work by Mellor et al. (2014) has provided a framework of implementation strategies for these technologies, but there remains very little academic understanding of how Industrial Additive Manufacturing may be implemented as a manufacturing system, nor the way in which the technologies interact with other system components.

This relative dearth of research has a number of implications for organizations adopting Additive Manufacturing technologies for real-world, industrial manufacturing. The absence of adequate knowledge of the management of new manufacturing technologies may impair the achievement of desired competitive advantage (Hyun and Ahn 1992). This suboptimal situation may be further compounded by implications for the wider supply chain; from a competitive perspective Christopher (1997) notes that it is "supply chains which compete, not individual companies". Understanding how the adoption of Additive Manufacturing technologies affect, and are affected by, the wider supply chain is an essential requirement for firms operating in competitive markets.

1.3 Motivations for the research

The overall aim of this study is to explore the nature of Industrial Additive Manufacturing Systems as implemented by commercial practitioners, with a specific focus on flexibility within the system and wider supply chain. The preceding section identified the context for this research, highlighting the progression of Additive Manufacturing technologies into commercial manufacturing environments, and noting the dearth of scholarly research that explores these from an Operations Management perspective. Acknowledging this context, this section explores the four principal motivations that underpin this overall aim of this study.

The first motivation for this study stems concerns the current dearth of research that considers Additive Manufacturing in terms of a manufacturing system. To-date the limited academic research has focused on the capabilities of individual Additive Manufacturing machines, but has not taken a systems perspective. As outlined in Section 1.2, contemporary manufacturing practice is far more complicated than 'just press print', and preliminary research has identified that this requires a plethora of different resources need to be managed and controlled to achieve production. A systems' perspective promotes an evaluation of 'wholeness' (von Bertalanffy 1969), encouraging the design and optimization of the whole manufacturing system and its resources, not just the individual machine. Already a wealth of established knowledge concerning the nature of manufacturing systems exists, and this study particularly utilizes the general concept of a manufacturing system (Parnaby 1979, 1987, 1991; Parnaby and Towill 2009a) to define, and subsequently explore the nature of Industrial Additive Manufacturing Systems.

The second motivation for this study arises from the identified potential for Industrial Additive Manufacturing Systems to satisfy different types of demand in commercial settings. As acknowledged in Section 1.2, applications of Additive Manufacturing have moved from one-off production of prototypes and custom parts to the production of much higher volumes extending into tens of thousands of parts. A progression can be seen from craft-like prototyping (D'Urso et al. 2000), through to Mass Customized production (Fogliatto et al. 2012; Reeves et al. 2011), towards enthusiasm for a Mass Production approach (Abrams 2015). Established strategy promotes the matching of process technology to appropriate volume-variety combinations (Hayes and Wheelwright 1979), and whilst several authors have suggested that Additive Manufacturing may lessen this constraint (Helkiö and Tenhiälä 2013; Tuck et al. 2008) there is a lack of empirical research to support this potential. It is recognized that such capabilities could enable Additive Manufacturing to have a major effect on manufacturing industry, though little research has focused on the commercial reality of this proposition and the resulting implications for Operations Management.

This exploration forms the basis of the third motivation for the research, concerning the competitive objective of flexibility. Flexibility within manufacturing systems concerns the ability to change in response to differing circumstances (Gerwin 1987), but without incurring significant penalties in terms of time, effort, cost, or performance (Upton 1994). The concept of flexibility is complex, however a large body of generalist Operations Management knowledge exists in terms of frameworks, typologies, and measures to help categorize and explain it. This detailed understanding has not been extended to Additive Manufacturing, for which many authors have identified it as being 'flexible' (e.g. Chimento et al., 2011; Onuh, 2001), but there is little consistency between studies regarding the meaning of 'flexibility' in this context. In most academic texts the flexibility concept has received a liberal interpretation, failing to explicitly connect it to the extensive research concerning the nature of flexibility in manufacturing systems. The types and measures of flexibility are poorly defined in terms of Additive Manufacturing, and it is therefore unclear as to what types of flexibility are enabled in Additive Manufacturing, and the extent to which these can be achieved. Given the expectation from many authors for Additive Manufacturing to effectively produce a wide range of different products at varying volumes, together with the identified progression from prototyping through to manufacturing, flexibility is an important characteristic that is very poorly understood. In this study flexibility is approached from a systems perspective, recognizing that the contribution of process technology is only one element of a system's flexibility and that for management it is important to consider the system as a whole.

The final motivation for this work is the very limited academic research on supply chain implications which arise from the utilization of Additive Manufacturing, particularly in terms of flexibility. The importance of effective management of supply chains is well established in research, but as yet there has been limited empirical research in an Additive Manufacturing context. One suggested explanation for this dearth is a perception that the technologies are not ready for commercial application. One of the principal dissertations in this area is that of Ranganathan (2007, p. 3), who argued that "the application of RM [Rapid Manufacturing] is only likely to occur in the future", thereby constraining consideration of supply chain implications to a futurist exploration, rather than an empirical examination of current observations. Whilst the technologies are indeed still in development, tens of thousands of machines are in commercial operation worldwide (Wohlers 2014), and are being used in a range of applications including medical (Bibb et al. 2009), automotive (Ong et al. 2008), and consumer (Barrass et al. 2008) applications. Although there has been little consideration of the *manufacturing* readiness for Additive Manufacturing, Brousseau et al. (2009) has highlighted Additive Manufacturing as being one of the most mature micro-manufacturing techniques in terms of *technology* readiness. Hence an exploration of the supply chain is both timely and feasible, and in this work specific focus is given to the flexibility of the Industrial Additive Manufacturing supply chain.

1.4 Research questions

In satisfaction of the overall aim of this study, the following four research questions are posed:

> **Research Question 1: How is an Industrial Additive Manufacturing System structured?**
>
> **Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?**
>
> **Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?**
>
> **Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?**

These research questions were developed in an iterative process, and are informed by a combination of:

i. The author's prior experience of Additive Manufacturing gained as a result of two year's employment as a Research Associate at Cardiff University's EPSRC Innovative Manufacturing Research Centre.
ii. Narrative and structured literature reviews conducted by the author and presented in Chapter 2 of this thesis.
iii. Industry developments identified in trade publications and through engagement with the Additive Manufacturing community in the duration of this study.

During the research the relevance of these research questions has been monitored through analysis of the empirical case research with industrial participants, together with careful observation of developments in academic knowledge. As an aid to the reader, in Figure 1.1 an overview of the research gaps, research questions, and contributions to achieving the overall aim of the study is presented. In this study each research question is tackled successively, and in doing so the nature of the system is defined, evaluated, and through extension to the supply chain a structured, iterative approach to the research is achieved.

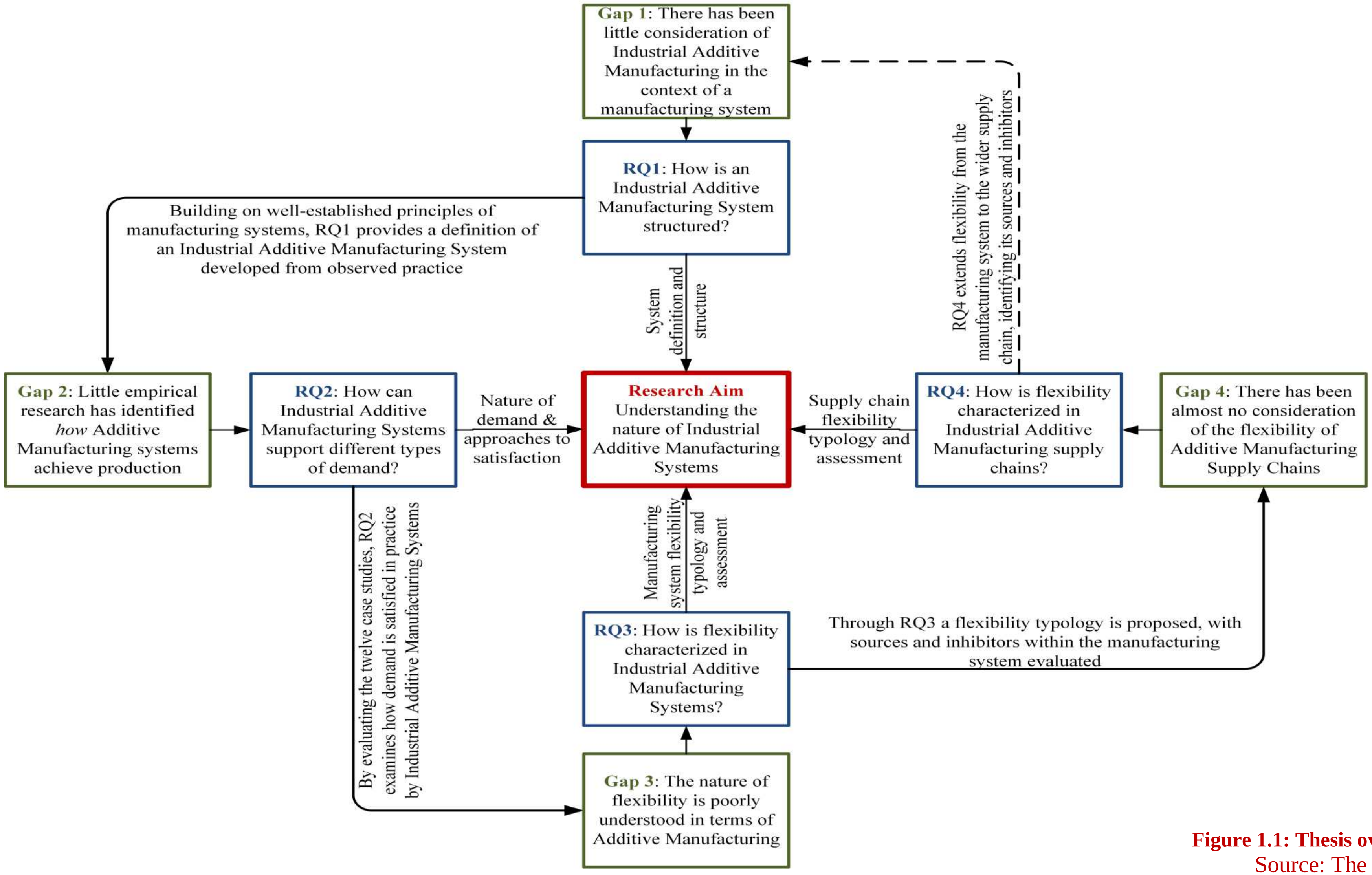

Figure 1.1: Thesis overview
Source: The Author

1.5 Structure of the thesis

The eight chapters within this thesis are ordered as illustrated in Figure 1.2. Some chapters are developed from the author's publications during the research process; as acknowledged by Daft (1995) in general this process of external review and feedback offers benefits and strengthens the work. It is emphasized that any elements of the published works for which the author did not make the majority input are omitted from this thesis, and that all texts have largely been rewritten. Unless explicitly stated in the text through quotation or citation, the author therefore asserts all work included in this thesis to be his own.

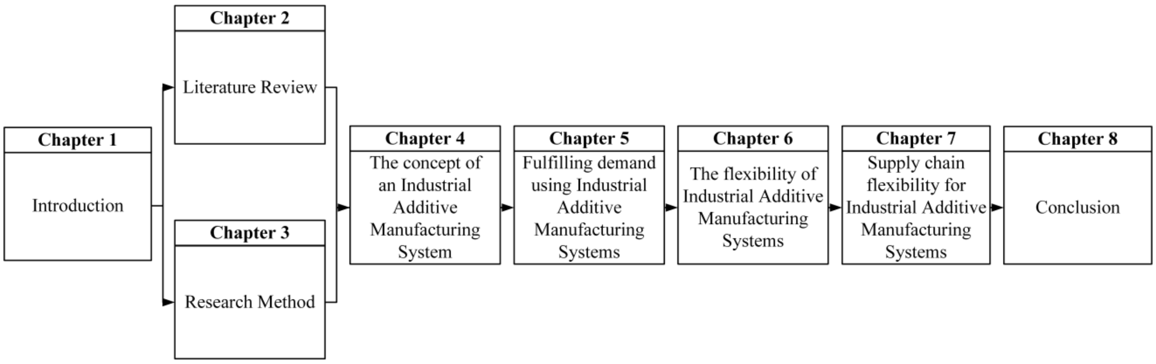

Figure 1.2: Thesis structure
Source: The Author

The first three chapters of the thesis provide the theoretical underpinning of the research, through which the research topic is presented, research gaps identified, and methodological choices justified.

Chapter 1 provides an introduction to the study, explaining the aim, motivation, and structure of the thesis.

Chapter 2 examines the extant literature relevant to this study through the process of narrative and structured literature reviews. Part 1 provides a theoretical basis for the concepts of manufacturing systems, flexibility, and supply chain flexibility, examining the fundamental underpinnings in established works, and the state of contemporary research. From these foundations, Part 2 explores the knowledge of these in the context of Additive Manufacturing using a structured approach to clearly define the boundaries of current research.

Chapter 3 explains the approach taken in the conduct of this research, justifying the use of the methods employed, and detailing how principal challenges were addressed. The chapter provides an overview of the data sources used in this research, and means of analysis (supported by Appendices A and D respectively).

The next four chapters of this thesis present the findings of the research in satisfaction of the individual research questions. Each chapter commences with an overview of its structure and methods employed in the conduct and analysis of the research, and linkage is made between existing theory and the focal research topic. In this manner, the way in which the research is conducted is clearly explained, together with an appropriate grounding in established operations and supply chain knowledge. The contribution of research is summarized within each chapter.

Chapter 4 underpins much of this thesis through its exploration and definition of an Industrial Additive Manufacturing System. This systems perspective carries through the remainder of the thesis, presenting Industrial Additive Manufacturing in the context of a multifarious set of controlled resources, rather than focusing solely on the machines.

Chapter 5 examines the operational characteristics of Industrial Additive Manufacturing Systems in their achievement of different manufacturing requirements. One of the three in-depth case studies presented in this chapter has been published in the Rapid Prototyping Journal, for which the full citation is:

- Soe, S. P., Eyers, D. R., Jones, T. and Nayling, N. 2012. Additive Manufacturing for archaeological reconstruction of a medieval ship. *Rapid Prototyping Journal* 18(6) pp. 443-450.

Chapter 6 addresses the nature of flexibility for Industrial Additive Manufacturing Systems. An earlier version of this work has previously been presented as a conference paper, for which the full citation is:

- Eyers, D. R., Potter, A. T., Gosling, J. and Naim, M. M. 2012. *The flexibility of Additive Manufacturing Systems*. In: *4th World Production and Operations Management Conference.* Amsterdam, The Netherlands, 2-4 July 2012.

Chapter 7 examines how the application of Industrial Additive Manufacturing affects the supply chain, with particular emphasis on supply chain flexibility. An earlier version of this work has previously been presented as a conference paper, for which the full citation is:

- Eyers, D. R., Potter, A. T., Gosling, J. and Naim, M. M. 2013. *Supply chain flexibility for Additive Manufacturing*. In: *20th International EurOMA Conference*. Dublin, Ireland, 7-9 June 2013.

The findings of the study are presented in the final chapter.

Chapter 8 forms the conclusion of this study, in which the work of the preceding chapters is drawn together. This chapter highlights the findings, contributions to knowledge, and limitations of the study. Based on these observations, an agenda is provided to direct future research.

These eight chapters are supported by four appendices, each of which provides additional material to support the main text.

Appendix A provides descriptions of the twelve cases explored in this study.

Appendix B considers the ethical implications of this study, and provides a detailed account of the practices employed in this research to promote ethical research, together with copies of research ethics forms approved by Cardiff University.

Appendix C provides an up-to-date review of the principal commercialized technologies, through which a novel classification is developed. This text has been developed and updated from an earlier version published in Assembly Automation, for which the full citation is:

- Eyers, D. R. and Dotchev, K. D. 2010. *Rapid Manufacturing for Mass Customisation Enablement*. Assembly Automation 30(1) pp. 39-46.

This paper was awarded a “Highly Commended” prize at the 2011 Annual Emerald Literati Awards.

Appendix D contains data extracts from this study that are used to inform the research presented in the main body of the thesis.

1.6 Chapter summary

This chapter has provided an introduction to the research topic, and explained the overall aim of this research which is addressed through four research questions. The structure of the thesis is explained and justified, and the linkages between this doctoral thesis and other scholarly outputs by the author are elucidated.

Chapter 2 Literature Review

Chapter Aims

1. Provide a foundation for the thesis from the relevant theories and concepts in published literature.
2. Provide a historical background and modern perspective on the research topic, and introduce relevant terminology.
3. Explain existing research gaps and develop research questions based on these opportunities.

2.1 Chapter overview

As shown in Figure 2.1, this is the first of two principally theoretical chapters that serve to underpin the empirical research undertaken in this study. The literature review is an essential part of any research project that identifies, evaluates, and explains the state of existing knowledge (Fink 1998). The findings of the literature review inform new work, both by providing knowledge on which new research may be developed, and also in enabling the researcher to be confident of the 'fit' of their contribution within the overall knowledge base.

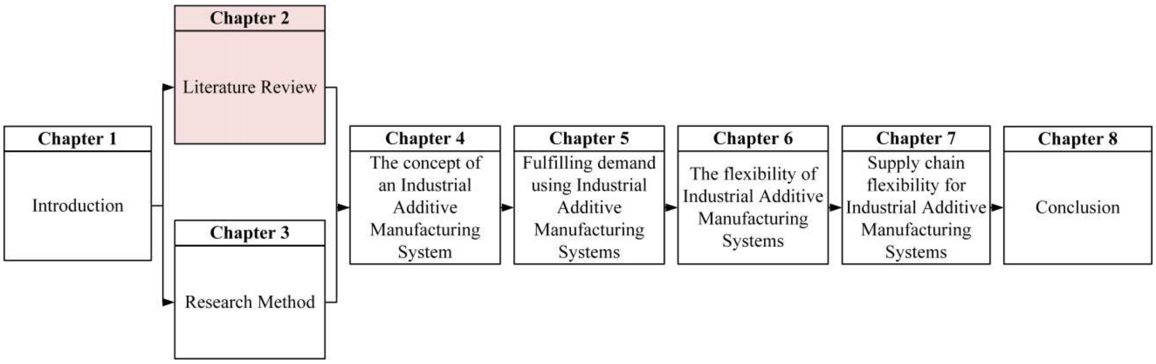

Figure 2.1: Thesis structure
Source: The Author

This chapter examines the literature concerning the concepts of manufacturing systems, variety and customization in manufacturing, and flexibility in terms of manufacturing and supply chains, with particular emphasis for these concepts in terms of Industrial Additive Manufacturing. To achieve its objectives, the chapter is split into two parts as shown in Figure 2.2.

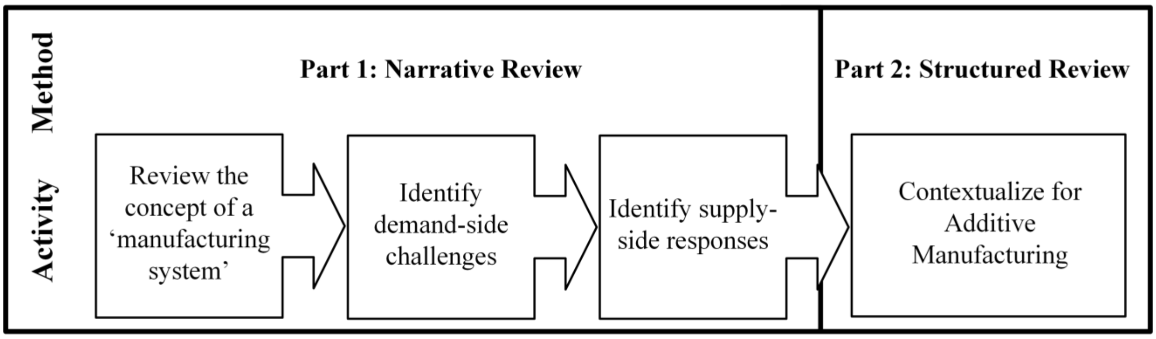

Figure 2.2: Structure of literature review
Source: The Author

Part 1 of this chapter examines research considering general Operations and Supply Chain Management concepts, providing the theoretical foundations on which the thesis is based. This part commences with an assessment of established literature to provide an appraisal on the concept of a 'manufacturing system'. As no single definition of a manufacturing system exists (Parnaby 1979), this review provides a clear definition of the notion of manufacturing systems used within study. Following this exploration of the manufacturing system concept, the remainder of Part 1 investigates relevant literature from two perspectives:

1. Demand-side issues of variety and customization that place challenges on the manufacturing system.
2. Supply-side flexibility responses from both the perspective of the manufacturing system and also the supply chain.

This part of the chapter therefore serves to critically evaluate existing approaches and challenges for manufacturing, providing both the context for the current study, together with the necessary detail to inform the development of analysis tools in Chapters 4 – 7.

Part 2 of this chapter examines four of the concepts from Part 1 in the context of Additive Manufacturing research. Using a structured literature review process, the extent of existing knowledge is demonstrated, providing a structured approach to the confirmation of research gaps and pertinent opportunities for investigation.

As an aid to the reader, Table 2.1 explains the linkage between the four research questions posed in this study, the two literature sections, and the location of subsequent research presented in later chapters of this thesis that satisfies the research questions.

Research Question	Part 1 Section(s)	Topic(s)	Reasons for inclusion	Part 2 Section	Primary Research Chapter
Research Question 1: How is an Industrial Additive Manufacturing System structured?	2.2	• Definition and purpose of manufacturing systems	• To identify the principal characteristics of manufacturing systems. • To explain how a transformative system interacts with its environment in the satisfaction of demand. • To define the concept of a manufacturing system in context of current study.	2.8	4
Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?	2.3 – 2.4	• Volume & variety • Customization	• To clearly explain the nature of different types of demand considered in this study. • To identify established perspectives on the impact of different types of demand on operations.	2.9	5
Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?	2.5	• Flexibility • Flexibility in manufacturing systems	• To provide a detailed appraisal on the nature of flexibility, and techniques for evaluation. • To explore the motivations for flexibility to support demand satisfaction.	2.10	6
Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?	2.6	• Supply chain flexibility	• To identify contemporary perspectives of supply chain flexibility types, and means for their assessment.	2.11	7

Table 2.1: Alignment of literature review to research conducted in this study
Source: The Author

PART 1: Theoretical underpinnings: Manufacturing systems, demand-side challenges, and supply-side responses.

This first part of the literature review serves to provide a theoretical underpinning concerning the Operations and Supply Chain Management concepts that are applied in this study in an Industrial Additive Manufacturing context. Few works have considered Additive Manufacturing from an Operations Management perspective (Bianchi and Åhlström 2014), and so this first part of the literature review provides an important foundation for the study.

2.2 Definition and purpose of a manufacturing system

Modern manufacturing builds on an extensive history of both commercial development and scholarly research. Sprague (2007) and Piercy (2012) chronicle a progression of manufacturing practice, from craft production, industrialization (e.g. Industrial Revolutions), standardization (e.g. Eli Whitney's interchangeable parts), mechanization and automation (e.g. Ford), management (e.g. Taylorism; Gilbreths), and through to a changing emphasis on quality and customer preference (e.g. Mass Customization). At each phase in history the nature of manufacturing has evolved, and with it, the nature of the manufacturing system has changed. Even world geography and culture has been linked to perspectives on systems, with Browne et al. (1996) claiming 'Western approaches' have been shown to favour a reductionist and mechanistic assessment of work, whereas 'Eastern approaches' embrace a more holistic systems viewpoint of the world.

As manufacturing organizations have grown and become more sophisticated the need to manage individual resources collectively has increased, which has partially been facilitated by improvements in technological capabilities (Hitomi 1996). The shifting focus from the individual resource to a consideration of the system requires managers to consider an 'overall approach' to management, allowing for more complex problems to be assessed than is possible through a 'piecemeal' optimization of individual resources (Jenkins 1981). A hard "systems perspective" originated in the mathematical and chemistry disciplines in the 1940's and 1950's (Parnaby and Towill 2009a); a softer systems approach for management was popularized in the 1970's and 80's. In defining a system, Hitomi (1996) identified it to consist of four basic attributes:

1. Assemblage. A system consists of a plural number of distinguishable units which may be conceptual, natural, or artificial.

2. Relationship. Several units assembled together are merely a group or set. For such a group to be a system, a relationship must exist between the units.
3. Goal-seeking. The whole system performs a certain function or aims at multiple objectives (measurable goals).
4. Adaptability to environment. A specific system will change to adapt to changes in its surroundings or external environment.

Modern manufacturing is typically considered with systems in mind, with contemporary topics such as Lean Manufacturing Systems (Womack et al. 1990), Agile Manufacturing Systems (Gunasekaran 1998; Lee 1998), and Flexible Manufacturing Systems (Browne et al. 1984a; Slack 1987) all embracing the systems perspective, though the concept of a ‘manufacturing system’ is not consistently applied in research. Manufacturing systems are “anything but simple” (Pound et al. 2014, p. 7), and this complexity has increased as a result of pressures for greater performance (Efthymiou et al. 2012), leading to the integration of a wide range of research topics being considered within the concept.

Manufacturing is a practical discipline, and it is unsurprising that this functional nature has underpinned many explanations of the concept. For example Groover (2014) considered a manufacturing system to encompass the nature of operations performed, the number of workstations, system layout, automation level, and part / product variety. Similarly, Lee (1998) found a manufacturing system to comprise of machining and assembly subsystems, which transfer a customer order to a realized product. More specifically manufacturing systems may be divided into two types: processing, and assembly (Chryssolouris 2006). In a review of approaches to the classification of manufacturing, McCarthy (1995) identified traditional considerations are based on operational characteristics, operational objectives, operational flow structures, or as either a combination or sub-classification of at least one of these. In his analysis of manufacturing systems, Williams (1988) differentiates from top-down (focusing on systems analysis for management applications such as those explored in the current research), and bottom-up (for systems synthesis in a functional context for engineering).

2.2.1 A top-down perspective of manufacturing systems

One of the most prolific authors on the topic of Manufacturing Systems was John Parnaby, who developed the field from his experience in chemical industries (Towill 2011) in what Williams (1988) identified as a top-down approach. Considering manufacturing as a transformative process, Parnaby (1979) identified a manufacturing system to be one in which raw materials are processed into products, gaining a higher value in the process. Within this definition manufacturing systems are shown to be both dynamic and complex, with individual processes, subsystems, and inter-system interactions all requiring integration and control. Despite differences in their application, Parnaby identified that four general principles may be applied to manufacturing systems:

1. A manufacturing system should be an integrated whole (a system comprised of subsystems).
2. A manufacturing system is a synthesis of energy consuming subsystems which process raw materials, with control systems that manage the system and its interaction with the environment.
3. Information flows and decision making processes are required to operate the system.
4. Operations are constrained such that the fundamental laws of science are satisfied.

The transformative model of a manufacturing system in which inputs are transformed into outputs is widely discussed in literature, and, as demonstrated by BSI (2013) is consistent with practice. There are however some notable permutations that affect its definition; for example Hopp and Spearman (2008) identified the ‘formal cause’ (or fundamental essence) of a manufacturing system involves only two elements: demand and transformation. The supply-side input is, in their view, encompassed by the whole transformative process and should not be considered distinct from it; in essence this definition blurs the boundaries between an internal manufacturing system and the supply-side element of the supply chain discussed in Section 2.6.

In the development of such a transformative manufacturing system, de Neufville and Stafford (1971) identified that there are three principal factors which should be considered:

1. The mechanics of the transformation process.
2. The values associated with the physical resources (inputs).
3. The values of the products (outputs).

Whilst each of these factors is important in the determination of the manufacturing system, only the mechanics of the transformation process are normally within control of the system designer, yielding the adapted transformation system (Figure 2.3). The nature of the inputs is determined by organizational requirements arising from market demand, which in turn must be transformed to meet outputs. Despite the inputs to a manufacturing system not being fully-controllable, Parnaby (1979) asserted that system control is attainable by careful design and a professional approach in the execution of the system; in other words a proactive approach to both the design and management of a system should be adopted to best ensure alignment with requirements.

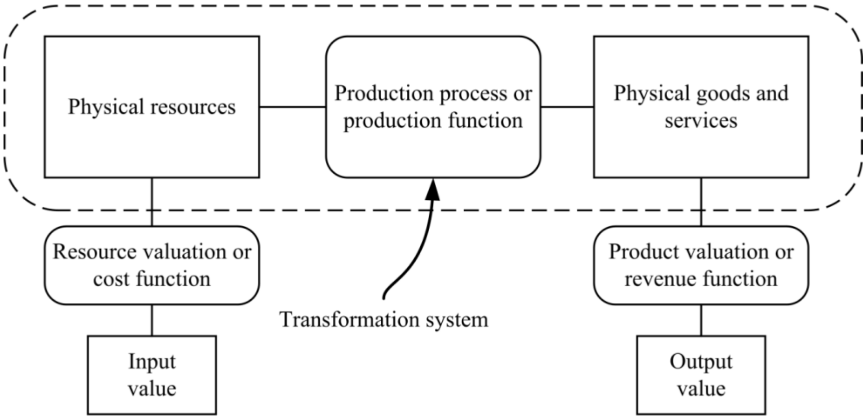

Figure 2.3: Extent of a designer's influence on the manufacturing system
Source: de Neufville and Stafford (1971)

2.2.2 Delimiting the elements of a manufacturing system

As demonstrated in the previous section, many definitions of a manufacturing system concern the physical resources employed in the transformative process. Jenkins (1981) identify system resources as the “four M’s”: Men (labour), Money, Machines, and Materials. More sophisticated definitions consider non-physical resources such as information (e.g. Chryssolouris 2006; Parnaby 1979; Parnaby and Towill 2009a), and it is important that the system is able to effectively manage different resource types. Bhattacharya et al. (1996) identified that a manufacturing system has both focus (in terms of the scale and scope) and alignment (to the requirements of the market). To afford increased focus in evaluation, systems may be decomposed into subsystems that make it easier to design and manage the plethora of different resources. Non-trivial manufacturing systems consist of a complex arrangement of components, each of which has a range of different attributes and capabilities. They exist as part of an overall company system, through which information and control passes between individual functional subsystems (Alcalay and Buffa 1963). The use of hierarchical breakdowns of the manufacturing system is commonplace (He et al. 2014), and BSI (2013) identify that a manufacturing system is considered at the factory level, subdivided into work centres/cells, and then into individual manufacturing resources (e.g. equipment).

Whilst splitting a complex system into smaller components for management purposes is logical, such division should be carefully evaluated. The objective of a manufacturing system design is to integrate the multitude of individual components to achieve a dependable, smoothly operating system that meets its overall objectives. A system’s performance is critically dependent on the effectiveness of each of the component parts to work together, not the independent performance of each (Ackoff 1997). The interaction between systems and subsystems yields ‘emergent properties’, and Mason-Jones et al. (1998) highlight that these are what make the system greater than the sum of its component parts. A system comprised of components must, in the long term, operate irrespective of continually changing constraints and external disturbances (Parnaby and Towill 2009a). If individual subsystems are properly aligned, when operated they are able to achieve predefined weighted objectives (Parnaby 1979). To appropriately manage the decomposition of a manufacturing system into subsystem components, Cochran et al. (2001) emphasize four basic requirements:

1. Objectives must be clearly separated from their means of achievement.
2. Low-level activities and decisions should be related to high-level goals and requirements.
3. Interrelationship between systems elements should be understood.
4. Effective communication across the organization of objectives and means.

Through this approach the system is designed to meet the requirements, and then the low-level activities and decisions (e.g. which machines should be operated? for how long? which product do we make first?) may be properly aligned to these overall requirements.

2.2.3 Managing disturbances to the manufacturing system

Since the transformative system relies on inputs and outputs that are external to the manufacturing system, it is identified that manufacturing systems exist within an environment where both materials and information flow (Figure 2.4). Such a transformative model is an open system, as it interacts with its environment and changes its internal structures and components in adaptation (Kast and Rozenzweig 1981). It is reliant on the environment to both provide inputs and to accept outputs from the system for its on-going survival, and where these are in balance a “steady-state” exists. Unlike the closed system that is subject to entropy, the open system that can adapt to environmental changes is able to maintain effective performance of its functions (Kast and Rozenzweig 1981).

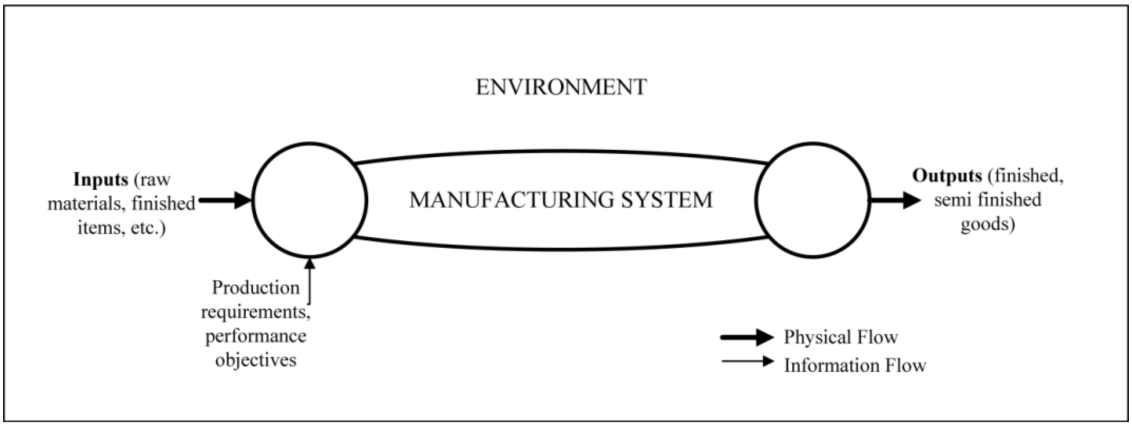

Figure 2.4: A manufacturing system in its environment
Source: Shewchuk and Moodie (1998)

However, environmental influences may be considered as disturbances, which unless handled appropriately will detract from the basic requirement of a manufacturing system for long-term stable operation (Parnaby and Towill 2009a). Robust systems are able to retain their performance in spite of disturbances, whereas resilient systems are able to recover to their original state after the disturbance has occurred (Spiegler et al. 2012).

Many disruptions to the system may be anticipated in advance, but their exact nature will be uncertain. Ho (1989) identified two principal groups of uncertainties:

1. Environmental uncertainty arising *outside* of the production system
2. System uncertainty arising *within* the production system

Although environmental uncertainties are external to the production system, they directly impact its operation. Supply chain uncertainties have been shown by van der Vorst and Beulens (2002) and Prater (2005) to be numerous and multifaceted. Uncertainties external to the system include the nature of demand and supply. Demand uncertainties may include required volumes, varieties (and customizations), and lead-times. Supply uncertainties arise from the performance of upstream suppliers to satisfy the input requirements for the focal system. Identification of the nature of environmental uncertainties by Gosling et al. (2013) found that demand, supply, process, and control uncertainties are closely related.

Uncertainties internal to the system may be subdivided as arising from internal supply and internal demand (Koh et al. 2002). Internal supply uncertainties may result from unexpected delays and shortages within the production system that have knock-on effects for later processes. Internal demand uncertainties exist where unexpected demand is experienced within the system, for example as a result of quality variation in manufacturing leading to part shortages.

Although it is conceptually useful to distinguish between the internal and external nature of uncertainties, the effective management of manufacturing systems requires that these are dealt with in a coordinated manner. Newman et al. (1993) identified that the use of buffers (of inventory, quoted lead-time, and capacity) have traditionally been employed within the manufacturing system to hedge against the negative impacts of uncertainties. These are, however, suboptimal approaches that inhibit the system operating at its full potential, and therefore reactive strategies to uncertainty are now commonplace. For manufacturing systems, two principal approaches are prevalent in the literature. The first is the proactive attempt to minimize the impact of uncertainty through intelligent planning of the production process in-line with the development of products. Postponement strategies are long established as a means of reducing the costs of uncertainty by delaying differentiation of demand (Bucklin 1965). More recently these have been linked to strategies for supply chain management (Feitzinger and Lee 1997; van Hoek 2001; Yang et al. 2004). A second approach to mitigating uncertainty is the design of a manufacturing system that can effectively change in response to the requirements placed upon it. Flexibility, and flexible manufacturing systems (FMS) have formed the basis of much work in providing an effective response to uncertainty in manufacturing (see Section 2.5). More recently, Wiendahl et al. (2007) has proposed that different types of changeability may arise at different hierarchical levels of the manufacturing system for different hierarchies of product:

1. Changeover-ability, through which single machines are able to perform different known options.
2. Reconfigurability, where a manufacturing system can reconfigure to produce different pieces of subsystems through reprogramming and re-routing work.
3. Flexibility, in which the entire production system switches to new (albeit similar) families of components.
4. Transformability, in which an entire factory structure can switch product families.
5. Agility, in which entire companies can move into new markets and manufacture new products.

Each level in the Wiendahl et al. (2007) framework is successively complex, and in practicality involves increasingly wider definitions of a ‘system’, from individual machines and cells through to the most complex arrangements within the network. The term *“changeability”* therefore refers to the ability to change a manufacturing enterprise at all levels (ElMaraghy 2006), not just within individual manufacturing systems. Notably, unlike flexibility in which a system moves to-and-from states, change is “permanent” (Oke 2005).

2.2.4 Controlling the manufacturing system

The effective operation of a manufacturing system requires that, despite the external influences placed upon it, long-term stable operation is achieved through having appropriate control systems in place (Parnaby and Towill 2009a). The importance of control within the manufacturing system is paramount, as Baker (1998, p. 300) observed “factory control is the central nervous system of a factory; it co-ordinates the use of the factory’s resources, giving the system its purpose and meaning”. Ideally, control systems should be designed with such flexibility that they are able to adapt to accommodate disturbances, however in practice this is not always the case (Brennan 2000).

Several different perspectives on the nature of manufacturing control have been offered in the literature. Conceptually, Baker (1998) demonstrates a simplified relationship between the manufacturing system and its internal information sources (sensors and actuators), and the external market-based information sources (Figure 2.5). A more detailed appraisal of control within a manufacturing production system was given by Parnaby (1979), who proposed that that control may arise at four levels:

1. A management control level which oversees the entire system.
2. A production control level which handles activities such as scheduling, inventory control, maintenance, and personnel allocation.
3. A process control level which manages the individual manufacturing processes.
4. A materials flow control level to manage materials through each stage of the manufacturing process.

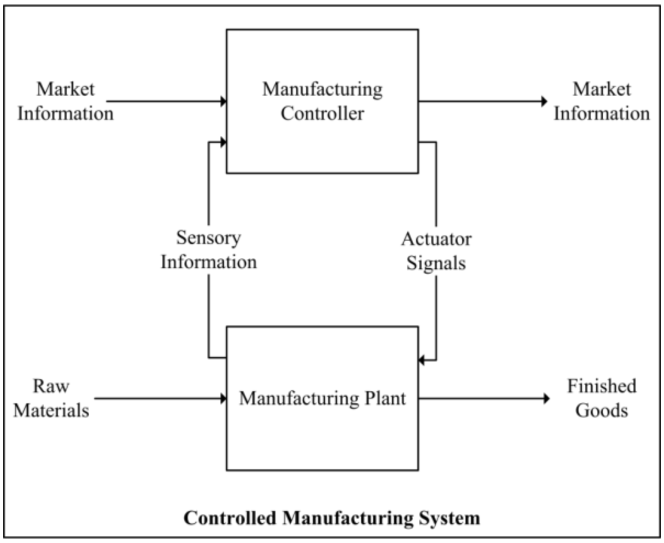

Figure 2.5: Control within the manufacturing system
Source: Baker (1998)

Parnaby (1979) therefore identified control within a manufacturing system as being multi-level, and hierarchical in nature. This is supported by He et al. (2014), who have claimed that manufacturing systems are always hierarchical, and advocate the control system should therefore follow this structure as much as possible. This hierarchical approach to the control of the internal production system is consistent with many of the early approaches to the control of manufacturing systems (e.g. O'Grady 1986). However Brennan and O (2004) identify that the functional activities undertaken in manufacturing control should be distinct from the architecture of the control system, allowing activities to be undertaken by one or more entities within the system, interconnected within the control architecture (Figure 2.6).

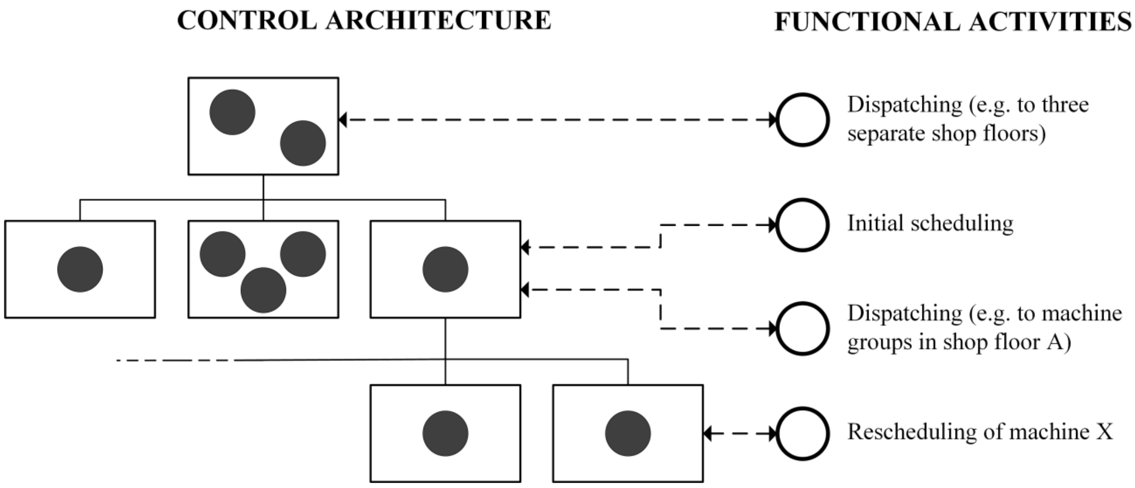

Figure 2.6: Functional activities and control architectures
Source: Brennan and O (2004)

Dilts et al. (1991) identified that different control architectures define the way in which process components interact, and affect the flow of monitoring and control information within the system. At the most fundamental level, control architectures allocate decision making responsibilities to control components; by changing the architecture the way in which the system is controlled may be substantially altered. Figure 2.7 presents the generic framework of four control architectures proposed by Dilts et al. (1991) in the context of automated manufacturing, which despite being almost a quarter of a century old, still remains a popular means of characterizing control architectures for generic applications in contemporary works (e.g. Haneyah et al. 2013). The following text overviews each control architecture, with a summary of both merits and demerits provided in Table 2.2.

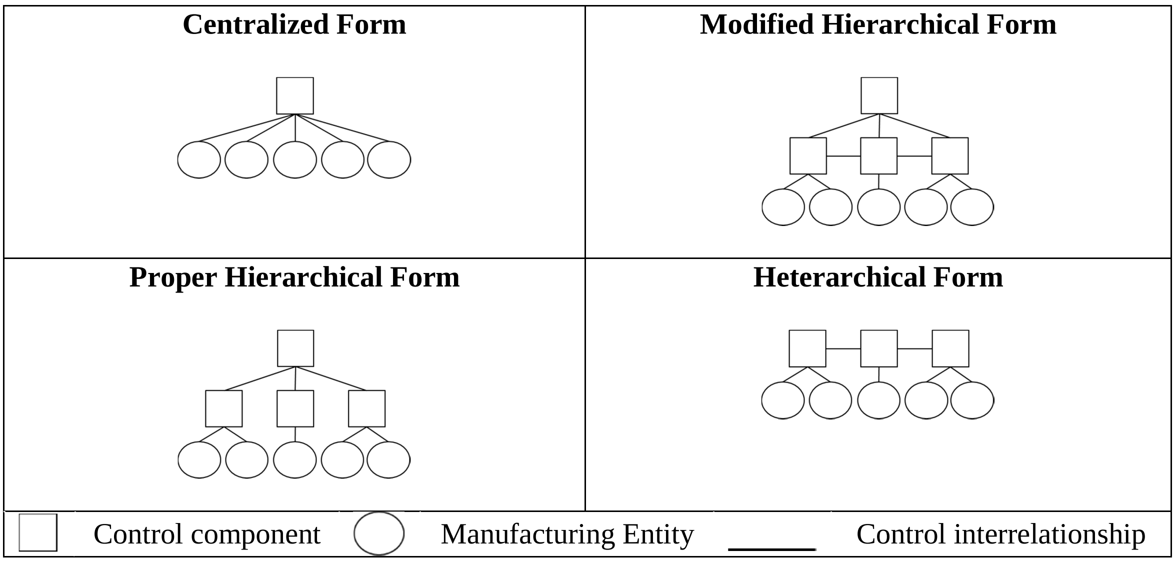

Figure 2.7: The four basic forms of control architecture
Dilts et al. (1991)

1. Centralized Form was the first form of manufacturing control system, in which a single control component makes decisions for all of the manufacturing entities of the system. In this approach, decision-making control occurs at a single location, with distributed non-intelligent controllers executing these decisions at a local level. As with the hierarchical forms described subsequently, the centralized form mirrors the physical hierarchy of a manufacturing system, but lacks operational flexibility as a result of the centralized control (Columbo et al. 2006; He et al. 2014).

2. Proper Hierarchical Form decomposes the manufacturing system into a number of different levels, for which each sub-layer is a slave to the master above it. In this form, control decisions occur top-down, with the aggregate decisions occurring at the uppermost levels and more detailed decisions made at lower levels (Jones and McLean 1986). Conversely, the system status is reported bottom-up to the uppermost levels. Effectively, such hierarchical approaches operate similarly to centralized architectures, with managerial activities such as scheduling occurring at higher levels, and execution at lower levels (Duffie and Prabhu 1994).

3. Modified Hierarchical Form is an extension on the Proper Hierarchical Form that allows communication in a peer-to-peer relationship between control system entities. In this form, greater autonomy is granted to the individual manufacturing entities, and greater processing and decision making performed by these than in the previous two forms (Dilts et al. 1991). This localization of control improves the robustness of the system to random disturbances, and its ability to respond quickly to changing conditions. However, vertical control and horizontal communication between entities requires management, which can be a challenge for hierarchical-based approaches (Morel et al. 2007).

4. Heterarchical Form arose in the 1980's as an alternative to the hierarchical approach to control. Heterarchical control architectures enable local autonomy for manufacturing entities, and removes the master/slave relationship found in the hierarchical architectures (Duffie and Piper 1986). The manufacturing control system is effectively distributed amongst a network of intelligent agent controllers, each managing their local resource. Importantly, the physical system configuration is transparent to the entities of the system: there is no need for these to know where other entities reside (Duffie and Prabhu 1994). Within a co-operative heterarchy, Duffie and Prabhu (1994, p. 95) identify:

1. Entities have equal rights of access to resources.
2. Entities have equal mutual access and accessibility to each other.
3. Entities have independent modes of operation.
4. Entities strictly conform to the protocol rules of the overall system.

Although heterarchical control systems promote fault tolerance and localized optimization, it is identified that this may be at the detriment of an overall global optimization for the manufacturing system (He et al. 2014).

In addition to these four architectures it is acknowledged that alternate approaches are also promoted for manufacturing systems. Increasing requirements for flexibility, robustness, responsiveness, and configurability are challenging the suitability of the traditional centralized and hierarchical control architectures (Leitão 2009), leading to other approaches being implemented including holonic and agent-based control architectures.

Control Architecture	Advantages	Disadvantages
Centralized	Global access to information for optimization Reduced number of decision-making units Central source of information	Reduced speed (as a result of managing many tasks) Reduced speed (as a result of variety) Single point of failure Difficult to modify / reconfigure
Proper Hierarchical	Phased introduction possible Redundancy of components for fault-tolerance Cost reduction through multiple, smaller, control systems Greater information processing capability through multiple systems Faster response time Complexity reduced, responsibility and authority limited	Potential for unreliability in communications links Potential for delays in communications Difficult to modify / reconfigure structure Potential of failure at one level to halt all lower levels
Modified Hierarchical	Phased introduction possible Redundancy of components for fault-tolerance Increased autonomy of manufacturing entities Management by 'exception'	Potential for unreliability in communications links Potential for delays in communications Difficult to modify / reconfigure structure Increased reliance on local data processing
Heterarchical	No supervisor; entities dynamically co-ordinate themselves Containment of faults within entities Reduction in system complexity Opportunities for modularity and extendibility Development cost reduction	Complexity in coordinating global system Reliance on communications links Potential for deadlock

Table 2.2: Comparison of control architectures
Source: The Author based on Dilts et al. (1991); Duffie and Piper (1986); Duffie and Prabhu (1994); Jones and Saleh (1990); Jones and McLean (1986); Mařík and Lažanský (2007)

2.2.5 Defining a contemporary manufacturing system

The preceding sections have demonstrated a wide range of perspectives on the nature of manufacturing systems and their analysis. This review has considered manufacturing as a transformative activity, and has therefore concentrated on the transformative perspective of manufacturing systems found in the literature. In particular, the seminal works of Parnaby (1979) and Parnaby and Towill (2009a) are acknowledged as of considerable relevance to understanding the nature of manufacturing systems. This review highlights three other important concepts particularly relevant to contemporary studies:

Structure: Manufacturing systems bring together a multitude of resources to form the relationships necessary to achieve identified objective(s) (Hitomi 1996). Consisting of subsystems, and typically arranged in a hierarchical manner, the advantage of manufacturing *systems* over individual manufacturing *resources* is (in theory at least), that a system's capabilities are greater than the sum of its parts (Mason-Jones et al. 1998). Definitions of manufacturing systems should therefore embrace the notion of this advantage, and identify the difference between resources grouped as a system, rather than as a set.

Environment: Manufacturing systems exist within organizations, and there is integration of information and control between the manufacturing system and the company within which it operates (Alcalay and Buffa 1963). They therefore exist within an internal environment (the focal organization / factory), and the wider external environment (upstream and downstream in the supply chain), and need to accommodate a variety of disturbances.

Control: The ability to effectively control the manufacturing system is essential, and this control may arise at different levels of abstraction within the system. Beyond this basic control definition, a number of different control architectures have been proposed in the context of automated manufacturing systems (Dilts et al. 1991), each of which has its own merits and demerits.

In the management of manufacturing systems, control shares some commonalities with these engineering-based origins, but as Parnaby (1979, p. 130) identified, "manufacturing systems involve many people and exist to serve people, and clear recognition of this fundamental point is critical to good control". Management control of a manufacturing system may therefore receive data from a variety of sources, and will be co-ordinated in different ways. It may be hierarchical through the four-level approach of Parnaby (1979), or could exploit one of the other control architecture approaches (e.g. as presented by Dilts et al. (1991)).

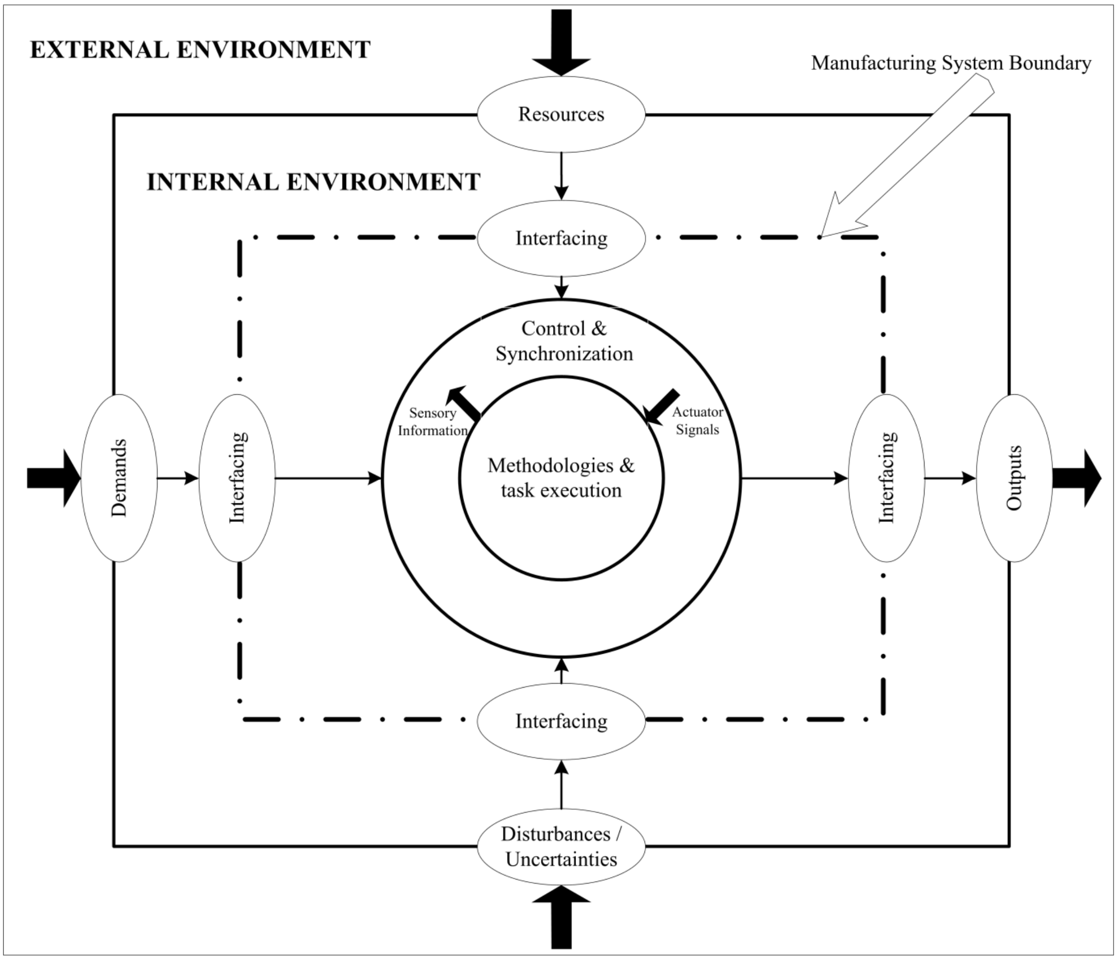

Figure 2.8: Concept of a contemporary manufacturing system
Source: The Author, adapted from Parnaby & Towill (2009) and Baker (1998)

In this study, the concept of a manufacturing system is defined as "a structured collection of manufacturing resources that are organized and controlled in order to transform input resources into useful outputs to satisfy market requirements". As demonstrated by Parnaby (1987), these resources include people, processes, machines, computers, information flows and organizational structures. This definition makes a distinction between the manufacturing resources of an organization, and other non-manufacturing resources.

Based on the literature review, an adaptation of the concept of a manufacturing system by Parnaby and Towill (2009a) is presented in Figure 2.8 to include the additional environmental and control considerations, and this forms the definition of a manufacturing system used in this work in the evaluation of Industrial Additive Manufacturing Systems. Notably, it delimits the manufacturing system and its internal environment as separate from the external environment; in other words identifying the manufacturing system and the other entities within the supply chain.

DEMAND–SIDE CHALLENGES

The transformative manufacturing systems described in Section 2.2 serve to produce products in satisfaction of demand, for which the following three sections identify some pertinent challenges.

2.3 Volume & variety

The Industrial Revolutions that took place in UK, USA, and several Western European countries in the Eighteenth and Nineteenth centuries emphasized the achievement of improvements in manufacturing productivity, often by the standardization of products and processes. At the turn of the 19^{th} century Eli Whitney promoted the use of standardized and interchangeable parts in his production system (Wilson 1995). Similarly, Taylor's (1911) Scientific Management is rooted in the identification and optimization of methods to maximise productivity through the identification of the 'best' approach to the conduct of work, and the implementation of standard operating techniques. Relative to the existing craft-based techniques, such emphasis on productivity encouraged better utilization of resources, and as a result of Mass Production, the achievement of economies of scale in manufacturing through high volume production.

The emphasis on high volumes and the achievement economies of scale to achieve low costs were dominant in Western thinking through to the 1970's, though increasing global competition and changing market requirements were beginning to challenge this logic. The seminal work of Skinner (1974) on manufacturing strategy highlighted that productivity was but one approach to the achievement of successful operations through cost-competition, and that instead the concept of 'focus' in manufacturing was required. Increasing demands for lower volumes may disrupt operations and impair productivity, and so Skinner advocated that factories concentrated on their core competencies, and where this meant tackling the issue of lower volumes, to install focused 'plants within plants'. Subsequent work by Vokurka and Davis (2000) identified that firms employing focus in their operations continued to enjoy higher performance than their unfocused counterparts.

There may be several reasons for a loss of volume in production, arising as a result of internal factors (e.g. changes in strategy, reduction in production capacity etc.), or as a consequence of factors external to the firm. One principal detractor from the achievement of higher volumes is a change in market requirements as a result of increased demand for *variety* in production. Variety may be defined as the number or collection of different things of a class of the same general kind; a variant is an instance of the class which exhibits slight difference from the norm (ElMaraghy et al. 2013). Product variety is the "the breadth of products that a firm offers at a given time" (Fisher et al. 1999, p. 297), and therefore may be considered in terms of the range of distinct products available. It is, however, unlikely that these would be unrelated: within a single factory a manufacturer is likely to produce Car_A, Car_B, and Car_C (each sharing some commonality), rather than Car_A, $Lemonade_A$, and $Pharmaceutical_A$. Commonality between product range items is possible when one considers that an individual product may be considered in terms of a hierarchy of other elements. Different granularities may be identified in the literature; for example Prasad (1998) identified the system (product) to be comprised of various subsystems and components, whilst a more detailed hierarchy of a whole product portfolio system is promoted by ElMaraghy (2009) in Table 2.3.

Hierarchical Level	**Description**
Product Portfolio	The range of different products offered by a company.
Product Platform	The set of sub-systems and modules (and related interfaces) that form a foundation used to produce a number of products that have common features.
Product Family	A collection of related products that share some characteristics, subassemblies, and/or parts/components.
Product	A collection of subassemblies/modules, the variation of which leads to different instances of the product
Product Module or Subassembly	Fully functional independent units that consist of more than one part/component and are intended to fulfil one or more technical function.
Part Family	A collection of parts that share some characteristics, parts and/or part features.
Part / Components	Objects that are non-decomposable/non-divisible without loss of function.
Part Features	Geometric or functional features.

Table 2.3: Part and product variant hierarchy
Source: ElMaraghy (2009)

The achievement of variety, and its management in operations and the supply chain are key determinants of a variety-influenced strategy (Ramdas 2003). Firms may compete with each other on the variety of different products that are offered, but such increased product line extension can have negative impacts for the brand, supply-chain relationships, production costs, and ultimately profitability (Quelch and Kenny 1994). Without careful management, increasing variety may lead to negative implications for set-up operations (number, duration, and cost), direct and indirect labour productivity, decision making, line balancing, quality, supplier management, inventory management, and uncertainty. A summary of literature concerning the implications of variety on operations is presented in Table 2.4.

Author(s)	**Research Topic**	**Summary of research findings**
Berry and Cooper (1999)	Implications of product variety on manufacturing performance	Achievement of competitive advantage through the offering of increased variety is heavily dependent on achieving the proper alignment between marketing and manufacturing strategy.
Hu et al. (2008)	Linkage between product variety and complexity in assembly and supply chain	Increasing variety requires workers to make more decisions concerning specific customer orders, leading to increased uncertainty in making choices. This leads to increased complexity, which is magnified through the manufacturing system and supply chain.
Lancaster (1990)	Nature of variety in different types of market	Increasing scale economies acts as a disincentive to increasing product varieties. Variety is offered as a means of competition, and as markets become increasingly competitive (or the threat of new competition exists), the variety offered will increase.
Mapes et al. (1997)	Impact of variety on performance objectives	Increased product variety leads to degradation in added value per employee, speed of delivery, reliability of delivery, and the rate of new product introduction.
Randall and Ulrich (2001)	Implications of product variety on supply chain structures and firm performance	It is beneficial to firms to match their supply chain structures to the type of product variety offered, in order to balance production costs and market mediation costs.
Roy et al. (2010)	Impact of high levels of variety on complexity for design and manufacture	Product variety affects all aspects of a business, and leads to increases in cost for product development, manufacturing, supply chains, and logistics.
Salvador et al. (2002)	Application of different types of modularity to overcome trade-offs in product variety	Different types of modularity are suitable at different volume-variety positions. High volume, low variety is most suitable for application of component-swapping modularity. Low volume, high variety is better served by combinational modularity.
Thonemann and Bradley (2002)	Implications of product variety on supply chain performance	Product variety has a high cost in circumstances where setup times are significant, and where the cost of variety is underestimated companies will offer greater variety than is optimal.
Wan et al. (2012)	Implications of product variety on unit fill rate and sales	As product variety increases, fill rates decrease non-linearly, though the rate of decrease lessens as variety increases. Sales performance and variety is inverse-U shaped: increasing variety initially benefits sales, but after the optimum level reached, cannibalization and negativities in fill rate harm.
Zipkin (1995)	How is performance affected in a multi-item production system?	As the number of products increases, even where a maximally flexible processor is able to responsively switch between products without the penalties of cost or time, production performance is hurt.

Table 2.4: Summary of established positions concerning the implications of variety on operations

Source: The Author

These issues contribute the notion of a trade-off between product variety and operational performance (Salvador et al. 2002), for which much research attention has been devoted. Linking volume and variety for products (at appropriate stages of the lifecycle) with the right approaches to manufacturing was demonstrated by Hayes and Wheelwright (1979, 1984) through their concept of a ‘product-process matrix’ (Figure 2.9 and Table 2.5). Although there is debate over the validity of this work to modern manufacturing when empirically evaluated (Ahmad and Schroeder 2002; Helkiö and Tenhiälä 2013; Safizadeh and Ritzman 1996), it does serve to reaffirm the potential of variety to have major implications for manufacturing and the importance of choosing the correct process types to balance cost and flexibility constraints.

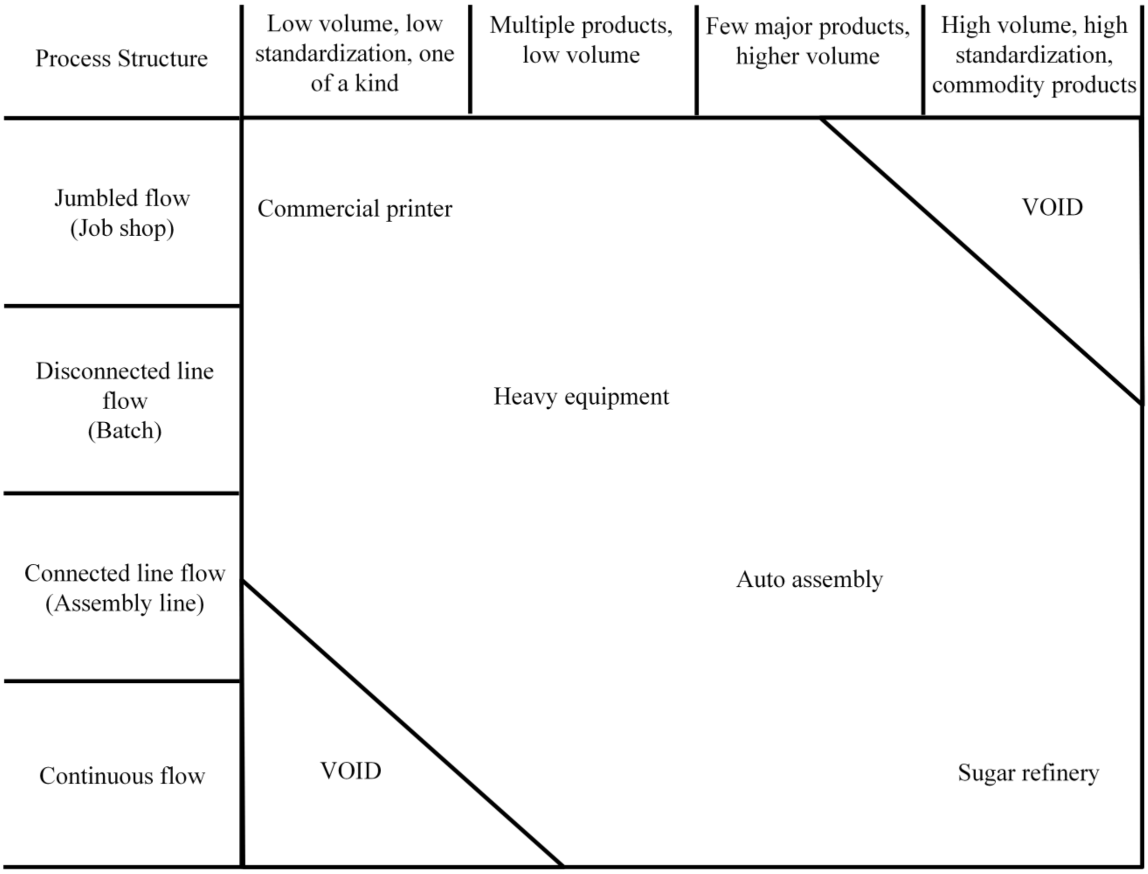

Figure 2.9: The product-process matrix
Source: Hayes and Wheelwright (1979)

Characteristic	Job	Batch	Line	Continuous
Equipment and physical layout characteristics				
Typical size of facility	Usually small	Moderate	Often large	Large
Scale economies	Some, firm level	Varies	Some, plant level	Large, plant level
Potential for learning improvements	Few, mainly in setups	Some	Moderate and continuous	Substantial and continuous
Process flow	A few dominant flow patterns	One or two single dominant patterns	A rigid flow pattern	Clear and inflexible
Type of equipment	Mostly general purpose, some specialization	Varies	Specialized, low and high technology	Specialized, high technology
Capital intensity	Low, as long as capital utilization is high	Varies	Varies, moderate capital intensity	Capital intensive; equipment seldom idle
Definition of capacity	Fuzzy, in monetary terms only	Varies	Clear, in terms of output rates	Clear, expressed in physical terms
Additions to capacity	Incremental over wide range	Varies	Incremental, but requires rebalancing	Some incremental, mostly in chunks
Bottlenecks	Shifting frequently	Shifting often, but predictably	Generally known and stationary	Known and stationary
Speed of process	Slow	Moderate	Fast	Very fast
Control over work pace	Worker and foreman	Worker, foreman, and production supervisor	Process design and management decisions	Equipment and process design
Set ups	Frequent	Some, not complex	Few and costly	Rare and very expensive
Run lengths	Short	Moderate	Long	Very long
Process changes required by new products	Often incremental	Often incremental	Incremental and radical	Often radical
Rate of change in process technology	Slow	Moderate	Moderate to high	Moderate to high
Direct labour and workforce characteristics				
Labour content (value added)	Very high	Varies	Low	Very low
Job content (scope)	Large	Moderate	Small	Varies
Worker skill level	High	Mixed	Low	Varies
Workforce payment	Hourly or piece rate	Often piece rate	Hourly, often tied to percentage of standard	Hourly or salaried
Wage rate per hour	High	Moderate	Generally low	Varies
End-of-period push for output	Much	Frequently occurs	Infrequent	None
Worker training requirements	High	Moderate	Low	Varies

Table 2.5: Characteristics of major categories of production processes
Source: Hayes and Wheelwright (1984)

2.4 Customization

The provision of variety within manufacturing occurs principally as a result of market demand for a range of solutions to meet requirements. Using the classification of ElMaraghy (2009), variety can arise at numerous hierarchical levels, including product, part, and even in terms of specific part features. This variety is, however, standardized: it has been designed, planned, and may be offered as part of a catalogue of options to the customer. In the 'post-industrial' world, many markets are increasingly heterogeneous, and with the application of technology traditional segmentation strategies are giving way to increasing personalization strategies (Kara and Kaynak 1997). Instead of satisfying demand through the provision of variety, the potential to customize products to meet the actual market demand has received considerable research attention. A customized product is one that specifically meets the needs of a particular customer (Mintzberg 1988). There is therefore a difference between simply offering a large number of variations of the product (with the objective of achieving a positive match through sheer number of permutations), and allowing a customer to customise their final purchase to their needs (Duray et al. 2000).

Lampel and Mintzberg (1996) make a seminal contribution to the literature on customization in their recognition of a continuum at which customization is performed within the value chain. Within this continuum they recognize that customization can be achieved at different points of the value chain, leading to the achievement of different degrees of customization. More specifically, the point of customer involvement in the production of a product determines the degree of customization that may be achieved (Lampel and Mintzberg 1996; McCutcheon et al. 1994). Earlier interventions by the customer may support a greater degree of customization, but as a consequence a trade-off between the degrees of customization and the ability of the manufacturer to respond in a sufficiently timely manner may arise. McCutcheon et al. (1994) coined the expression "customization-responsiveness squeeze" to characterise this problem. Furthermore, as the degree of customization increases, so does uncertainty and error, leading to extended development times and increased requirements for rework (Xie and Tu 2006). In this conventional customization, customers may have to wait longer for their items, and pay more for the customization privilege.

Mass Customization is a specific type of customized manufacturing, first introduced by Davis (1987) as being when "the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously be treated individually as in the customised markets of pre-industrial economies". In essence, Davis proposed individualised manufacturing whilst maintaining the economies of scale enjoyed in typical Mass Production. Subsequently, Pine (1993) suggested that the goal for Mass Customisation is to satisfy this individualised customer demand at comparable prices to Mass Production through the provision of a variety of products.

This definition blurs the distinction between variety and customization, and Pine later clarified the definition: "Today I define Mass Customization as the low-cost, high volume, efficient production of individually customized offerings'' (Pine, quoted in Piller 2007). Mass Customization therefore places specific challenges on manufacturers to overcome competing performance objectives for operations.

The satisfaction of manufacturing constraints in the realisation of Mass Customized products is an important aspect of the concept. Early literature focused heavily on cost, with the concept of Mass Customization requiring firms to provide "individually customised products and services at the low cost of a standardised, mass production system" (Hart 1995). The attributes of Mass Customization are non-typical of the normal paradigm for manufacturing management, where traditionally customisation will be associated with creativity, but not the efficiency gains of Mass Production (Duray et al. 2000). Only by achieving economical manufacturing for very small batch sizes will Mass Customization be price competitive when compared to Mass Production alternatives (McTeer Jr. 1998). Firms adopting Mass Customization are therefore challenged to achieve low volume manufacturing which is as economically efficient as high volume mass production, and also to maintain these efficiencies in non-manufacturing activities. Specifically, products should be manufactured or assembled (or a combination of both) to satisfy an individual customer order. Doing this within an acceptable time which is less than the customer's preparedness to wait is challenging, since quick response deliveries are usually based on standardisation, whilst increasing product varieties require flexibility and innovation (McCutcheon et al. 1994).

Mass Customisation is therefore at odds with the original trade-off theory on both the cost and delivery time competitive capabilities. In setting out his original position on trade-offs, Skinner (1969, p. 141) claimed "you can't have it both ways". However, in elaborating on previous definitions of Mass Customisation, Pine et al. (1993, p. 111) proclaim "companies can overcome traditional tradeoffs… companies can have it all". In order to satisfy customer demand, Mass Customization requires the use of the best technologies and most appropriate suppliers at every step of the order fulfilment process, including advanced order management systems, reliable Just-In-Time order fulfilment by suppliers, and flexible in-house manufacturing using advanced production technologies (Duray and Milligan 1999).

Kumar et al. (2007) identify that the focus of recent academic research has moved consideration of Mass Customization from single to multiple trade-offs. Manufacturing operations compete on a multitude of criteria, including cost, quality, speed, dependability, and flexibility, and a core tenet of Mass Customization is the achievement of customization without incurring a penalty on these objectives. An industry survey of 102 UK manufacturing firms by Squire et al (2006) provides a detailed examination on the existence of trade-offs in Mass Customisation. At higher levels of customisation, trade-offs were evident for both manufacturing costs and delivery lead times, though these could be abated for delivery reliability and non-manufacturing costs. Techniques such as modularity, often espoused as a Mass Customisation enabler, did not significantly affect this position. However, in the partial customisation approach that engaged the customer at the assembly phase of manufacturing, trade-offs were not observed. Instead, the authors observed partial customisation to be a cumulative capability, achieved through standardisation of product and process using the concept of modular product architectures and postponement.

SUPPLY-SIDE RESPONSES

To respond to demand-side challenges in terms of variety and customization the concept of 'flexibility' is often considered. The following two sections examine the nature of flexibility from the perspective of the manufacturing system, and also in terms of the wider supply chain.

2.5 The concept of flexibility

2.5.1 Definition

Flexibility is a term used throughout the English language, for which a number of definitions exist:

- "able to be bent easily without breaking; pliable" (Collins English Dictionary 1998);
- "ability to be easily modified", and "the willingness to change or compromise" (Oxford Dictionary of English 2005).
- "yields to influence" (Webster's Revised Unabridged Dictionary 1913).

In common usage, flexibility can therefore be considered a characteristic of a subject involving capability for adaptation without excessive difficulty. However, care is needed with such definitions since a distinction exists within the Operations Management research between the concepts of flexibility and adaptability (Bordoloi et al. 1999), and flexibility and changeability (ElMaraghy 2006; Wiendahl et al. 2007).

The concept of flexibility has a long academic pedigree, with roots in economic and organizational literature from the early 1900's (Sethi and Sethi 1990). In terms of the Operations and Supply Chain Management domains most relevant to this study, the term 'flexible' has received much research attention, initially in the context of manufacturing flexibility, but more recently in the consideration of the broader concept of supply chain flexibility. Although the origins of academic discussions on manufacturing flexibility can be traced back to the early 1980's (including Gerwin 1982; Slack 1983; Zelenović 1982), consensus on what flexibility *is* remains contested. By 1990 at least fifty definitions of flexibility could be observed in the literature (Sethi and Sethi 1990), and by 2006 this plethora of suggested definitions had increased to 141 (Petkova and van Wezel 2006). Numerous reviews (e. g. Beach et al. 2000; Bernardes and Hanna 2009; de Toni and Tonchia 1998; Sethi and Sethi 1990; Stevenson and Spring 2007) have addressed the issue of defining flexibility. A selection of commonly cited definitions is provided in Table 2.6, though as yet no single definition can be considered authoritative. Several authors have offered explanations for the lack of consensus, and to some extent this is justified by Sethi and Sethi (1990), who identified flexibility to be "a complex, multidimensional, and hard-to-capture concept". Oke (2005, p. 974) further posited that "because flexibility cuts across the entire organization and academic literature, it has proved difficult to adequately conceptualize and understand". From an operational perspective, Upton (1994) noted that such ambiguity hampered effective management. Similarly, the failure to understand flexibility has been considered the main cause for flexible manufacturing systems failing to achieve expected performance (Gupta and Buzacott 1989), and for management making costly inappropriate investments (Hill and Chambers 1991). Slack (2005) observed that the preoccupation in the research for defining flexibility has lessened in recent explorations, with the focus now concerning the positioning of the topic as a core operations competence. Despite this acknowledgement, the most recent major review of flexibility (Jain et al. 2013) still identifies that poor managerial understanding of flexibility, together with a shift from operational to strategic application has inhibited its usage.

In the current study, a definition based on Upton (1994) and Gerwin (1987) is adopted: "flexibility is the ability of a system, through its constituent components, to effectively change or react with little penalty in time, effort, cost, or performance in order to respond to shifting circumstances". This definition defines the scope (the system), the action (to change or react with little penalty), and the purpose for the capability (to respond to changing circumstances). It also emphasises flexibility as a potential ability, rather than a permanently operative capability; this is therefore a potential causal power that is not always active.

Source	Definition
Zelenović (1982)	The flexibility of a production system is a measure of its capacity to adapt to changing environmental conditions and process requirements.
Slack (1983, 1989)	How far and how easily you could change what you want to achieve.
Gerwin (1987)	Flexibility is the ability to respond effectively to changing circumstances.
Sethi and Sethi (1990)	Flexibility of a system is its adaptability to a wide range of possible environments that it may encounter. A flexible system must be capable of changing in order to deal with a changing environment.
Upton (1994)	Flexibility is the ability to change or react with little penalty in time, effort, cost, or performance.
Bordoloi et al. (1999)	Flexibility is the ability to change states.
Vokurka and O'Leary-Kelly (2000)	Manufacturing flexibility reflects the ability of firms to respond to changes in their customers' needs, as well as to unanticipated changes stemming from competitive pressures.
Das (2001)	Manufacturing flexibility can be characterized as the ability of a manufacturing system to change states across an increasing range of volume and/or variety, while adhering to stringent time and cost metrics… and can be manifested in different forms and at different levels in an organization.
Zhang et al. (2002)	The organization's ability to meet an increasing variety of customer expectations while keeping costs, delays, organizational disruptions and performance losses at or near zero.
Buzacott and Mandelbaum (2008)	Flexibility in manufacturing and services is a concept that indicates how much leeway we have in the decision making process and in the manufacturing or service system to obtain and maintain good solutions to our operations problems under a variety of conditions.
Fernandes et al. (2012)	Manufacturing flexibility is the ability to deal with a changing environment and can be seen as a competitive priority, but acquiring flexibility has a cost and should be valued.

Table 2.6: Selected definitions of flexibility in literature
Source: The Author

2.5.2 Motivations for flexibility

The achievement of flexibility is seldom the goal of an organisation, typically it is only a means to other ends (Slack 1987). What those ends might be has been given consideration by a range of researchers. Narasimhan and Das (1999) identify that rapid technology shifts, higher risk levels, increased globalization, and greater customization pressures are all motivations for firms to adopt flexibility. Similarly, Chambers (1992) suggested that flexibility was motivated by changes in the market, and the arrival of advanced processing equipment and systems technologies. Gerwin (1987) found flexibility to be a strategic requirement in order to be responsive to customer requirements. de Toni and Tonchia (1998, p. 1593) identified five conditions demanding flexibility: variability of demand, shorter life-cycles (of products and technologies), increased product range, increased customization, and shorter delivery times.

Hyun and Ahn (1992) identified that flexibility can be considered at three principal levels, akin to a top-down perspective of the operations strategy:

1. at the **strategic** level as an enabler of competitiveness;
2. at the **tactical** level in the ability to hedge against uncertainties; and
3. at the **operational** level in the achievement of smooth production flow.

Flexibility as a **strategic** aid to competitiveness may be identified in a range of literature. Abdel-Malek et al. (2000) found that over 90% of managers recognize the ability to achieve flexibility in manufacturing as a key strategy to maintain competitiveness. At the strategic level flexibility provides the ability for firms to compete against each other by being able to respond to changing requirements. In flexibility literature such changes in requirements are often linked to changes in marketplace demand. For example, Gerwin (1993) suggested that managers considered flexibility to enable competitiveness by allowing firms to quickly respond to changing market conditions in the provision of goods to meet changing customer requirements. Similarly Vokurka and O'Leary-Kelly (2000) summarized flexibility to include these customer requirements, however also extend their explanation to also incorporate “unanticipated changes stemming from competitive pressures”. Upton (1995) identified that the achievement of low costs and high quality were no longer adequate competitive weapons, and that by focusing on flexibility a competitive objective over rivals could be achieved; today flexibility is typically identified as one of the competitive priorities of operations (Slack et al. 2010).

There are multiple approaches evident for flexibility at the strategic levels. Beach et al. (2000) noted that there was still some debate over whether to use flexibility either as a reactive capability in response to changing conditions, or as proactive tool to promote competitiveness.

Mirroring battlefield concepts on strategy, Swamidass (2000) highlighted that the strategic value of flexibility can be leveraged either offensively, defensively, or as a combination of both:

1. Flexibility in offense concerns the ability of the firm to respond to new opportunities in the market (by introducing new products, or quickly refreshing product portfolios).
2. Flexibility in defence desensitizes the system to adverse changes, allowing the manufacturer to better cope with uncertainties in the external environment.
3. Flexibility in both offense and defence allows for improvements in efficiency through better resource utilization, reductions in changeover costs, and improvements in capacity management.

Flexibility as a **tactical** response was identified by Hyun and Ahn (1992) as the potential capability to change as a result of uncertainties. Early authors such as Newman et al. (1993) identified that in the passage of time, uncertainties affect manufacturing systems leading to them becoming unbalanced and requiring corrective intervention. They highlighted the usage of buffers to help smooth the effects of external uncertainties in order to keep the system in 'balance' (Figure 2.10). de Neufville and Scholtes (2011) identified that uncertainties can arise from many sources, and as a result, the ability of a system to achieve a multitude of different types of flexibility is advantageous.

There are different types of uncertainty that a system may need to accommodate. de Meyer et al. (2002) identified that there are four types of uncertainties which include general variation (performance factors varying randomly but within a predictable range), foreseen uncertainty (identifiable and understood influences that occur in unpredictable ways), unforeseen uncertainty (major influencing factors cannot be predicted, or deemed so unlikely as to not be expected), and chaotic uncertainty (unforeseen events that wreck all plans).

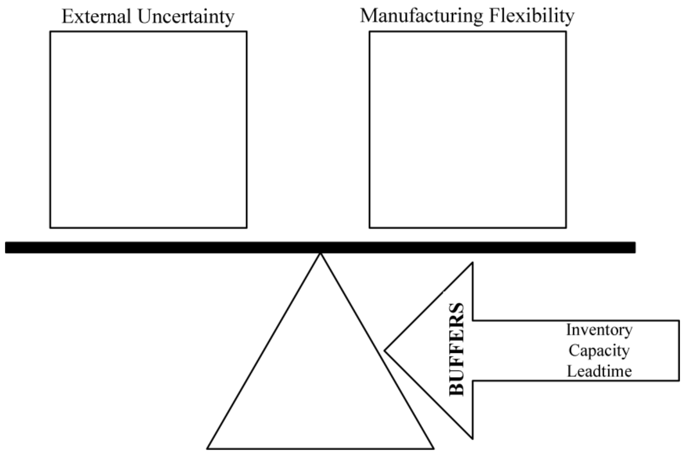

Figure 2.10: Relationship between manufacturing flexibility and external uncertainty
Source: Newman et al. (1993)

Explorations by Sawhney (2006) demonstrate uncertainties to arise both externally and internally to the manufacturing system, and link different flexibility types to the abatement of these (Figure 2.11). Similar to the notion of external flexibilities, system input uncertainties are identified to exist outside of the manufacturing plant (either upstream in supply, or downstream in demand). Likewise, process uncertainties align with the notion of internal uncertainty (considering supply and demand factors within the focal operation). Additionally, uncertainties may exist in output, which represents uncertainty concerning the performance factors of products arising from the system.

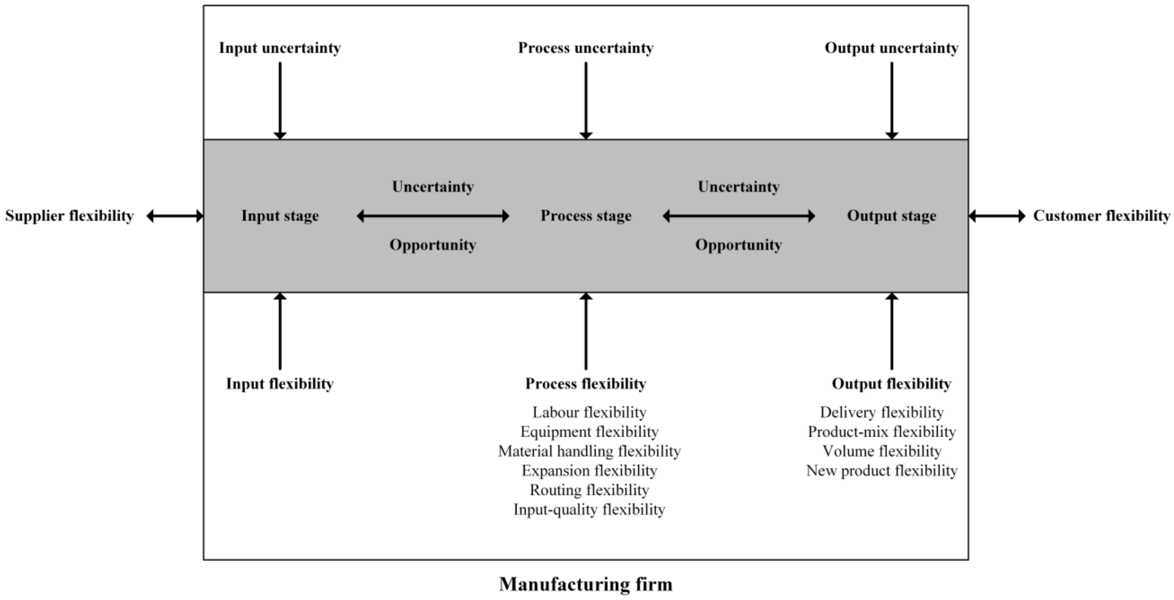

Figure 2.11: Flexibility and uncertainty
Source: Sawhney et al. (2006)

The operational level is that which is closest to the production environment, and is thus most closely linked to the resources that are employed to achieve the production flow. Hyun and Ahn (1992) identified that from a temporal perspective, operational-level flexibilities are those with the shortest term, linking them to 'operational' issues. These may involve day-to-day decision making concerning specific resource allocation, or reacting to immediate demands previously unknown. Flexibility is the operation's shock absorber (Slack 1991, p. 78), and it is at the operational level that flexibility is employed either reactively or proactively to deal with this. Gupta and Buzacott (1989) noted early on that almost all production systems enjoy some degree of flexibility, and it was only the introduction of systems explicitly identified as "Flexible Manufacturing Systems" that brought attention to the concept. Operational flexibilities resultant from the application of advanced manufacturing technologies may be one of several determinants of higher order flexibilities (Narasimhan and Das 1999). Different flexibility types within the operation were identified as mitigating different uncertainty types (Figure 2.12); for example, external uncertainties related to the market demand for different kinds of products will necessitate that the manufacturing operation is able to achieve mix flexibility. For internal uncertainties such as breakdowns, the ability to achieve routing flexibility is important, effectively by moving work to functioning levels of the operations.

Nature of uncertainty	Flexibility type
Demand for the kinds of products offered	Mix
Length of product life cycles	Changeover
Appropriate product characteristics	Modification
Machine downtime	Rerouting
Amount of aggregate product demand	Volume
Meeting raw material standards	Material
Timing of arrival of inputs	Sequencing

Figure 2.12: Flexibility types and uncertainty
Source: Gerwin (1987)

2.5.3 Perspectives of flexibility

In Figure 2.13 a framework of different perspectives on the concept of flexibility is developed by the author in recognition of the different ways in which the topic has been addressed in the literature. The extensive exploration and debate over flexibility in the academic literature has yielded a number of different perspectives on the concept, with much emphasis on how the concept is perceived differently depending on the stakeholder perspective.

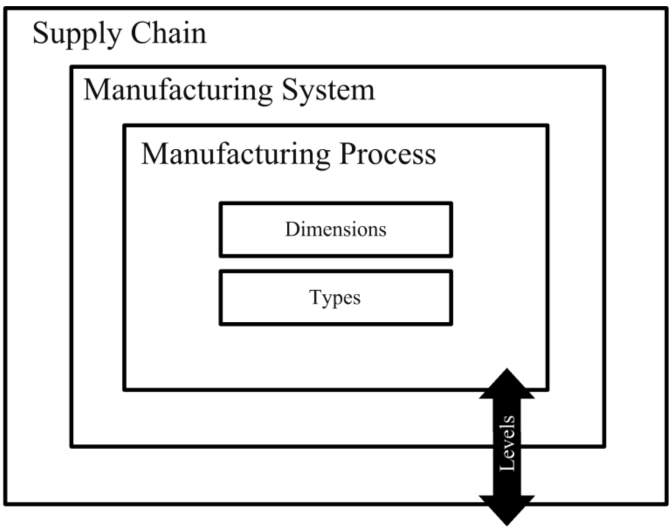

Figure 2.13: Multiple perspectives on flexibility
Source: The Author

Similar to uncertainty, flexibility can also be considered from either internal or external perspectives. Internal flexibilities are those which are perceived within the operation (e.g. the managers and workers), whilst external flexibilities are those which are seen from the outside (e.g. customer or perhaps managerial) viewpoint (Upton 1994). The distinction between these perspectives is viewed by Oke (2005) as a significant source of confusion in discussions on flexibility, through which three important considerations are blurred:

1. How flexibility is perceived external to the manufacturing system
2. How flexibility is characterized at the manufacturing system level
3. The tools and techniques that are able to deliver flexibility

Customers are often unfamiliar with the nature of flexibilities within manufacturing systems, or of the economic or organizational consequences of them (Chen and Tseng 2007). Indeed, they may have incorrect perceptions of the flexibility of a firm, but this may be of little consequence since customers may not care how an order is satisfied, providing it is satisfied (Oke 2005). As such, perceptions on flexibility can be likened to the concept of encapsulation. The outside market and customers have an external perspective which may be considered to only be interested in the capability of operations to be flexible; the actual mechanics of flexibility achievement (the internal perspective) may regarded as a 'black box' for which they have little interest. As Zhang observed:

> "Standing alone, flexible competencies are not adequate to build a substantial competitive edge. While competencies are important, customers do not value them directly. They are unwilling to pay more because machines and workers are flexible. Customers value the manifestation of these competencies, which is the capability of the organization to provide the right product, at the right time, and in the correct quantity."
>
> *Zhang et al. (2003, p. 187)*

For the researcher, perspectives on manufacturing flexibility are therefore an important consideration in the design and conduct of the research. The way in which the flexibility of a manufacturing system will be considered by different participants in the product fulfilment process (whether designer, operations manager, assembly worker, downstream merchandiser or retailer, or final customer) will be informed by their differing exposures.

In addition to the different perspectives on flexibility, it is evident that different levels of analysis exist in the assessment of flexibility. Early studies (e.g. Browne et al. 1984b) focused on the concept of flexibility with emphasis on the machine contributions. By contrast, Slack (1983, 1987, 1988) extended the discussion to consider flexibility at the manufacturing system level, without the constraint of particular manufacturing technology. Through interviews with manufacturing managers it was identified that flexibility of the total manufacturing system was derived from the flexibility of individual structural and infrastructural resources (Figure 2.14). This systems-based perspective has synergies with the concept of the Manufacturing System presented earlier in this chapter, particularly in terms of the different types of resources and their hierarchical arrangement contributing to the flexibility of the total system.

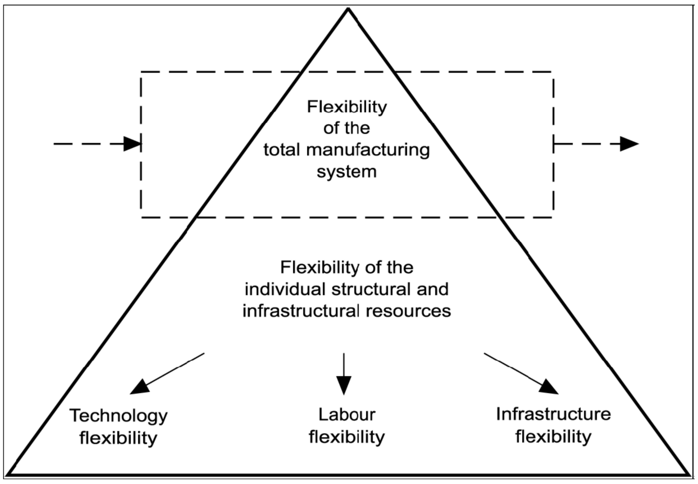

Figure 2.14: Flexibility of the manufacturing system
Source: Slack (1987), (2005)

Similarly, Gerwin (1987) identified that managers, when considering flexibility of their operations, typically identified five different levels: machine, function, process, individual factory, or the company's entire factory system. Sethi and Sethi (1990) identify three levels (component/basic, system, and aggregate) at which flexibility may be considered. A more graduated perspective is the five levels offered by Koste and Malhotra (1999) including individual resources, shop-floor, plant, functional, and business unit. Within such studies, the focus is predominantly assigned to the capabilities of different levels of the organization to contribute to flexibility through their operations, however little research has demonstrated the potential for firms to exploit a cumulative contribution to overall flexibility arising from individual levels. Koste and Malhotra (1999) are careful to note that, although their hierarchy has five levels, a lack of empirical evidence exists to confirm any lateral relation between them.

Whilst these are measures of flexibility within an individual firm (implying some hierarchy in the nature of the organization), such categorization has limitations. The most obvious is the failure to consider flexibilities that arise outside of the production environment; for example Vokurka and O'Leary-Kelly (2000) highlight that manufacturing flexibility arises from strategy, environmental factors, organizational attributes, and technology. Studies which focus on operations, rather than partial operations flexibility through solely considering the manufacturing processes are more insightful (Slack 2005). A flexible factory within an inflexible organization is unlikely to yield optimum benefit. Similarly, beyond the total control of the organization, flexibility within the supply chain has become an increasingly pertinent topic in the last fifteen years.

2.5.4 Types of flexibility

The concept of flexibility is multifarious, and several taxonomies have been developed in the research. Numerous flexibility types are named in the literature, however as Shewchuk and Moodie (1998) noted, a type is not the same as a measure. Flexibility *types* are those which provide a descriptive definition of the concepts, whereas *measures* provide a means to evaluate a particular flexibility type under given conditions.

Early typologies yielded a range of flexibility types. Through interviews with managers, Gerwin (1982) focused at operational level flexibilities, identifying that flexibility, when discussed in the production environment, may be considered to be one of five types (mix, parts, routing, design-change, volume). Similarly, Slack (1983) found that flexibility could be delimited to four types (product, quality, mix, volume). Browne et. al (1984b) surpassed this with eight categorisations. Based on a review of the literature, Sethi and Sethi (1990) increased this to eleven (machine, material handling, operation, process, product, routing, volume, expansion, program, production, market). The large number of flexibility types that have been proposed in literature often causes confusion since many are substantially similar. Several seminal papers have attempted to categorize and summarize the extensive numbers into more manageable taxonomies (Beach et al. 2000; Das and Abdel-Malek 2003; de Toni and Tonchia 1998; Sethi and Sethi 1990; Shewchuk and Moodie 1998). Notably, not all flexibility types are created equal, with some viewed as having more importance than others. Suarez et al. (1996) argued that in spite of the range of specific flexibility types offered in a number of taxonomies, only four basic “first order” types of flexibility exist: mix, volume, new product, and delivery time. These are the identified as the most fundamental flexibility types, and are the basis on which all other “lower-order” flexibility types are reliant.

2.5.5 Dimensions of flexibility

The concept of flexibility does not have a single dimension, with several authors identifying multiple facets of flexibility. Slack suggested flexibility as being a multidimensional attribute of a manufacturing system, with the two accepted dimensions of *range* and *response*[1] (Slack 1987, 1988)[2] proposed as suitable descriptors. The range dimension concerns the multitude of states or behaviours a system may enter. In principle, one system capable of an increased number of states relative to a second system may be considered to possess a higher degree of flexibility. However, whilst a system with a higher range capability than another may be able to move between states, if doing so is difficult or costly then this must be regarded as an inhibitor of flexibility. This cost is recognised in the response dimension, which provides a measure of the ease with which a system may move between states.

Many authors have contributed to the debate over the definition and dimensions of flexibility. Notable concepts relevant to this study include Upton (1994, 1995) who identified *uniformity* to be a relevant dimension of flexibility, to include the concepts that a flexible system should be able to work at a comparable level when producing from the defined range of products. Systems that enjoy uniformity in the range (set) of products should be capable of producing each with equal degree of effort. By extension Koste and Malhotra (1999) considered the range dimension to be further sub-classified into *range-number* (representing the number of potential variants a plant could produce), and *range-response* (reflecting the heterogeneity of the plant).

The ease of change (or response dimension) has also received attention. Gupta and Buzacott (1989) identified that the *ability to change* in a flexible system was determined by the system's *sensitivity* (the toleration of the system to a change before performance is degraded), and *stability* ("the size of each disturbance for which it may meet performance levels expected of it").

2.5.6 Measurement of flexibility

There has been a strong motivation within the flexibility research to identify appropriate measures by which to assess flexibility, but in many instances limitations in the proposed assessment techniques are significant. Measurement of flexibility has been approached both qualitatively and quantitatively. The ability to quantify flexibility has remained a significant challenge for researchers. Unlike flexibility types (which consist of a flexibility name and

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[1] Upton (1994) calls this mobility

[2] Slack (1983) originally posited that the dimensions of flexibility numbered three: range, cost, and time, however in later works the cost and time dimensions were amalgamated into the single response measure.

description), flexibility measures provide a value for a given flexibility under given conditions (Shewchuk and Moodie 1998). As these conditions change, flexibility becomes more difficult to assess. Whilst flexibility is therefore an extremely important concept for manufacturing systems, it is very hard to quantify (Parnaby 1987).

In principal, flexibility measures should enable academics and practitioners to assess different enablers of flexibility on these grounds; however numerous problems exist when trying to quantify flexibility. In developing their own measures for flexibility, Koste et al. (2004) critique a number of existing studies, finding problems in underlying assumptions, insufficient focus, and inadequate attention to the multi-dimensional nature of the concept. Moreover, the approach taken to the development of measurements has been inconsistent, and therefore the success of these has been 'sporadic' (Parker and Wirth 1999). In their review, Jain et al. (2013) identify sixteen different ways of quantifying machine flexibility alone; when this is combined with the vast number of flexibility types the achievement of a consistent approach to flexibility measurement in practical manufacturing environments is unfeasible.

The challenge of flexibility measurement has led Buzacott and Kahyaoglu (2000) to ask whether flexibility should be measured, with their conclusion being that it should only be measured with respect to a particular change or disturbance. Many variables that are difficult to measure or control affect flexibility. In proposing a mathematical assessment of a particular machine's flexibility, Brill and Mandelbaum (1989) identified that its determination is linked to a number of factors, of which many (e.g. decision maker views, weighted importance of tasks etc.) may be considered rather judgmental. Furthermore, researchers are often reliant on perceptual measures (Corrêa 1994), which Vokurka and O'Leary-Kelly (2000) identify are informed by the judgement of the informant to gauge flexibility.

A particular problem with flexibility is that, as both Slack (1983) and Upton (1995) have argued, it may be considered a potential, rather than a realized attribute of a manufacturing system. This potential may therefore be constrained by the decisions of managers, or the particular condition of the market, rather than the actual capability which the system could achieve. Providing a quantitative assessment of a given system through experimentation in such circumstances would be problematic: arguably, the same system under different management and/or in a different company would produce different results. Slack further argues that measures of flexibility must be considered with the other performance objectives (i.e. cost, quality, speed, delivery time) in mind, and warns against attempts to develop a single measure for flexibility.

Some of the most detailed studies on the measurement of manufacturing flexibility are achieved when the focus is narrowed to a particular flexibility type, though these remain open to scholarly debate. Some types of flexibility are more amenable to quantification than others, though it is noted that this is also somewhat subjective and can vary by the dimensions considered. For example, consistent with Slack (1988) on the two dimensions of flexibility (range and response), Bateman (1999) examined the measurement of mix flexibility. Range was shown to be the number of products being currently produced from the overall number of products offered, whilst response (the ease with which the system changes between the products) was linked to the relative ease of changeovers for the machine. This assessment provides a quantified measure of *current* mix flexibility that is acknowledged to be relatively easy to compute, but fails to acknowledge the implications which arise when the *potential* flexibility of a system is evaluated. For organizations employing flexibility at the tactical level (as a hedge against uncertainty) this is a notable issue, since this technique for assessment fails to accommodate future products which could be made by the company, but are not within the current range offered.

Other researchers have shown economic pragmatism in their assessment of flexibility. The approach taken by Rogalski (2011) acknowledges a feasible economic range in which the volume can vary. As shown in Figure 2.15, the bigger the 'flexibility space' between breakeven point and maximum capacity, the greater the flexibility of the system. Although the total costs rise as a result of increasing volumes, overall revenues increase to a greater extent, and as a result the penalty observed as a result of exploiting volume flexibility is more than compensated by the overall increase in revenues.

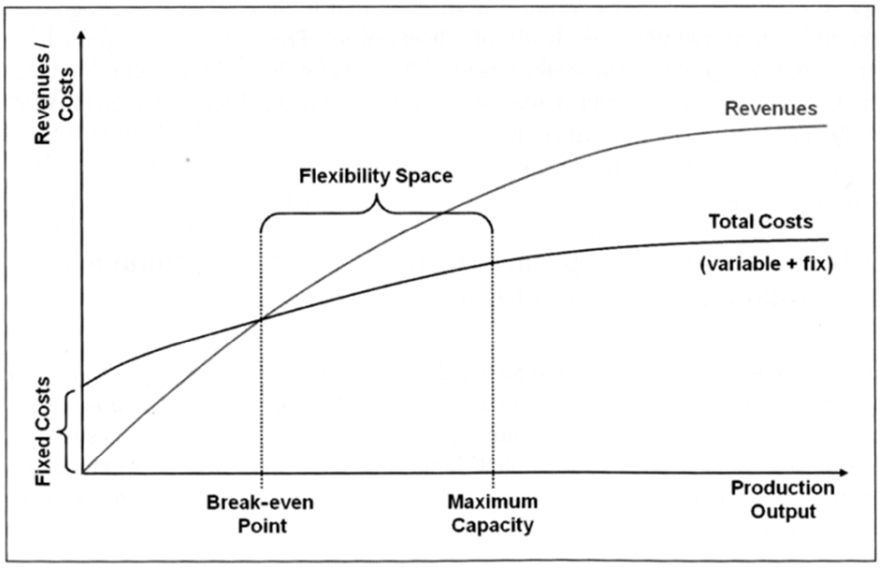

Figure 2.15: Determining the volume 'flexibility space'
Source: Rogalski (2011)

A similar pragmatic approach is suggested by Chryssolouris (2006) who examined flexibility through the notion of "Penalty Of Change (POC)". In this approach, flexibility is calculated as the penalty of making the change multiplied by the probability of its occurrence. The closer POC is to zero, the more flexible the focal resource is. An extension of this concept has been demonstrated by Mourtzis et al. (2012), who utilize the POC concept to evaluate a combination of product and volume flexibilities. The POC concept therefore allows an evaluation of flexibility, taking into account the practical requirements for it. Systems that offer a high degree of flexibility, but for which there is no requirement for it are not considered flexible, just as those that have low degrees of flexibility but with much requirement are also considered inflexible. Flexible systems are those which achieve flexibility in types for which there is a high probability that it will be demanded. Although conceptually simple, the POC requires quantification of the cost of change, and also the probability of change. For simple systems this might be feasible, but three limitations are evident:

- Manufacturing systems are inherently complex, and it is difficult to accurately capture or estimate the costs of any particular change.
- Where demand cannot be forecast with a good degree of confidence, assessment of probabilities of change may lack accuracy.
- The range of possible change permutations may inhibit the utilization of the tool. Whilst retrospective assessment of past changes may help to understand realized flexibilities, the total range of potential opportunities may be unknown, and therefore incalculable.

2.5.7 Operationalizing Flexibility in the manufacturing system

Although there is much enthusiasm for flexibility in the literature, from an operational perspective its advantages are not always so clear. Whilst flexibility may be regarded as one of the five competitive objectives for operations, its achievement is not a panacea for competitive manufacturing. In many cases, the achievement of desirable flexibility types comes at a cost: although the definition objective is for penalty-free change, in practice the achievement of flexibility is subject to trade-offs (Boyer and Lewis 2002). Companies must therefore carefully balance their flexibility capabilities with their requirements, since anything else is suboptimal:

> "A firm may be less flexible, but still be more efficient, because this configuration is what the environment it operates in requires… On the contrary, a firm may be very flexible, but suffer from excess flexibility as regards the environment's requirements. Thus, an efficiently flexible organization is one that is adapted to what the environment needs."
>
> *Lloréns et al. (2005, p. 276)*

This viewpoint echoes the early work of Hayes and Wheelwright (1979, 1984), in which different approaches to flexibility are promoted based on the volume and variety characteristics of the product being made. Achieving requisite flexibility through investment in manufacturing and computational technologies does not necessarily lead to increased flexibility; indeed, the reverse may be the case (Upton 1995). Firms also need to decide how to implement their flexibility capabilities – whether proactively to gain competitive advantage, or reactively to hedge against uncertainties (Beach et al. 2000).

2.6 Supply chain flexibility

2.6.1 Definition

Supply chain flexibility arose from the earlier work on manufacturing flexibility, and is a concept that Slack has noted to be a major omission from his original works (Slack 2005). Supply chain flexibility has arisen as a result of increased focus on the contribution that the supply chain makes to the overall competitiveness of organizations, and is recognized by Sawhney (2006) as addressing the restrictions inherent in manufacturing that evaluate flexibility in terms of the individual firm, rather than the interdependencies between supply chain partners.

Contemporary research still identifies the concept as emergent (Merschmann and Thonemann 2011; Moon et al. 2012; More and Babu 2008; Purvis et al. 2014) and, similar to the concept of flexibility in a manufacturing context, definitions, typologies, and measures are still in formation. Despite the ongoing development of the concept, a number of similarities may be observed between the flexibility of manufacturing systems and the flexibility of supply chains:

1. Supply chain flexibilities are multifaceted (often using similar type definitions).
2. Supply chain flexibilities are dimensional; Prater et al. (2001) identify these as the speed of response and degree of flexibility (akin to Slack's Range & Response dimensions).
3. Supply chain flexibilities can be potential, rather than active capabilities (Stevenson and Spring 2007).
4. Measurement of supply chain flexibility is under-developed and a good conceptual understanding has not been achieved (Bernardes and Hanna 2009; Moon et al. 2012)

Table 2.7 provides a summary of some of the most frequently cited definitions of supply chain flexibility in contemporary research, together with some other recent contributions. Consistent to these definitions is the principal notion that supply chain flexibility brings the concept of flexibility from a single organization into the context of multiple supply chain entities.

Source	Definition of supply chain flexibility
Vickery et al. (1999)	Supply chain flexibility encompass those flexibilities that directly impact a firm's customers (i.e. flexibilities that add value in the customer's eyes) and are the shared responsibility of two or more functions along the supply chain, whether internal (e.g. marketing, manufacturing) or external (e.g. suppliers, channel members) to the firm.
Lummus et al. (2003)	The flexibility of entire supply chain is a result of the flexibility components at each node of the supply chain and their interrelationships.
Duclos et al. (2003)	Flexibility in the supply chain adds the requirement of flexibility within and between all partners in the chain, including departments within an organization, and the external partners, including suppliers, carriers, third-party companies, and information systems providers. It includes the flexibility to gather information on market demands and exchange information between organizations.
Das and Abdel-Malek (2003)	The robustness of the buyer-supplier relationship under changing supply conditions.
Sánchez and Pérez (2005)	The shared responsibility of two or more functions along the supply chain, whether internal (marketing, manufacturing) or external (suppliers, channel members) to the firm.
Kumar et al. (2006)	The ability of supply chain partners to restructure their operations, align their strategies, and share the responsibility to respond rapidly to customers' demand at each link of the chain, to produce a variety of products in the quantities, costs, and qualities that customers expect, while still maintaining high performance.
Stevenson and Spring (2007)	Supply chain flexibility encapsulates components of flexibility inherent at the inter-firm level together with those at the intra-firm level.
Merschmann and Thonemann (2011)	Supply chain flexibility embraces a process-based view and also includes the core processes procurement/sourcing and distribution/logistics. Thus, it is a much broader concept, considering flexibility from the perspective of the entire value chain.

Table 2.7: Definitions of supply chain flexibility in literature
Source: The Author

2.6.2 Motivations for the achievement of supply chain flexibility

As with flexibilities in manufacturing, supply chain flexibility concerns the ability to adapt to changing conditions and may be reactively or proactively deployed (Stevenson and Spring 2007).

Change within the supply chain may arise as a result of uncertainties, and supply chain uncertainty refers to:

> "decision making situations in the supply chain in which the decision maker does not know definitely what to decide as he is indistinct about the objectives; lacks information about (or understanding of) the supply chain or its environment; lacks information processing capabilities; is unable to accurately predict the impact of possible control actions on supply chain behaviour; or, lacks effective control actions (non-controllability)."
>
> *van der Vorst and Beulens (2002, p. 413)*

Environmental uncertainties may exist in demand, supply, or as a result of competition (Yi et al. 2011), and in practice it is likely that firms may experience a combination of these simultaneously. Merschmann and Thonemann (2011) demonstrated that matching supply chain flexibility and uncertainty appropriately leads to improved performance for companies. Unlike manufacturing flexibility, supply chain flexibility places much emphasis on the relationship between buyers and suppliers to work together to overcome uncertainties in the achievement of supply chain flexibility. For example, Das and Abdel-Malek (2003, p. 171) identify that supply chain flexibility concerns the 'robustness' of the buyer-supplier relationship to adapt to changing conditions. Likewise Sánchez and Pérez (2005, p. 682) consider it to be "the shared responsibility of two or more functions along the supply chain, whether internal (marketing, manufacturing) or external (suppliers, channel members) to the firm". These definitions imply collaboration and attempts to sustain relationships, but this need not be the case. In the context of engineer-to-order projects, Gosling et al. (2010) highlight the way in which supply chain flexibility can be exploited by the selection and de-selection of vendors as necessary to overcome uncertainties and achieve the objectives of the specific project. Similarly, Lao et al. (2010) find that flexibility arises as a result of supplier flexibility and supply network flexibility. Flexibility in this sense is the ability to reconfigure the supply chain to meet challenges as they arise, and these studies identify this to be a continual activity that seeks to optimize the supply chain for changing circumstances. In this manner, *flexibility* and *changeability* in the supply chain are somewhat overlapped: whilst literature on manufacturing flexibility has considered this distinction in some detail, the same is not true for supply chain flexibility research.

Being able to achieve flexibility in the supply chain allows fundamental paradigmatic choices to be enabled. For example, Prater et al. (2001) identify that flexibility in the supply chain (and in manufacturing) can support supply chain agility. By extension, through the exploitation of sourcing and vendor flexibility, Purvis et al. (2014) further identify the potential to adopt the alternative paradigms of lean, agile, and leagile supply chain management.

2.6.3 Evaluating supply chain flexibility

As identified in Section 2.5, the long-established concept of manufacturing flexibility has received much academic attention, but this has led to considerable confusion over types and measures. For the comparatively emergent supply chain flexibility concept, although there is far less literature, already it is evident that consistency in assessment between studies is very limited (Table 2.8). From the literature evaluated, there is however particular consensus towards Logistics/Delivery and Supply/Sourcing as being accepted for supply chain flexibility.

In terms of methods, whilst there have been several quantitative approaches taken (e.g. Moon et al. 2012; Sánchez and Pérez 2005; Swafford et al. 2006; Vickery et al. 1999), there is a notable presence of qualitative assessment techniques that attempt to understand the nature and sources of flexibility. Yi et al. (2011) used interviews to examine the actions taken by companies to enable different types of flexibility, and in doing so demonstrated how strategic choices could enable one (or more) flexibility types. A similar approach was taken by Gosling et al. (2010) and Purvis et al. (2014) who drew examples from case studies to examine how sourcing and vendor flexibility types were achieved, and by Stevenson and Spring (2009) in their evaluation of buyer-supplier activities to support flexibility. These latter two studies drew extensively on the usage of managerial comments and quotes to explain the nature of different flexibility types, and their achievement.

In Table 2.9 an appraisal of the research methods is provided, together with an evaluation by the author of the depth and breadth of these studies

- Approaches that have focused on breadth, over depth have typically employed large scale surveys that seek to explore different types of flexibility, and quantify its nature.
- Conversely, studies that are more focused on how individual flexibility types are achieved typically adopt more qualitative assessments in a small number of supply chains using case studies informed by interviews.

Depth is considered in terms of understanding the nature / enablement of flexibility, whilst breadth concerns the extensiveness of the investigation with regards to the number of research participants or industries represented. There remains a notable deficit in studies that are able to achieve both breadth and depth in their evaluation which is consistent with the current evaluations of the topic as being ‘emergent’. In light of this observation, it must be acknowledged that the application of the supply chain flexibility concept is therefore difficult, and given these constraints it is necessary to adequately choose appropriate methods to investigate the concept.

Identified Supply Chain Flexibility Component	Vickery et al. (1999)	Lummus et al. (2003), (2005)	Duclos et al. (2003)	Garavelli (2003)	Pujawan (2004)	Sanchez & Perez (2005)	Kumar et al. (2006)	Swafford et al. (2006)	Stevenson & Spring (2009)	Lao et al. (2010)	Gosling et al. (2010)	Merschmann & Thonemann (2011)	Yi et al. (2011)	Soon and Udin (2011)	Moon et al. (2012)	Purvis et al. (2014)	Total
Access	☑					☑											2
Automation									☑								1
Customer Service												☑					1
Design									☑			☑					2
Expansion									☑								1
Information Systems		☑	☑						☑						☑		4
Labour									☑								1
Launch	☑					☑											2
Logistics / Delivery		☑	☑	☑	☑	☑	☑	☑	☑			☑	☑	☑	☑		12
Machine									☑								1
Market			☑			☑			☑			☑					4
Material Handling									☑								1
New Product					☑		☑		☑			☑					4
Operations		☑	☑					☑	☑				☑	☑	☑		7
Organizational Design		☑	☑						☑				☑				4
Postponement						☑											1
Process				☑					☑								2
Product	☑					☑						☑					3
Production					☑				☑								2
Program Output									☑								1
Responsive							☑	☑				☑					3
Routing						☑			☑								2
Supply / Sourcing		☑	☑	☑	☑	☑	☑	☑		☑	☑		☑	☑	☑	☑	13
Target Market	☑																1
Transshipment						☑											1
Vendor										☑	☑					☑	3
Volume	☑					☑			☑								3

Table 2.8: Literature perspectives on supply chain flexibility components

Source: The Author

Publication	Research method employed	Data Source	Depth	Breadth
Vickery et al. (1999)	Survey	65 respondents	Medium	High
Lummus et al. (2003)	Conceptual	-	-	-
Duclos et al. (2003)	Conceptual	-	-	-
Garavelli (2003)	Simulation	9 simulations	Low	Medium
Pujawan (2004)	Single case study using developed worksheet	1 case	Medium	Low
Lummus et al. (2005)	Delphi study	13 participants	High	Medium
Kumar et al. (2006)	Conceptual	-	-	-
Sanchez & Perez (2005)	Survey	126 respondents	Medium	High
Swafford et al. (2006)	Survey	135 respondents	Medium	High
Stevenson & Spring (2009)	Case studies	16 cases (20 interviews)	High	Medium
Gosling et al. (2010)	Case study	2 cases	High	Low
Lao et al. (2010)	Survey	201 respondents	Medium	High
Merschmann & Thonemann (2011)	Survey	85 respondents	Low	High
Soon and Udin (2011)	Case studies	4 cases	Medium	Low
Yi et al. (2011)	Case studies	5 cases	Medium	Low
Moon et al. (2012)	Survey	192 respondents	Medium	High
Purvis et al. (2014)	Case study	2 cases	Medium	Low

Table 2.9: Approaches to evaluating supply chain flexibility
Source: The Author

PART 2: A review of literature in the context of Additive Manufacturing

The purpose of this section is to explore existing research concerning the four research questions (as shown in Table 2.10). In doing so, this section provides a contextualisation of the concepts explored in Part 1 of this chapter for Additive Manufacturing, underpinning the empirical research presented in chapters 4-7 of this thesis.

Focal Research Question	**Section**
Research Question 1: How is an Industrial Additive Manufacturing System structured?	2.8
Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?	2.9
Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?	2.10
Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?	2.11

Table 2.10: Alignment of structured literature review to Research Questions
Source: The Author

2.7 Structured literature review method

To comprehensively evaluate the established research pertinent to this study, a structured review of the published literature was performed. This was motivated by a desire to explore a wide range of literature, but to do so in such a way that supported focus and replication. In Figure 2.16 the four principal stages of the structured review process performed in this research are shown.

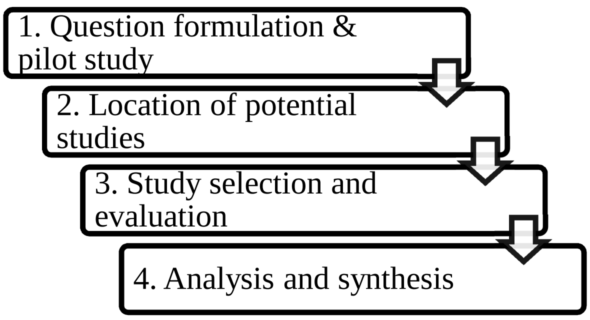

Figure 2.16: Activities conducted in the structured review
Source: The Author

Stage 1: The central question underpinning this review was refined to “What is the current state of knowledge for Industrial Additive Manufacturing Systems in the satisfaction of demand?”, and through a pilot study relevant keywords and databases were identified. By selecting relatively broad keywords that promoted breadth in the nature of results observed, combined with the inclusion of a number of different scholarly databases, the intention was to locate a wide range of relevant publications for inclusion in the review.

Through this piloting approach, six identified characteristics of the literature were demonstrated:

1. The terms ‘Additive Manufacturing’, ‘Rapid Manufacturing’, ‘Rapid Prototyping’, ‘Rapid Tooling’, and ‘3D Printing’ are used with little precision, and are frequently interchanged in the literature. It is therefore necessary to analyse the literature mindful of this ambiguity.
2. There has been little distinct emphasis on ‘Industrial’ Additive Manufacturing, and so searches omitted this term, but the analysis must be made mindful of this decision.
3. ‘Rapid Prototyping’ is a term commonly used in the Computer Science disciplines, particularly in software development and search results are inflated by this irrelevant concept. Although some filtration can be conducted on journal-topic basis, it is not possible to exclude this concept from the review.
4. The concepts of ‘manufacturing systems’ and ‘flexibility’ are ambiguous in the literature; whilst a large number of searches identify these words being employed, they are not used in a manner applicable to this study. Nevertheless, these papers must still be evaluated.
5. The terms ‘variety’ and ‘customization’ are used broadly, and the initial results yielded were considered unmanageable. By focusing search terms explicitly on Mass Customization, context is given to narrow the investigation to a manageable activity, with results that are more relevant to the focal topic.
6. There has been very little consideration of supply chain flexibility in the context of Additive Manufacturing. For this reason a more general search for supply chain articles is needed to underpin the concept, together with a wider search of databases specifically related to supply chain flexibility.

Stage 2: Keyword searches on scholarly databases were performed to identify potentially relevant literature as shown in Figure 2.17. Keywords in list A were combined with list B in order to generate search terms, which were executed and results recorded using the EndNote citation manager. The pilot study identified disparity in the spelling of customization; as a result wildcards were used for Mass Customization to include both ‘s’ and ‘z’ spellings. Similarly, flexibility literature was also identified as including ‘flexible’, and so a wildcard was used to identify literature. In the case of supply chain flexibility, the pilot searches demonstrated a general dearth of any research in this area, and as a result a search of the more generalist Google Scholar database was included to maximise search results.

The searches yielded 2,642 potentially relevant papers, and using the EndNote reference manager, a database of publications was built for subsequent review. Fink (1998) identified that literature reviews must have two screens: practicality/feasibility and quality. The practical constraints on the researcher mean that it is not possible to obtain and critique all papers, and it is recognized that this is a limitation of the method. Emphasis must therefore be made on gaining the most relevant, quality works. Papers were downloaded through either the publisher's online repositories, or where identified as particularly relevant, individually sourced from the British Library. For those inaccessible in this manner, extensive efforts were made to ensure the author was confident that this would not be to the detriment of the review: titles and abstracts were read, journal applicability considered, and author profiles accessed to identify likely relevance. The researcher is therefore confident that within defined boundaries of the review it has been possible to locate the most relevant studies for this evaluation. In addition to peer-reviewed journal papers, materials from conferences and trade publications were deemed to be valid contributions; as Denyer and Tranfield (2009) have noted in the related 'systematic' review process, these sources can provide useful insights and are therefore included in this review, but the author is mindful of potential quality variations in these works that are often not peer-reviewed.

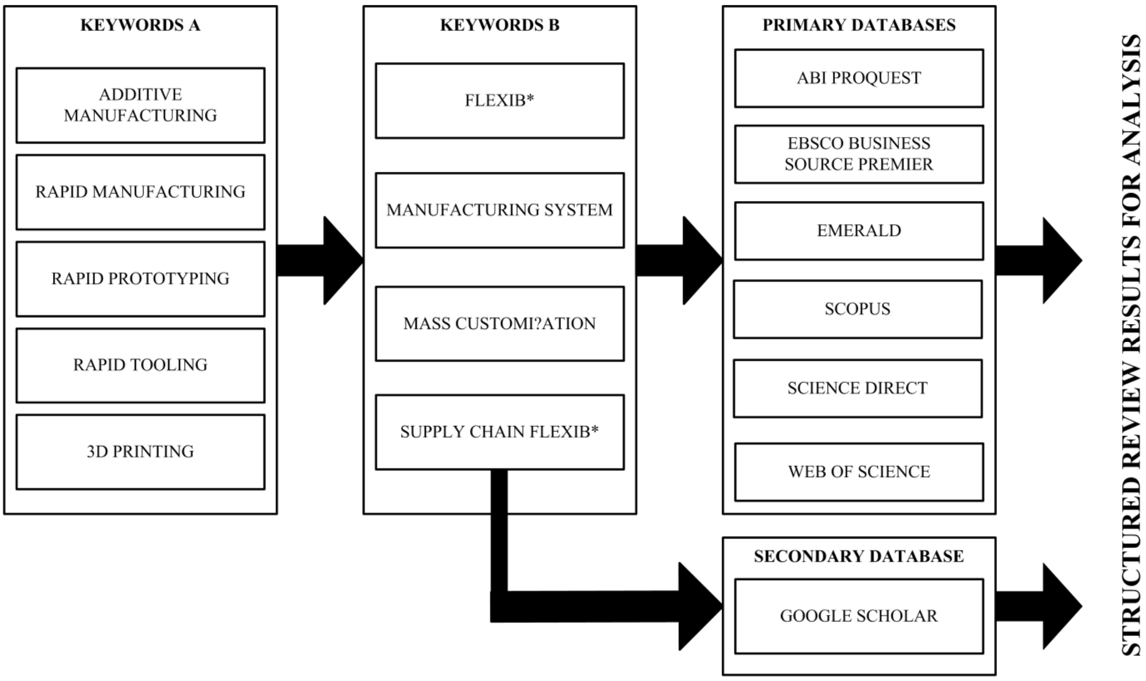

Figure 2.17: Structured review process
Source: The Author

Stage 3: Each article returned in the search was examined and assessed according to its relevance. For each paper the title and abstract were read for relevance, and an electronic search of the article was made to evaluate how the keywords were relevant to the work. Each paper was classified on a five-point scale of relevance, and where appropriate, references were followed-up in a ‘snowball’ method. Particularly relevant journals such as International Journal of Production Economics, International Journal of Operations and Production Management, Journal of Operations Management, and Rapid Prototyping Journal were hand-searched to locate any further relevant texts not identified through this approach.

Despite the broad search terms yielding 2,642 potential papers, less than 10% of these were identified as having any potential relevance to this study, and of these very few have given explicit attention to the focal topics confirming the continued existence of a research gap.

Stage 4: Once the relevant papers were identified they were analysed and synthesized to produce a review of the literature relevant to the research questions identified in this research. Six months prior to the submission of this thesis, the structured review searches were repeated to identify any additional recent papers that were relevant to the review, and these were added to the study.

2.8 Literature perspectives on the nature of Industrial Additive Manufacturing Systems

The structured review demonstrated a lack of consideration for Additive Manufacturing from a ‘systems’ perspective, with very little alignment between current studies and the manufacturing systems concept developed in Part 1. Although the term ‘system’ is frequently used by authors, in practice this typically refers only to Additive Manufacturing technologies in operation, focusing particularly on the focal manufacturing technologies (e.g. Espalin et al. 2014; Gibson and Shi 1997; Johnson et al. 2014; Krauss and Zaeh 2013; Levy et al. 2003; Onuh and Hon 1998), or a collection/combination of focal technologies (e.g. Lopes et al. 2012; Zhong et al. 2004). The majority of authors do not make clear distinctions in their research between ‘technologies’ and ‘manufacturing systems’; a notable exception to this is the acknowledgement of the differences between the two in the work of Armillotta (2008). This finding is important, since by identifying the overall dearth of literature concerning systems in a context familiar to Parnaby’s concept of a manufacturing system, an important research gap is demonstrated for the current study.

Several studies do consider the ‘system’ to be more than the technologies, with emphasis typically considering the functional activities undertaken in the achievement of a manufacturing objective. For example, in proposing a system to enable both design and manufacture, Wang et al. (2004) presented a series of activities and enabling resources (Figure 2.18). Each module of the system achieves a specific objective, and work flows through the system to create parts. A similar modular system was proposed by Ding et al. (2004), in which four systems components (Virtual Prototyping, Digital Prototyping, Physical Prototyping, and Rapid Tooling) were combined to achieve manufacturing objectives. For these authors, systems are modular, with each module being integrated to achieve the objectives of the overall manufacturing system. Notably, the research focus for each module of the system is on the technological contribution, with no real demonstration of other system resources (e.g. labour), or their management.

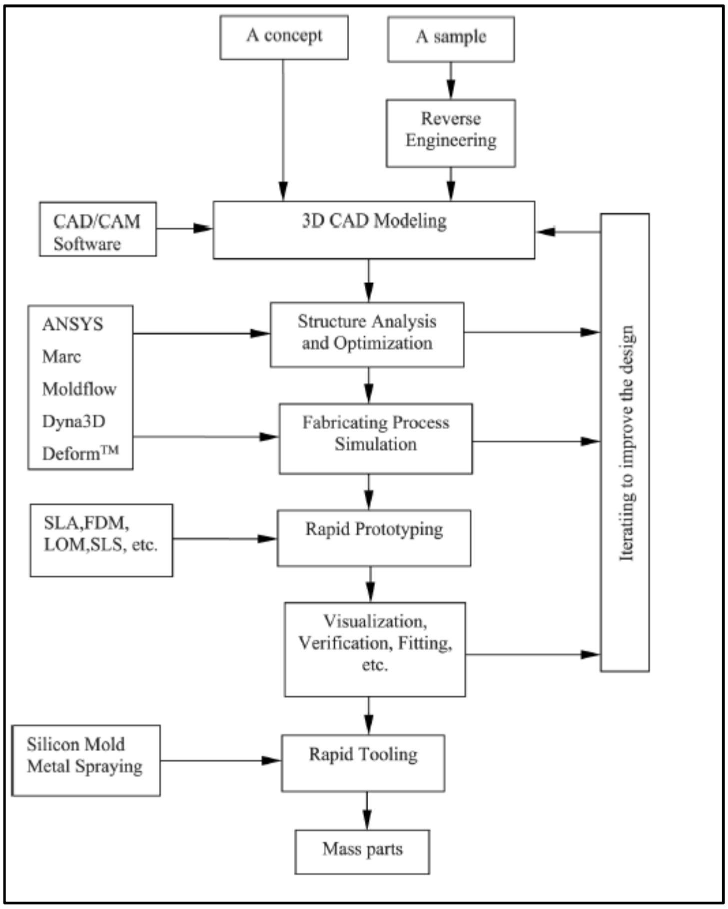

Figure 2.18: Activities in an integrated modular manufacturing system
Source: Wang et al. (2004)

In extension to these functional assessments, the concept of distributed manufacture using Internet technologies has been identified by a number of authors as a potential exploitation opportunity. These include integrated systems for 'e-manufacture' (Cheng and Bateman 2008), 'devolved manufacturing' (Bateman and Cheng 2002), and 'tele-manufacturing' (Lan 2009; Lan et al. 2004; Lan et al. 2002, 2003). Although these latter studies tend to focus more on the technicalities of implementation, they do provide a useful resource that demonstrates the technologies integrated with the satisfaction of demand, particularly in terms of customer designs.

Despite the majority of authors focusing on a machine-based perspective of the system, several authors have suggested more holistic implementation frameworks that characterise a number of the components of a manufacturing system. Through their evaluation in terms of Rapid Manufacturing systems, Nagel and Liou (2010) and Stoble (2007) provide the most authoritative appraisal of a system. Acknowledging the lack of research in this area (as supported by the current structured review), they proposed that the manufacturing system is comprised of five key components:

1. Production planning (software)
2. Control system
3. Motion system
4. Unit manufacturing process (e.g. a Rapid Manufacturing machine)
5. A finishing process

Although Nagel and Liou (2010) focused on engineering linkages between the system components (e.g. electrical, mechanical), from a managerial perspective this identification of components provides a useful alignment to Parnaby's manufacturing system concept. More recent work (Mellor et al. 2014) has developed a framework for implementation of Additive Manufacturing. Part of this framework has highlighted 'systems of operations', which provides some alignment to the current study. Within this concept, Mellor et al. (2014) identified the activities of design, process planning, quality control, cost accounting, and systems integration as being relevant to the concept of a system.

These most relevant publications of Nagel and Liou (2010) and Mellor et al. (2014) have identified process planning and control as being relevant components of a system, which is in-line with the manufacturing system concept presented in Part 1. It was not possible to identify any appropriate control architectures literature within the structured review, however some practical aspects of the attainment of control were found. It was particularly evident that in their implementation, Additive Manufacturing systems may be identified as having either centralized or decentralized approaches. In centralized architectures Nagel and Liou (2010) focused on control from the perspective of electrical or mechanical control, including PLC's, OEM integrated systems, and DIY systems produced by the manufacturer. Hoske (2013) note that for 3D printers, a lack of feedback inhibits closed-loop control. Similarly, Espalin et al. (2014) highlighted the use of reconfigurable real-time controllers to operate the system, and the role for both hardware and software to support control objectives using finite state machines. For decentralized architectures (e.g. web-based), consideration of system control has on Internet-based 'tele-control' (Luo et al. 1999; Luo et al. 2001) in which the control of the physical manufacturing processes is achieved remote to the physical machines.

Some inconsistencies between studies are also apparent. For example, although process planning has been identified as part of the system, in their evaluation of the concept Jin et al. (2013a) identified it to consist of four activities (orientation determination, support structure determination, slicing, and tool-path generation) that are *distinct* from the manufacturing system (which is taken to consist only of the fabrication technology). Similarly, most studies make no mention of the ability of the system to change, yet Putnik et al. (2013) noted the requirement for Additive Manufacturing to be able to scale to meet changing requirements (at system, organization, and business levels). Such observations highlight that the nature of Additive Manufacturing Systems is poorly defined in literature.

A final perspective of Additive Manufacturing in the context of manufacturing systems is the role which the technologies may play within 'conventional' approaches to manufacturing. Additive Manufacturing technologies have been identified as contributors to other types of manufacturing system: Gunasekaran (1999) highlighted the role of Rapid Prototyping technologies in the achievement of an overall agile manufacturing system, which has been empirically evaluated by Vinodh et al. (2009a).

Research Question 1: How is an Industrial Additive Manufacturing System structured?

Whilst existing literature has given extensive consideration to the concept of manufacturing systems in general (as evidenced in Section 2.2), this is not the case for Additive Manufacturing. For many Additive Manufacturing publications the 'system' term is often identified to be pleonastic, or referring only to the individual machine technology. Within this section only a few publications are shown to consider other resources within the 'system' concept, though these lack detail and give very limited consideration to concepts such as control beyond an individual machine focus.

A systems perspective promotes evaluation of 'wholeness' (von Bertalanffy 1969), and as demonstrated in Section 2.2 focuses on the many elements that are integrated and controlled in the formulation of a manufacturing system (Hitomi 1996; Parnaby 1979; Parnaby and Towill 2009a). This approach offers the potential to better understand and manage Industrial Additive Manufacturing, and given the demonstrated dearth of literature research question 1 is posed.

2.9 Literature perspectives on the utilization of Industrial Additive Manufacturing Systems in the satisfaction of different demand types

As acknowledged in Section 1.2, enthusiasm for Additive Manufacturing technologies to be used in a wide range of applications is growing, and for an overview of current applications the reader is directed to recent reviews (e.g. Gibson et al. 2015; Petrovic et al. 2011). Based on the procedure described in Section 2.7, the current review explores two areas of relevance to this study:

1. Attributes of Additive Manufacturing that may support the fulfilment of Mass Customized demand (Section 2.9.1).
2. Approaches to the management of the technologies in support of different demand types (Section 2.9.2).

As explained in Section 2.7, the 'Mass Customization' keyword was identified as an appropriate means to focus the literature search, and in Section 2.9.1 the focus of the review concerns how this particular type of customized production is achieved through Additive Manufacturing. In Section 2.9.2, management considerations are presented, in which the focus of analysis is extended to consider a range of different demand types, not just Mass Customization. In the conduct of the literature search a large number of potential results were identified, highlighting the relevance of the topic to industry, though it is acknowledged that (relative to peer-reviewed academic texts) many of these articles lack quality, often with little empirical evidence to underpin their claims. As a result, these are not included in this review which greatly reduces the number of texts to be discussed in this section, and therefore constrains consideration to the most pertinent and useful works.

2.9.1 Attributes of Additive Manufacturing that support different demand types

There are a number of commonalities in the literature concerning the characteristics of Additive Manufacturing that support different demand types, and in Table 2.11 relevant literature is synthesized to demonstrate the principal characteristics identified as supporting Additive Manufacturing in the production of customized products. The most commonly observed characteristic concerns the production of custom or new products (typically through new geometries), though other justifications exist in terms of cost [C], time [T], or uniqueness [U] (in terms of being able to produce otherwise impossible products) as shown in Table 2.11. Whilst these characteristics are identified in the context of Mass Customization, they are also relevant for different demand types in terms of volume and variety considered in this study.

Publication	Waste elimination [C]	Material cost reduction [C]	Labour costs reduction [C]	Setup elimination [C] [T]	Tooling elimination [C] [T]	Complex geometry /new products [U]	Low Volume production [C] [T]	Mid Volume / High volume [C] [T]	Responsive/On Demand production [T]	Increased automation [C] [T]	Increased material range [C] [T]	Improved quality / performance [C][U]
Anderson (2013)							☑					
Anonymous (2011a)	☑		☑			☑	☑		☑	☑		
Anonymous (2011b)	☑				☑	☑						
Anonymous (2012a)						☑						
Anonymous (2012d)		☑				☑	☑					
Atzeni et al. (2010)					☑	☑						
Bak (2003)	☑	☑	☑	☑								☑
Bassoli et al. (2012)						☑			☑	☑	☑	
Berman (2012)	☑	☑			☑					☑		
da Silveira and Sousa (2011)									☑			
Dove (2004)	☑	☑	☑	☑								
ElMaraghy et al. (2013)				☑		☑						
Eyers and Dotchev (2010)						☑					☑	
Fox (2013)						☑						
Fox (2014)			☑									
Graham-Rowe (2006)						☑						
Günther et al. (2014)								☑				
Helkiö and Tenhiälä (2013)				☑		☑	☑					
Hessman (2013)						☑						☑
Hessman (2014)						☑						
Holmström and Partanen (2014)						☑			☑			
Jackson (2008)						☑	☑		☑			
Lim et al. (2012)	☑											
Lott et al. (2011)					☑	☑						
Ma et al. (2007)									☑			
Merrill (2014)					☑	☑			☑			
Pallari et al. (2010)						☑	☑					
Petrick and Simpson (2013)						☑	☑		☑			
Petrovic et al. (2011)	☑				☑	☑			☑			
Reeves et al. (2011)					☑	☑	☑		☑			
Schubert et al. (2014)						☑	☑					
Tuck et al. (2008)			☑			☑	☑		☑			☑
Waetjen et al. (2009)						☑						
Walters (2014)									☑			
Yap and Yeong (2014)						☑					☑	
Zhang and Bernard (2014)						☑						

Table 2.11: Attributes of Additive Manufacturing supporting customized production
Source: The Author

2.9.2 Management implications for Additive Manufacturing

Fogliatto et al. (2012) observed that, with the exception of Bateman and Cheng (2006), there has been little management consideration of the use of Additive Manufacturing for Mass Customization. Despite much enthusiasm for the technologies supporting Mass Customization, and as shown in 2.9.1 some explanation as to how this is achieved, only a small number of articles are found in the current review to extend beyond the capabilities of the technologies. In this section consideration is given to four management issues pertinent to the current study, extending the customization concept to consider different demand types, and issues of responsiveness and integration.

2.9.3 Production volume

Within the literature there is some focus on the opportunities for Additive Manufacturing technologies to competitively operate at a range of production volumes, though there are notable inconsistencies between the studies and in many cases very little empirical support for the claims made. The emphasis in the literature tends to focus on cost, with particular attention on comparability with other manufacturing technologies. For example, a widely-cited article (Anonymous 2011) in a series of publications by The Economist on the potential for 3D printing has identified plastic parts are competitive with conventional production techniques at volumes of 1,000 units, and expected this to increase as technologies matured. There is, however, no explanation of the nature of these parts, nor the comparable manufacturing technology that would produce them. Similarly, Anderson (2013) noted the perceptions of one practitioner that the technologies could yield volumes of 2000-3000 units annually. Berman (2012) identify that 3D printing is suitable for 'small to medium' production runs, whilst Günther et al. (2014) has identified that in the production of cores for faucets, production of 50,000 pieces using Additive Manufacturing is already a 'reality'.

The variation in these observations suggests Additive Manufacturing may, depending on the criteria of assessment, feasibly operate at different volume outputs. Anonymous (2012d) identify that there are "barely any economies of scale in Additive Manufacturing, the technology is ideally suited to low-volume production", which Merrill (2014) extends to observe "economies of scale evaporate and mass customization becomes a reality. A batch size of one costs the same as 100 or 1,000". However, several sources draw upon and adapt a cost-model for Laser Sintering originally offered by Hopkinson and Dickens (2003), and subsequently revisited by Ruffo et al. (2006b). These evaluations focus on the competitiveness of the focal Additive Manufacturing technology relative to conventional alternatives, and in doing so emphasize the breakeven point for which Additive Manufacturing is viable. Notably, an important observation that affects the findings of these studies is made by Atzeni et al. (2010), who identified that such comparisons do not acknowledge the potential to design parts differently in order to optimize them for different production processes. By redesigning parts to better suit Additive Manufacturing, improvements to the products produced and the viability of manufacture may be affected.

In addition to this competitive evaluation of Additive Manufacturing versus conventional approaches, there has been some suggest of complimentary strategies being employed. In an opinion piece, Petrick and Simpson (2013) identified that future manufacturing will take two paths: one in which conventional manufacturing technologies address high volume production and achieve economies of scale, whilst low volume customized production will be tackled by using Additive Manufacturing.

2.9.4 Production variety

In addition to production volume, several authors have extended their considerations to include the variety (or customization) required to satisfy demand. Such notions traditionally align to variations on the product-process matrix (Hayes and Wheelwright 1979), and to the different types of production process that are best suited to balance cost and flexibility.

Both Anonymous (2012a) and Günther et al. (2014) highlight that, at present, Additive Manufacturing technologies are engaged in batch processing to fulfil demand, though the potential exists to change. By increasing the throughput of the machines and reconfiguring layouts, Anonymous (2012a) identify the potential to move towards a line-based process. Going further, in proposing additional automation in the process equipment, Günther et al. (2014) envisage the opportunity to achieve continuous processing using Additive Manufacturing technologies.

Vinodh et al. (2009b) has suggested that Additive Manufacturing may support agile strategies, and as shown in Figure 2.19, Lee and Lau (1999) identified that an agile production network in which Additive Manufacturing technologies were employed could theoretically accommodate all potential combinations of volume and variety. Focusing on the individual machine, Tuck et al. (2008) suggested that the absence of labour and a high degree of automation in Additive Manufacturing could support all volume levels, whilst still achieving a high degree of variety (Figure 2.20), though this was not evaluated in the study. More recently, in an extension of the basic product-process matrix, Helkiö and Tenhiälä (2013) identify potential investigation could explore whether the capabilities of Additive Manufacturing could enable a ‘deviation from the diagonal’ as a result of their ability to produce a wide range of complex parts. For each of these examples it is recognized that emphasis is placed on the capability of the individual machines, and manufacturing systems considerations previously explored in Section 2.8 are omitted.

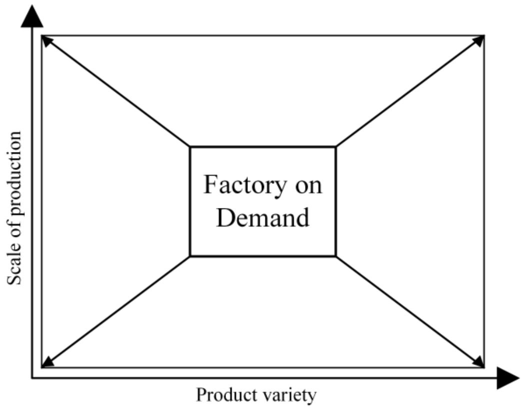

Figure 2.19: The 'factory on demand' concept
Source Lee and Lau (1999)

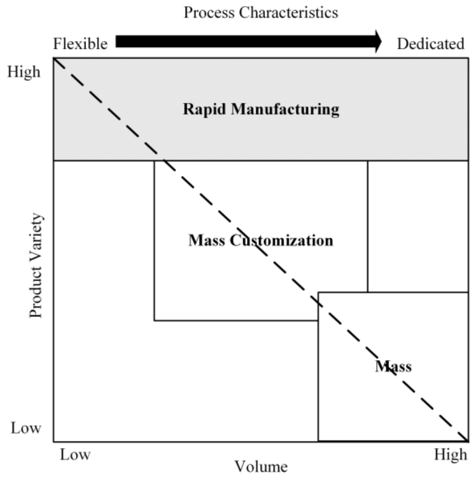

Figure 2.20: Manufacturing supply characteristics
Source: Tuck et al. (2008)

2.9.5 Responsiveness to demand

The achievement of appropriately timely response to demand was demonstrated in a number of studies (Table 2.11), and typically the literature has identified responsiveness as arising from the capability of the process technologies. Such examples include Jackson (2008), who demonstrated Laser Sintering processes to reduce overall product lead-times, and Ma et al. (2007) who identify Rapid Prototyping to support customer driven customization and to enable rapid changes to product designs.

To compliment these process capabilities, additional opportunities can arise from the design and co-ordination of parts. For example, Hu (2013) highlights the potential for Additive Manufacturing to responsively contribute to the production of modules of an overall product. Furthermore, Pallari et al. (2010) suggest that by implementing distributed manufacturing (rather than a centralized 'factory' approach), single-day lead-times might be further reduced to a matter of hours. This manufacture may be achieved in an 'on-demand' environment; for example, Lager et al. (2014) foresee on-demand manufacture of spare parts as a reality, a practice which is shown to affect the need to hold inventories of finished parts, which both accelerates product fulfilment and dramatically affects the supply chain (Holmström and Partanen 2014; Holmström et al. 2010; Khajavi et al. 2014; Walter et al. 2004).

2.9.6 Integration of Additive Manufacturing and other technologies

In the previous sections several authors have been identified as considering the opportunity to integrate Additive Manufacturing with manufacturing technologies, but overall this has received little scholarly attention. By comparison, more detailed work has considered the integration with Internet technologies. For example, in recognizing the need to consider more than just the manufacturing technology in the achievement of customized manufacture, Bateman and Cheng (2006) demonstrated the alignment of manufacturing technology, mass customization principles, and internet communications to support a ‘devolved manufacturing’ platform. Related work by Lee and Lau (1999), Berlak and Webber (2004a), Cheng and Bateman (2008), and Reeves et al. (2011) propose variations on the concept, linking together the customer with one or more Additive Manufacturing companies to achieve customized manufacture.

Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?

In a focused consideration of the literature it is shown that much enthusiasm exists for Additive Manufacturing in the satisfaction of different demand requirements, for which the analysis has summarized these characteristics in terms of cost, time, and uniqueness. It is, however, recognized that there is comparatively little empirical data to support many of the propositions.

For the management of different demand types a limited amount of literature is identified to show a lack of alignment in expectations for volume and variety. Authors disagree over the most feasible production volume ranges, and the effectiveness of measures for cost assessment have been questioned. Nevertheless, Tuck et al. (2008) have posited the ability of Rapid Manufacturing to competitively achieve high variety at all production volumes. In separate work concerning the established product-process matrix, Helkiö and Tenhiälä (2013) suggest that Additive Manufacturing technologies, by virtue of their ability to produce a wide range of parts, might achieve a ‘deviation from the diagonal’. When considered together, these two propositions suggest that Additive Manufacturing technologies may offer an effective capability to satisfy different types of demand, however there is no empirical evidence to support these conjectures and no consideration has been given in terms of the manufacturing system. This leads to the proposal of research question 2.

2.10 Literature perspectives on the flexibility of Industrial Additive Manufacturing Systems

In Section 2.8 it was shown that the concept of a manufacturing system has received little attention in the context of Additive Manufacturing; it therefore follows that assessment of flexibility from a systems perspective will also be constrained. As a result, this review examines Additive Manufacturing, rather than focusing on Industrial Additive Manufacturing Systems.

The pilot study identified the usage of the terms ‘flexible’ and ‘flexibility’ extensively in Additive Manufacturing literature, however this varies considerably between authors, and in many cases there is little explanation of why or how flexibility arises. For example, in a survey of expert informants evaluating the nature of direct writing technologies Mortara et al. (2009) identified that the majority of respondents thought flexibility was an ‘indispensable’ component of the concept’s definition, though the nature of flexibility is unspecified in the paper.

With the exception of the author’s prior work (Eyers et al. 2012a), the structured review identified no explicit typology or measurement system to assess the nature of flexibility for Additive Manufacturing Systems. It is, however, possible to collate a range of flexibility capabilities identified in existing literature as being facilitated by Additive Manufacturing, which form the basis of the structured review.

2.10.1 Flexibility capability 1: Flexibility in process operation

Within the literature much emphasis is given to different Additive Manufacturing technologies offering flexibility in their ‘processes’, though neither the nature of this process flexibility nor its achievement is clearly defined. Several authors (Gu et al. 2012; Jiang et al. 2013; Pfleging et al. 2007) advocate that Additive Manufacturing technologies offer ‘high levels’ of process flexibility, but the measurement of this capability is unspecified. Process flexibility is found as being ‘good’ (Ma et al. 2013), and in the context of specific applications, is an advantageous capability (Kuo and Su 2013). Similarly, Additive Manufacturing promotes flexibility in cellular manufacturing (Onuh 2001), although again the nature of this is undefined in literature.

Other authors are more precise in their treatment of the term. West et al. (2001) ascertain that for Stereolithography, process flexibility concerns the number of different process variables that can be handled, and leads directly to both accuracy and efficiency in part fabrication. Flexibility in this sense therefore concerns the various parameters that an operator can choose in the preparation of the machine for production. In a similar manner, Wilden and Fischer (2007) associate high process flexibility with efficiency in production. Gibson (1996) identify that in reality, Additive Manufacturing processes are less flexible than some conventional counterparts; to alleviate this issue he suggests the combination of conventional and additive systems in an integrated manufacturing cell.

2.10.2 Flexibility capability 2: Accelerated and On-Demand Manufacture

Grzesiak et al. (2011) identified that Additive Manufacturing reduces the number of activities that are necessary in the fulfilment of a customer order (e.g. design drawing, tooling, and transportation of unfinished goods), and in doing so improve responsiveness to customer orders by shortening lead-times. By removing many elements of conventional manufacture, Additive Manufacturing has been termed “a flexible factory in a box” (Alpern (2010) cited in Berman 2012).

The ability to fabricate products “on-demand” can be identified in the literature as relevant to flexibility, though it is typically linked with other characteristics. For example, Ruffo and Hague (2007) consider flexibility to take two forms: the ability to achieve on-demand production, and variety of products that can be produced by the processes. Similarly, in highlighting the potential to use Additive Manufacturing in order to produce components faster than using conventional techniques, Reinke (2007) suggests flexibility comes from the range of items and speed at which they are produced. Flexibility in the ability to feasibly produce low volumes from short production runs has been identified as advantageous by both Chhabra and Singh (2012) and Ford et al. (2014). By extension, this capability has been predicted by Pérès and Noyes (2006) as advantageous to exploration of space, allowing on-demand production of parts rather than the holding of inventories.

2.10.3 Flexibility capability 3: Flexibility in design

One of the often-cited characteristics of Additive Manufacturing is the design ‘freedom’ that is afforded by removing many of the constraints arising through “Design for Manufacture” (Hopkinson et al. 2006b). Numerous authors have linked the ability to create a range of designs to the notion of flexibility (Bak 2003; Ghosh et al. 2010; Gibbons and Hansell 2005; Karevan et al. 2013; Rechtenwald et al. 2010; Yeong et al. 2004). Several authors consider design flexibility in terms of the ability to create complexity in designs (Bourell et al. 2011; Brenne et al. 2013; Zhang et al. 2012); in this sense design flexibility concerns the range of complexities than can be achieved. By extension, the ability to customize existing designs has been identified as a further capability of design flexibility for Additive Manufacturing (Melchels et al. 2012).

Unlike 'conventional' approaches to manufacturing, the ability to easily change designs has been shown by Anonymous (2012c, 2013) as enabling product enhancement, often through the ability to make iterative developments as the product is refined. More specifically, Heralić et al. (2012) observed the potential to make design changes late in the design cycle as being afforded by the design flexibility of Additive Manufacturing.

2.10.4 Flexibility capability 4: Flexibility to produce a wide range of parts

The flexibility of Additive Manufacturing processes has also been linked to the range of parts that can be produced. In theory, an Additive Manufacturing machine which produces a plastic drinking cup could just as easily have made the casing of a computer mouse or a decorative desk ornament. Rosen (2004) highlights "[Additive Manufacturing] systems will be very flexible in that they will be capable of fabricating a wide variety of parts, and, potentially, products or modules"; additionally flexibility may also extend to producing a range of customized parts (Craeghs et al. 2010). Rechtenwald et al. (2010) suggest that while flexibility arises from the ability to produce small series of parts and a range of geometries, flexibility also needs to be considered in terms of other attributes of parts produced, for example, mechanical, electrical or optical. Different parts may therefore be distinct on many functional attributes other than merely their geometries. For example, flexibility has been shown in terms of surface complexity (Wong et al. 2007) and surface finish (Kumar and Choudhury 2002). Akin to process flexibility, Prabhu et al. (2005) identify that the ability to vary the process parameters in order to control the way the parts are produced will further support the flexibility of Additive Manufacturing.

2.10.5 Flexibility capability 5: Ability to fabricate a wide range of complex geometries

The ability of Additive Manufacturing processes to fabricate a wide range of complex shapes is one of the most commonly identified uses of the 'flexibility' term. Emphasis in the literature (e.g. Anonymous 2012b; Gu et al. 2009; Jee and Sachs 2000a; Jin et al. 2013b; Schaaf 2000; Schmidt et al. 2007; Song et al. 2012) tends to focus on the ability to achieve a wide range of different shapes, particularly when compared to conventional approaches to manufacture). Several authors (Chhabra and Singh 2011; Ding et al. 2011; Emmelmann et al. 2011; Ilardo and Williams 2010; Leuders et al. 2013; Storch et al. 2003; Yasa et al. 2011; Zaeh and Ott 2011) identify Additive Manufacturing as offering 'geometric' flexibility of various degrees. Flexibility characterised by the ability to produce a range of geometries is implied by Jee and Sachs (2000b); a more specific statement by Thijs et al. (2010) identified flexibility to arise from the ability to simultaneously produce a range of geometries in the same build. Habijan et al. (2013) identify that the layer-based approach to manufacture promotes an almost unlimited geometric complexity for parts. More specifically Levy et al. (2003) find that undercuts, overhangs, and free-form shapes are easily produced through Additive Manufacturing, which they suggest characterises flexibility for low volume and customized production. Similarly, Zhang et al. (2013) observed flexibility in terms of the ease of achieving complex shapes relative to conventional approaches. At the most enthusiastic for this capability, Butscher et al. (2013a) and Butscher et al. (2013b) described the capability to achieve free-form shapes as “outstanding”.

Brandl et al. (2012) identify that powder-bed based Additive Manufacturing processes are able to offer the highest capability for geometric flexibility and accuracy compared to other approaches. For the resin-based stereolithography process, Canellidis et al. (2013) highlight the importance of the optimization of geometric flexibility to cost-effectively manufacture (e.g. by the achievement of optimal build chamber utilization).

2.10.6 Flexibility capability 6: Flexibility of materials

For many authors, flexibility for Additive Manufacturing can be considered in terms of the range of materials that can be processed by an individual machine (Butscher et al. 2013a; Butscher et al. 2013b; Butscher et al. 2012; Furumoto et al. 2012a; Furumoto et al. 2012b; Hon et al. 2008; Jean et al. 2005; Levy et al. 2003; McMains 2005; Song et al. 2012; Zhang et al. 2013). No evidence could be found of a quantification of this range, however it was identified that some processes offer far more opportunity than others, either in terms of the materials used or the way in which they are processed (Dadbakhsh et al. 2012; Glardon et al. 2001).

2.10.7 Flexibility capability 7: Ability to fabricate products without tooling

For many authors the elimination of tooling from manufacturing represents the underpinning characteristic which qualifies the technologies as ‘flexible’. Chimento et al. (2011) make explicit their observations, claiming Additive Manufacturing technologies are able to “increase manufacturing flexibility by eliminating the need for part-specific tools”. This is echoed by Xiong et al. (2013) and Bak (2003), who find the elimination of tooling also reduces cost of production. As tooling requires both design and investment and constrains the range of parts which can be produced, its elimination is claimed to support increased manufacturing flexibility. This also supports product fabrication directly from 3D design models, which is observed by some authors (Overmeyer et al. 2011; Pérès and Noyes 2006) as a characteristic promoting the flexibility of Additive Manufacturing.

2.10.8 Identified limitations in existing flexibility assessments

Each of the seven capabilities is identified as being a consequence of specific Additive Manufacturing technology attributes. The implication of many existing studies is that by possessing some or all of these capabilities, Additive Manufacturing is therefore inherently flexible. However, such inferences have two principal deficiencies when evaluated in conjunction with the extensive literature that has considered the complex nature of the flexibility concept:

1. In describing the nature of the flexibility achieved by Additive Manufacturing, the multifarious nature of flexibility is only partially recognized via existing capability-based assessments. Although numerous flexibility typologies exist, detailed appraisals concerning the nature of different flexibility types have received little application for Additive Manufacturing. It is therefore unclear which *types* of flexibility afford each of the capabilities.
2. Existing assessments have typically focused on individual machines in their evaluations of flexibility, rather than giving consideration to the system-based viewpoint espoused in Section 2.2. Additive Manufacturing machines do not exist in isolation of other manufacturing and fulfilment processes, and as a result these machine assessments offer only a partial insight into the total flexibility that can be achieved through Industrial Additive Manufacturing Systems.

Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?

Flexibility is important concept, forming one of the five principal performance objectives typically associated with Operations Management. As demonstrated in Section 2.5 it is a complex concept for which consensus over its nature has not been achieved, with many different interpretations of its definition, constituent types, and approaches to measurement. There is, however, a long and well-established perspective on flexibility arising from manufacturing systems, rather than focusing on individual machine resources. By comparison, the current section has demonstrated a lack of detailed attention in the context of Additive Manufacturing. Although many publications describe Additive Manufacturing as ‘flexible’, most use the term ambiguously and from an Operations Management perspective it is often unclear what types of flexibility the authors refer to or how it is achieved. Existing research can be categorized into seven distinct flexibility ‘capabilities’, however these do not have a strong alignment with the flexibility types familiar in Operations Management. Furthermore, there is no clear mechanism for flexibility evaluation either in terms of the machine or manufacturing system.

2.11 Literature perspectives on the flexibility of supply chains for Industrial Additive Manufacturing Systems

Through the pilot study and initial research by the author (Eyers et al. 2013), it was identified prior to the conduct of the structured review that extremely few considerations of supply chain flexibility in the context of Additive Manufacturing had been made in the research. In order to broaden the literature search results from Google Scholar were included in this part of the structured process; however upon review only four papers were identified as relevant:

1. Eyers et al. (2013) is only paper to focus specifically on the topic in the context of Additive Manufacturing, and is the author's earlier work that is developed further in Chapter 7. This conference paper serves to highlight a dearth of knowledge for supply chain flexibility, and demonstrates an initial evaluation of an Additive Manufacturing supply chain.
2. The study of Karania et al. (2004) evaluated the capabilities of specific conventional processes relative to a specific Additive Manufacturing technology, and whilst they did not examine supply chain flexibility *per se*, they did note its enablement through minimization of initial costs and lead-times. In this manner, Additive Manufacturing is identified as supporting flexibility in the supply chain by reducing the penalty of change between different products.
3. Nyman and Sarlin (2012) focused on potential implications of 3D printing on the supply chain, and noted the potential to achieve flexibility arises in the location of the decoupling point. Noting the potential for flexibility in manufacturing in general, this study also highlights the potential for different supply chain strategies to be enabled through the decoupling point adjustment.
4. In the development of a desktop 3D printer, Lipton et al. (2012) noted that modularity in its motor design promoted flexibility within the supply chain for this type of machine. Although this is not developed further in this paper, from the text it is envisaged that flexibility arises from opportunities to source a standard, modular motor from a range of suppliers, rather than bespoke offerings.

Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?

Within Section 2.7 the emergence of supply chain flexibility as an emergent topic for operations management research was identified, and its nature explored. A progression from the concept of manufacturing flexibility, supply chain flexibility acknowledges the importance of managing whole supply chains, not just individual components.

The current section has demonstrated that (with the exception of the Author's prior work) there has been almost no evaluation of the concept in the context of Additive Manufacturing. The inclusion of the related 3D printing materials indicate that flexibility within the supply chain needs to take into account the supply of the machines themselves, and also the contribution Additive Manufacturing makes to supply chain strategies. The finding of this review confirms the existence of a research gap, motivating the final research question of this study.

2.12 Chapter summary

Manufacturing systems, including their control systems need to be effectively designed in order to respond to disturbances arising from changing market circumstances in a competitive global marketplace (Brennan and O 2004). In response to this observation in Part A the main concepts of manufacturing systems, variety/customization, flexibility, and supply chain flexibility were examined to understand their nature, and to highlight the principal aspects that will be considered in the current study.

This theoretical understanding is contextualized in terms of Additive Manufacturing in Part B, where the research gaps that justify the research questions posed in this study have been demonstrated through the structured review process and an up-to-date synthesis of current research for each has been presented. The structured literature review highlights that, as yet, little explicit research attention has been given to real-world implications of Additive Manufacturing. It has been shown that despite the enthusiasm for Additive Manufacturing, thus far studies have focused almost exclusively on individual process technologies and machines, and have not embraced the concept of a manufacturing system in their assessment. Current approaches have demonstrated some semblance of functionally linked resources, but the absence of a detailed systems perspective on this topic is a notable omission for both research and practice. Furthermore, whilst much enthusiasm surrounds Additive Manufacturing for low-volume and customized manufacture as a result of its 'flexibilities', these capabilities are poorly understood, particularly in terms of the implications for the supply chain.

Chapter 3 Research Design

Chapter Aims

1. Explanation of the philosophical positioning which underpins this research.
2. Justification for the research instruments selected in this study.
3. Examination of the advantages and limitations of the approach taken.

3.1 Chapter overview

At its most basic, research design can be colloquially identified as a "logical plan for getting from *here* to *there*, where *here* may be defined as the initial set of questions to be answered, and *there* is a set of conclusions (answers) about those questions" (Yin 2009, p. 26). For doctoral research this plan is complex, often convoluted, and is informed and constrained by a number of factors. Creswell (2009) identified that the design of a research study can be considered as an intersection of philosophy and related strategies, enacted through the use of specific methods. This chapter commences with an exploration of the methodology of this research, in which a critical examination of the philosophical underpinnings of the study is conducted. This investigation serves to explain the beliefs and attitudes of the researcher, and the extent to which alignment between principal philosophical positions is demonstrated. From this exploration the selection of appropriate methods and rejection of those deemed incompatible with the philosophical position is undertaken. In this way, the most fundamental questions regarding what kinds of data should be gathered, where it should come from, and how it should be analysed (Easterby-Smith et al. 1991) are tackled.

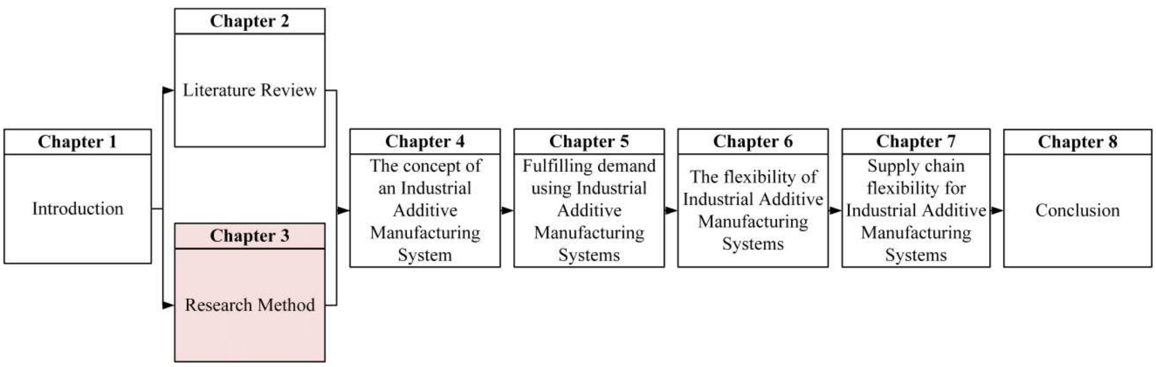

Figure 3.1: Thesis structure
Source: The Author

Doctoral studies such as this are required to make a novel contribution to knowledge, for which there are a multitude of potential approaches that may be taken. In setting up the research a careful balance is needed to ensure that the project is manageable within the resource constraints, but is not so prescriptively defined that the answers are already largely known at the outset: in order to gain new knowledge we must not already know the answer in advance (Daft 1983). As a result, flexibility in both the problem definition and the research approach is necessary to enable the exploration of the unexpected. Within this chapter the premise of a single linear approach to the design of this study is examined and rejected, as it is recognized that real-world research does not move smoothly between research question and answer via a well-organized data collection system (Robson 2011). Whilst it is essential that research is designed before its conduct, the author is mindful of the guidance of Simon:

> "Do not wait to start your research until you find out *the* proper approach, because there are always many ways to tackle a problem – some good, some bad, but probably several good ways. There is no single perfect design. A research method for a given problem is not like the solution to a problem in algebra. It is more like a recipe for beef stroganoff; there is no one best recipe."
>
> *Simon (1969, p. 4)*

Within this chapter the 'recipe' for the study is presented, and a justification is given for the inclusion of each 'ingredient'. As an exploratory study the use of an abductive approach to research is taken (Dubois and Gadde 2002; Kovács and Spens 2005), leading to iterations between theory and data. Furthermore, the author subscribes to the notion of a crucial interplay between theory and method (van Maanen et al. 2007), and consequently the design of the study has been shaped as a result of interactions between these. Detailed consideration is given to the strategies and methods applied within this research, demonstrating their applicability, limitations, and explaining how they were implemented. Ethical considerations of this research have been summarized in Appendix B, along with appropriate actions taken by the researcher in the conduct of the study.

3.2 Research paradigms

There have been many interpretations of the term *paradigm* in the context of academic research, and as a result there is discrepancy over the usage of the term in social science research (Morgan 2007). Simplistic definitions delimit the term as being the distinction between qualitative and quantitative research, however a fuller consideration is given by Denzin and Lincoln (2005), who identify that it comprises the epistemological, ontological, and methodological premises of the individual researcher. Similarly, Morgan (1979) proposed that a research paradigm can be considered at three levels: the philosophical (to capture a complete view of reality); the social-organizational (concerning the conduct of the researcher in terms of their school of thought), and at the technique level (in terms of the tools and methods used in the execution of the research). Within this study, the perspective of 6 and Bellamy (2012) is observed, where a paradigm is the shared understanding of what should be examined, what counts as data, what questions are important, how data should be interpreted, and what is an acceptable in the answering of research questions.

Within this definition of a paradigm, two particularly important concepts are acknowledged:

Epistemology considers what constitutes acceptable (or valid) knowledge (Bryman and Bell 2011; Saunders et al. 2012). Knowledge may be attained in a variety of ways, and an individual's epistemological beliefs confirm which approaches are acceptable. Notably for the wider development of the research area, attention to epistemological issues is important as they have a major influence on the quality of theoretical developments (Narayanan and Zane 2011).

Ontology is concerned with "the nature of reality" (Saunders et al. 2012), and asks the fundamental questions about what is 'real'. If epistemology concerns 'knowing', then ontology concerns the nature of 'being' (May 1997). Ontological considerations require the researcher to consider the nature of social phenomena, and to evaluate whether they are inert or a part of social interaction (Bryman 2012).

Therefore, ontology is the 'reality' that researchers investigate, epistemology is the relationship between that reality and the researchers, and methodology is the technique used to investigate that reality (Healy and Perry 2000). It is important to recognize that an interplay exists between ontology and epistemology; as Hitchcock and Hughes (1995) identify, ontological assumptions give rise to epistemological assumptions. What is perceived as real influences beliefs about reality (and vice-versa), and therefore it is not feasible to separate considerations of epistemology and ontology.

It is acknowledged that debates over the nature of philosophical perspectives towards research are challenging to define and explain, and that there are many philosophical positions with which an individual may associate themselves that will result in different 'answers' being obtained. In Social Science research great emphasis is placed upon this element of scholarly endeavour, since it is only by understanding the implications of the beliefs of the researcher that an appreciation of the implications for the conduct of the study can be gained. Recognition of different perspectives of philosophy was exemplified by Burrell and Morgan (1979), who provided a schema for understanding the assumptions of social science in which ontology, epistemology, human nature, and methodology may be considered on continua (Figure 3.2).

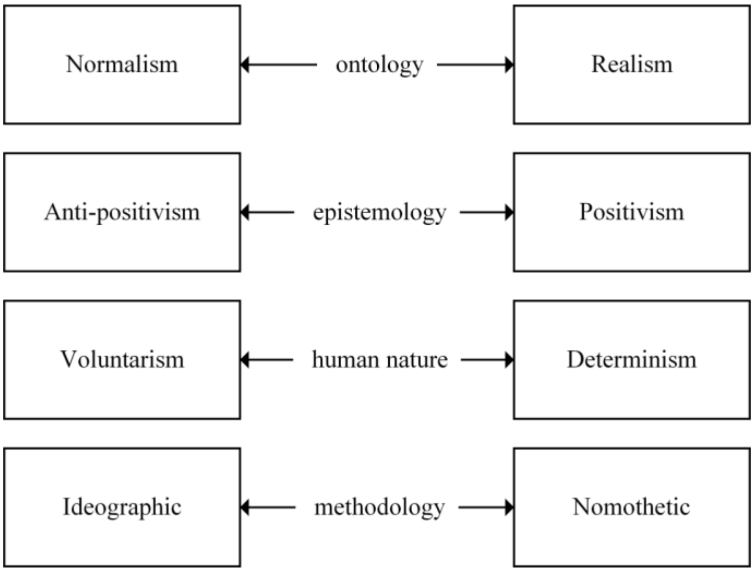

Figure 3.2: The subjective - objective dimension
Source: Burrell and Morgan (1979)

The use of such continua in the definition of philosophical positions is frequently employed. Many focuses are delimited by their epistemology; often this constitutes positivistic positions at one extreme, and an alternative (and apparently incompatible) anti-positivist position at the other, and in Table 3.1 a synthesis of such evaluations is provided. From a pedagogic perspective the use of such delineations may improve accessibility to the concepts by allowing basic assumptions to be established (Remenyi et al. 1998), and help to link paradigms with their methodological approaches (Figure 3.3). Continua can, however, imply some degree of linearity between the attributes and attempt to identify formal boundaries between philosophical positions that may be less distinct than may be implied. There is no seamless progression between categorizations, and in many instances some characteristics may overlap. Many authors disagree over the components of these positions, and even if one could compile an accepted list of assumptions that align with each philosophical position, this may have little utility since as Easterby-Smith et al. (2008) observe, in implementation no one philosopher can be identified as exhibiting all characteristics of a particular perspective anyhow. The consequences of this situation are not necessarily a problem, since as Sayer (2000) notes, fuzzy distinctions are not always fatal.

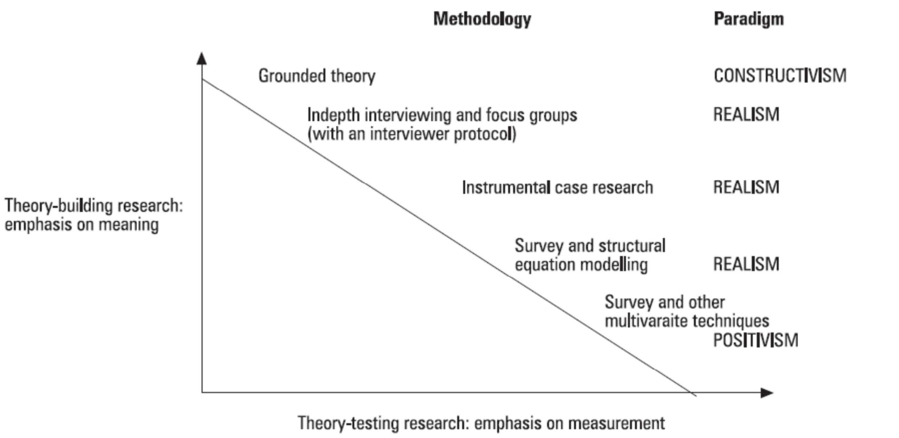

Figure 3.3: Methodologies and related paradigms
Source: Healy and Perry (2000)

	Approach taken			
	Positivist	**Realist**	**Constructionist**	**Pragmatist**
What is ‘reality’?	A definable ‘reality’ or ‘truth’ exists and is observable. Naive realism – “real” reality but apprehendible	A “real” reality but only imperfectly and probabilistically apprehendible	There is no ‘reality’ or ‘truth’ beyond our experiences	Reality is tentative and ever-changing; achievements in research should be considered as provisional, rather than definitive. Reality is objective and socially constructed
What is the goal of academic enquiry?	Acquisition of the ‘truth’	A more informed understanding of the multiple possible ‘truths’	A more informed construction of the world	The solution of practical problems in a practical world
Relationship between the research and the ‘researched’	None – objectivity sought	The researcher is not independent of the ‘researched’	The researcher is not independent of the ‘researched’	The researcher is not independent of the ‘researched’
What should be the role for values?	None – objectivity sought	Subjective - personal value system influences what is researched and how	Part of ‘reality’ – subjectivity celebrated	Subjective - personal value system influences what is researched and how
What kind of approach?	Predominantly based on observability or measurability with the aim of seeking ‘evidence’; experimental/manipulative ; verification of hypotheses; chiefly quantitative methods	Methodological pluralism embraced; blending of methods performed to best understand interactions between objects	Predominately based on discourse and meaning with the aim of seeking a more informed understanding of the world	Whatever works to satisfy the research question
What kind of data is preferred?	Predominately quantitative	Quantitative and qualitative	Predominately qualitative	Whatever works for the research question

Table 3.1: An overview of research approaches
Source: The Author, based on (Cohen et al. 2011; Guba and Lincoln 2005; Meredith et al. 1989; Mingers et al. 2013; Robson 2011; Sumner and Tribe 2004; Wass and Wells 1994)

3.2.1 Positivism

The origins of the positivist paradigm are typically attributed to 19th Century work by Comte (1865), in which all genuine knowledge is based on experience and can only be advanced by experimentation and observation (Cohen et al. 2011). In positivism, the ontological assumption is made that reality is separate and distinct from the researcher. This means that, given enough attention to the design of a study, it is possible for research to take place as if the researcher were not present, and the observer is therefore independent of the phenomena being observed and the research is value-free. In positivistic research, the aim is to identify the laws which serve to explain observations; these laws may be derived from a hypothesis which has been demonstrated to be true. Positivistic enquiry is typically associated with research that involves quantitative data (Punch 2005), and tends to result in the conduct of deductive research (Gill and Johnson 2002). In positivist Business Management research, principal research methods are questionnaires and experimentation under controlled conditions.

3.2.2 Anti-positivism

At the other extreme of the continuum is the anti-positivist belief in a world that is not knowable or explainable through the scientific method and establishment of causal laws. One perspective on an anti-positivist approach is Social Constructionism, which asserts that reality is a social construction, with the purpose of research to be the analysis and explanation of how this arises (Berger and Luckmann 1967). Several examples of socially constructed concepts are given by Boghossian (2001) including money, newspapers and citizenship. For each it is argued that their existence is a consequence of a social construction – for example, there is a social agreement a newspaper exists (it is not simply just a collection of pages containing text). Likewise the Doctorate qualification exists as by social agreement on the capabilities of the individual and the credibility of the assessors and awarding institution, else it is only a piece of paper with a University crest. For social constructionists, the nature of knowledge and reality are specific to individual social contexts; for example a Tibetan monk has a different perspective on reality than an American businessman (Berger and Luckmann 1967).

Burr (1995) recognises therefore that there cannot be objective facts in social constructionism. Indeed, there is even no single definitive understanding; whilst commonalities between ‘versions’ of can be found, Stam (2001, p. 294) observes that “what counts as social constructionism is often dependent on the author’s or critic’s aims”.

3.2.3 Realism

A third philosophical position is that of realism, and the realist social scientist:

> "is likely to claim that social entities (e.g. markets, class relations… etc) exist independently of our investigations of them…. That many of these qualities are disputed and not directly observable (and hence refracting to quantification) does not rule them out of consideration for analysis, a position that distance realist- from empiricist- or positivist-orientated analysis. Furthermore, that these disputed entities exist independently of our investigations of them distances realism from postmodernism."
>
> *Ackroyd and Fleetwood (2000, p. 6)*

The critical realist approach to research has become increasingly popular in business and management studies as a result of "growing dissatisfaction with the inherent explanatory limitations of postmodern and post-structuralist epistemologies and their grounding in a social constructionist ontology" (Reed 2005, p. 1629). The ontological position of the critical realist author shares some commonality with that of the positivist, since the world 'out there' is deemed to exist independently of the researcher's knowledge of it (Thomas 2004). However, the critical realist asserts that it is the interpretation of the world that is made by the individual which makes it meaningful. Reality is not 'formed'; instead descriptions of reality are developed to express the essential properties through both thought and language (Outhwaite 1983).

In critical realism, Bhaskar (1975) emphasised the importance of ontology, and that a 'stratified ontology' exists, emphasising the distinction between the real, actual, and empirical in terms of causal powers. Sayer (2000) characterised the *real* as 'whatever exists' – whether or not it is understood by the researcher – and concerns objects, both their structures and their powers. The *real* can be physical (as an object), or social (as a construct), and possesses causal powers (capabilities to behave in certain ways), and causal liabilities (susceptibilities to change). By comparison, the *actual* concerns what the causal powers do when activated, and what the results of such activations are. Finally, the *empirical* relates to the domain of experience and perceptions that are held by individuals.

Explanation in critical realism depends on identifying these causal mechanisms, rather than the 'usual approach' which finds causation the result of regular occurrences; according to Sayer (2000, p. 14), "what causes something to happen has nothing to do with the number of times we have observed it happening". Furthermore, causal powers are both irreducible and not always active, and their future activities are potentials, not certainties (Sayer 1992). This is contrary to the automatic correlation of events typically associated with positivism (Easterby-Smith et al. 2012).

This possibility of causal powers can be identified using Collier's example:

> "Wine cheereth the heart of God and man, according to the Good Book – but not so long as it is tightly corked in its bottle"
>
> *Collier (1994, p. 9)*

The potential for the causal powers of wine is well known; whilst corked it is not activated, and only on consumption may the activation occur. If consumed with excessive quantities of other alcohol, the resultant sickness is the result of an unrealised power (in that it has had its effects, but not those which would have occurred when consumed as intended), yet this sickness would be a potential, and not always a certainty.

3.2.4 Pragmatism

Some researchers take a pragmatic approach (often referred to as 'whatever fits'), which focuses on the research question under investigation, thereafter selecting the appropriate epistemological and ontological positioning as a secondary consideration (Saunders et al. 2009; Taskakkori and Teddlie 1998). As Johnson and Onwuegbuzie (2004, p. 16) observe, "the bottom line is that research approaches should be mixed in ways that offer the best opportunities for answering important research questions". Whilst positivists believe knowledge is objective, and anti-positivists find it to be too complex to be known by a single perspective, pragmatists 'fall somewhere in between positivists and anti-positivists' (Goles and Hirschheim 2000, p. 261). Pragmatists accept truth, meaning, and knowledge as both tentative and temporal. Achievements in research should be considered as provisional, rather than definitive since reality is ever-changing (Maxcy 2003; Robson 2011). Despite the potential flexibility that such a position may offer the researcher, it is interesting to note that within Operations Management research pragmatism is identified as relatively uncommon (Kiridena and Fitzgerald 2006).

3.3 Research philosophy and Operations Management research

3.3.1 Evaluation of philosophical positions within Operations Management research

Although justification of research philosophies is important in many social science fields, it is notable that few Operations Management researchers make reference to their own philosophical beliefs in publications. Research issues of epistemology and ontology have received little attention in Operations Management journal publications, save only a tendency to call for more attention in this area. An illustration of this may be found by a keyword search for 'epistemology' within the Journal of Operations Management from inception through to volume 32 inclusive (1980-2014). Whilst this is only a single journal, it is recognized as being one of the premier quality outlets for Operations Management research (Harvey et al. 2010). Within the search only four relevant publications may be identified that discuss the implications of epistemology on their work. The earliest text of Meredith et al. (1989) calls for "a broader epistemological stance concerning knowledge creation", yet these search results identify this has not been forthcoming.

The somewhat emergent and fluid nature of Operations Management may, in part, explain this dearth. Whether Operations Management even exists as a discipline in its own right is contested (Pilkington and Meredith 2009). Operations Management bridges a range of well-established disciplines (e.g. Engineering, Management, Mathematics, Operations Research), all of which have their own established perspectives towards research philosophies. Different facets of Operations Management are therefore influenced by the perspectives which cascade from the established disciplines, making unification problematic, and this is further compounded by the internal differences within these established disciplines. For example, within Business Management the potential for a wide range of methodologies and methods exists and there is no one 'accepted' approach to this type of research (Wass and Wells 1994).

The problem with a failure to address issues of epistemology and ontology is that individual researchers are unable to make informed choices in their work (Wass and Wells 1994, p. xv). Such omissions do not enable the Operations Management researcher to simply ignore philosophical considerations– as Collier (1994) identifies:

> "A good part of the answer to the question "why philosophy?" is that the alternative to philosophy is not no philosophy, but bad philosophy. The 'unphilosophical' person has an unconscious philosophy, which they apply in their practice - whether of science or politics or daily life."
>
> *Collier (1994, p. 17)*

Even where it is not explicitly stated, it is important to observe that Operations Management research has typically adopted a positivistic stance, much of which arises from its origins and association with Operations Research. In reviewing the International Journal of Operations and Production Management (IJOPM), Taylor and Taylor (2009) identify that since the 1970's whilst there has been a movement towards empirical methods, research has still been conducted within a positivist philosophy. This is particularly notable since, relative to other outlets for Operations Management research, IJOPM is one of the most receptive journals to methods traditionally aligned with non-positivistic philosophy (Craighead and Meredith 2008). Within the neighbouring field of Supply Chain Management, Burgess et al. (2006) similarly identify that research is dominated by positivistic enquiry. The reliance of Operations Management on positivistic enquiry has been identified as detrimental its development, with Autry and Flint (2010) identifying that such an approach constrains the extent to which phenomena are being examined. If other approaches were executed with the same rigour, then these studies would be "able to make observations about operations and supply management phenomena that positivist approaches by definition omit due to their focus on theory testing" (Autry and Flint 2010, p. 2).

3.3.2 Justification for a Critical Realist approach in this study

Although explicit discussions of research philosophy are seldom reported, as Klassen and Menor (2007) identify, Operations Management scholars often aim to find laws and theory by conducting "scientific" research. Such is the apparent extent of the positivistic prevalence in published Operations Management research, an existing path that has been well trodden is implied, and in terms of academic publication a positivistic perspective is more clearly adopted and accepted by reviewers. This expectation is relevant, since as Nieuwenhuis (1994) observes, researchers are often obliged to shape their research practice to the requirements of their audience. It would however be incorrect to identify positivism as the only option. Indeed, as Meredith et al. (1989) and Autry and Flint (2010) suggest, such an eventuality has contributed to constraint in the development of Operations Management research, and a move towards interpretative and observation based investigation increases the relevance of the findings for a management audience (Gunasekaran and Ngai 2012).

The author has an established background in Engineering research and practice, and aligns with the positivistic assumption that the world 'out there' is deemed to exist independently of the researcher's knowledge of it (Thomas 2004). Similarly, he has sympathy to the positivistic traits such as Durkheim's guidance for the social scientist to adopt 'the same state of mind as the physicist, chemist or psychologist when he probes into a still unexplored region of the scientific domain' (Durkheim 1964, p. xlv). However, this acceptance focuses principally on the rigour with which investigation should be conducted. The nature of the research undertaken within commercial organizations involving the complexities and peculiarities of both human and machine behaviours leads to an assessment by the author that naïve positivism and the laws under which it operates are inadequate to understand and communicate the findings of this research.

Whilst the author may therefore be identified as adopting a somewhat anti-positivist approach in this study, it is distinct from the very opposing end of the continua at which interpretivism is located. The author rejects the fundamental belief that *everything* is based in discourse and socially constructed. As Ackroyd and Fleetwood (2000) identify, if everything comes down to discourse then it would be possible to simply talk undesirable things away, and this is not a position supported by the author.

Hence it is Critical Realism that offers a philosophy with which the author is most in alignment, which Thomas (2004) notes 'bridges' alternative philosophical stances. Dobson (2002) observes that "knowledge of reality is resultant from social conditioning… it cannot be understood independently of the social actors involved". The author adopts an ontological position which accepts the views and opinions of research participants as valid social contributions to the research, and which enables the use of social methods such as interviews. By extension, the acceptance of a Critical Realist perspective required the author to subscribe to the notion of causal powers (and their relative operation and potential operation) as being applicable to the study.

Characteristic	Explanation	Relevance to this study
Stratified Ontology	The real, actual, and empirical are distinguished separately.	The researcher acknowledges the world to be full of emergence, and accepts that causal powers may exist in different states.
Research is limited and mediated by perceptual and theoretical lenses	Epistemic relativity is supported (that knowledge is always local and historical), but not *judgmental* relativity (that all viewpoints must be equally valid) (Mingers et al. 2013).	It is acknowledged that the research is influenced by the researcher; this is not a limitation but a consequence of the nature of enquiry.
Support for a range of methods	Different types of knowledge objects exist, which have different ontological and epistemological characteristics, requiring a range of methods to access them (Mingers et al. 2013).	A multiple methods, predominantly qualitative approach is adopted in this study to collect data from a range of respondents.
Value-laden enquiry	Reality is not 'formed'; instead descriptions of reality are developed to express the essential properties through thought and language (Outhwaite 1983).	The researcher identifies himself to bring his own values to the enquiry, and must recognize this in the conduct of the research.
Causation	Causal powers are both irreducible and not always active, and their future activities are potentials, not certainties (Sayer 1992).	That causal powers are potentials, not certainties is a fundamental tenet to the work on flexibility: flexibilities may be unrealized.
Retroduction	Retroduction is often deemed synonymous with abductive enquiry (Mingers et al. 2013).	Enables alignment between Critical Realism and a Systematic Combining (abductive) approach.

Table 3.2: Characteristics of Critical Realism relevant to this study
Source: The Author

3.4 Selection of the research approach

3.4.1 Deductive, inductive, and abductive approaches to research

Factor	Deduction	Induction	Abduction
Departing Point	Theoretical Framework	Empirical observations (theory is absent)	Empirical observations (unmatched by/deviating from theory)
Aim	Testing/evaluating theory (Falsification or verification)	Generating and building theory	Developing new understanding by incorporating existing theory (where appropriate) or building/modifying theory
Drawing Conclusions	Corroboration or falsification	Generalization/transferability of results	Suggestions (for future directions, theory/paradigm/tool)
Generalization	From the general to the specific	From the specific to the general	From the iterations between the specific and general

Table 3.3: Comparison of research approaches

Source: The Author, developed from de Brito and van der Laan (2000) and Saunders et al. (2012))

In Table 3.3 the three principal approaches to research are compared. Bryman and Bell (2011) identified the most prevalent view on the relationship between theory and research is the deductive approach in which a theory or hypothesis is developed, operationalized, tested, and the observations which arise from the testing process are compared with the assertions of the theory or hypothesis (Gill and Johnson 1991). In this approach, which is prevalent in positivism, theory is either corroborated or discarded.

Induction offers an approach to research in which general theory is developed from initial observations. In what is often termed a ‘bottom up’ approach, patterns in observations are identified, leading to the generation of hypothesises which are then tested to result in the formation of specific theories; as more observations are made which support the theory then it is strengthened (Hamlin 2003). As a result, this approach is prevalent in interpretism, and typically employs a qualitative strategy.

Both deduction and induction imply a one-way approach to theory and data: either the research moves from theory to data (deduction) or data to theory (induction). Abduction allows a two-way iteration between theory and data (Saunders et al. 2012). The abductive approach is somewhat unusual for Operations Management research (de Brito and van der Laan 2000), and has previously been considered as a compromise between the extremes of pure deduction and induction (Atkinson and Delamont 2005). However, in the iterations between empirical data collection and theoretical development that constitutes an abductive approach, a more realistic perspective of the practice of applied management research may be achieved. Data analysis and data collection frequently overlap (Eisenhardt 1989), and van Maanen et al. (2007) emphasize that in management research:

> the flow of research is lengthy and uneven, is seen most clearly in hindsight, and, perhaps most important, is contextually idiosyncratic, often chaotic, and always personal. How we arrive at conclusions, insightful or otherwise, is difficult to penetrate when publication norms do not favor the presentation of results in the manner in which they evolved and when the personal history of how the research process unfolded over time may be revised or forgotten as the project moves towards its final printed version.
>
> *van Maanen et al. (2007, p. 1146)*

The complex and 'messy', non-linear nature of research is accepted as being relevant to the type of research conducted in this study. Abductive research begins with an observation and/or a theory which deviates from the expected norm, leading to an anomaly in understanding which is addressed through iterative research to either extend the existing theory, or propose a new one (Kovács and Spens 2005). In the context of business research, this iterative approach has been coined 'Systematic Combining' (Dubois and Gadde 2002, 2013). Particularly for the Case Study research method, Systematic Combining has been shown to allow an 'intertwining' of theory and empirical observation in the conduct of the research study. It is identified that "theory cannot be understood without empirical observation, and vice versa" (Dubois and Gadde 2002, p. 555), and through Systematic Combining it is possible to develop research through iterations of the processes of matching, and seeking direction and redirection (Figure 3.4).

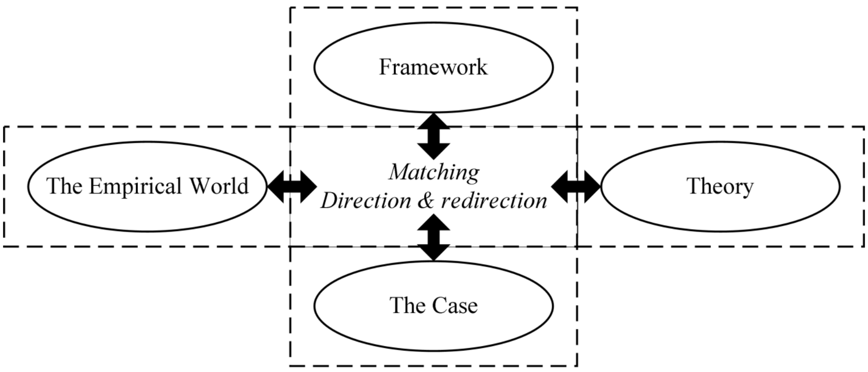

Figure 3.4: Systematic combining
Source: Dubois and Gadde (2002)

The adoption of an abductive approach (Figure 3.5) in this research has several motivations. Importantly, the approach aligns with the other elements of the paradigm. It is often viewed as being synonymous with the retroduction espoused by Bhaskar (1975) in Critical Realism, and supports the qualitative case-based research which is conducted in this study. Furthermore, since this study transfers established theories (e.g. flexibility) to the context of Industrial Additive Manufacturing, the abductive approach allows for an exploration of its suitability (and consequential development) in this research context through iterations between collecting data within organizations and the assessment of established theory. Through abduction, the author brings knowledge of theory to the research setting from both Operations Management and Engineering, and through iterations of the Systematic Combining process is able to identify theoretical linkage and development requirements.

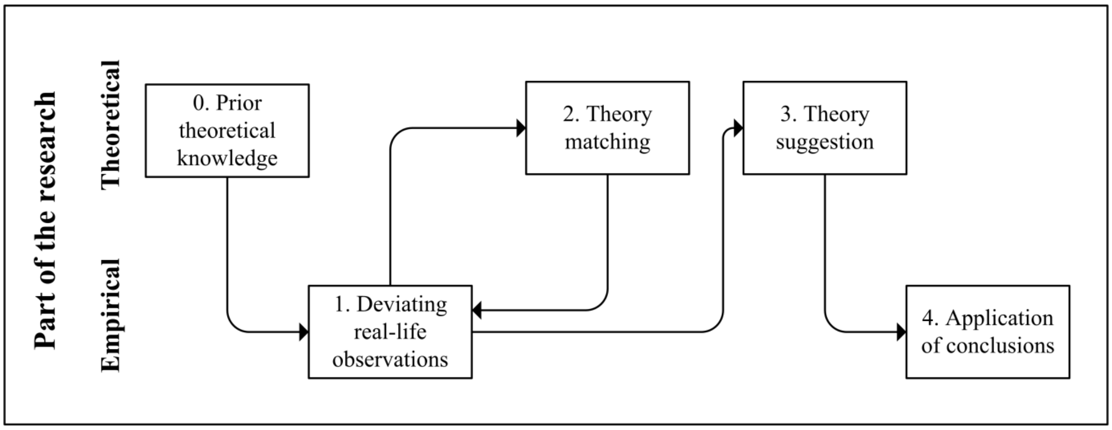

Figure 3.5: The abductive research process
Source: Kovács and Spens (2005)

3.4.2 Justification for exploratory qualitative research

The literature review highlighted a general dearth of knowledge pertaining to the nature of flexibility for Additive Manufacturing systems or supply chains. In recent years Additive Manufacturing has developed from a focus on the creation of functional prototypes to the fabrication of end-user parts (Hopkinson et al. 2006b; Wohlers 2012). The limited volume of academic research in this area, combined with the current pace of market and technological change must be appreciated in the design of the study. As a result, this research takes an exploratory approach to tackling the research questions previously developed in Chapter 2.

Phillips and Pugh (2000) identify that studies which explore relatively uncharted areas are appealing, but inherently more risky in terms of achieving a successful execution. Collis and Hussey (2003) identify that for such studies, the intention is to gain familiarity with the research domain, identifying insights, hypothesises and directions for further research rather than forming conclusive answers to problems or issues. This does not mean that exploratory research has no findings; rather that it serves to build the foundations and provide the initial results in a new area. To achieve this objective, this exploratory work builds upon the author's prior commercial and academic experience in operations, engineering, and manufacturing, bringing this knowledge together with extant Additive Manufacturing literature and the empirical research conducted in this study.

The exploratory nature of this work and the selection of an abductive approach to the research supports the use of research instruments that are principally of a qualitative nature. Such an approach aligns with Edmondson and McManus (2007), who highlight that where the state of prior knowledge may be broadly described as nascent, the use of qualitative methods of enquiry is commonplace (Table 3.4).

State of Prior Theory and Research	**Nascent**	**Intermediate**	**Mature**
Research questions	Open-ended inquiry about a phenomenon of interest	Proposed relationships between new and established constructs	Focused questions and/or hypotheses relating existing constructs
Type of data collected	Qualitative, initially open-ended data that need to be interpreted for meaning	Hybrid (both qualitative and quantitative)	Quantitative data; focused measures where extent or amount is meaningful
Illustrative methods for collecting data	Interviews; observations; obtaining documents or other material from field sites relevant to the phenomena of interest	Interviews; observations; surveys; obtaining material from field sites relevant to the phenomena of interest	Surveys; interviews or observations designed to be systematically coded and quantified; obtaining data from field sites that measure the extent or amount of salient constructs
Constructs and measures	Typically new constructs, few formal measures	Typically one or more new constructs and/or new measures	Typically relying heavily on existing constructs and measures
Goal of data analyses	Pattern identification	Preliminary or exploratory testing of new propositions and/or new constructs	Formal hypothesis testing
Data analysis methods	Thematic content analysis coding for evidence of constructs	Content analysis, exploratory statistics, and preliminary tests	Statistical inference, standard statistical analyses
Theoretical contribution	A suggestive theory, often an invitation for further work on the issue or set of issues opened up by the study	A provisional theory, often one that integrates previously separate bodies of work	A supported theory that may add specificity, new mechanisms, or new boundaries to existing theories

Table 3.4: Three archetypes of methodological fit in field research
Source: Edmondson and McManus (2007)

A comparison between qualitative and quantitative research is provided in Table 3.5. Qualitative research is informative, detailed, reflexive, subjective, holistic, and flexible (Sarantakos 1998), and enjoys a strong alignment with Critical Realist research. It is traditionally associated with explorative work, however it is suitable for use beyond the exploratory (Spanjaar and Freeman 2006). Maxwell (1996) identifies five motivations for which qualitative studies are particularly suited, for which Table 3.6 demonstrates their relevance to this study.

Feature	Quantitative Methodology	Qualitative Methodology
Nature of Reality	Objective; Simple; Single	Subjective; Problematic; Holistic
Causes and Effects	Nomological things; cause-effect linkages	Non-deterministic; no cause-effect linkages
Role of Values	Value neutral; Value-free enquiry	Value-bound enquiry
Natural and Social Sciences	Deductive; Model of natural sciences - based on strict rules	Inductive; Rejection of natural sciences model - no strict rules: interpretations
Methods	Quantitative, mathematical, extensive use of statistics	Qualitative, less emphasis on statistics, verbal and qualitative analysis
Researchers' Role	Passive; is the 'knower' and separate from the subject	Active; 'knower' and 'known' are interactive and inseparable
Generalizations	Inductive generalization	Analytical or conceptual generalizations; time and context specific

Table 3.5: Perceived differences between qualitative and quantitative research
Source: Adapted from Sarantakos (1998)

Motivation	Relevance to this study
To understand the meaning research participants give to events and situations	It is acknowledged that different perceptions exist on the capabilities of Industrial Additive Manufacturing to achieve flexibility within operations and the wider supply chain. Through a qualitative approach it is possible to gain depth of understanding.
To understand the context within which research participants act, and how this affects their actions.	This study is interested in the practicalities of Industrial Additive Manufacturing, which is likely to be affected by the idiosyncrasies of individual companies in the conduct of their manufacturing. Qualitative research enables explorations of how individual characteristics affect the way in which research participants make decisions.
To understand the process by which events take place	Each of the purposes identified by Maxwell is relevant to this research, and therefore the selection of qualitative methods is appropriate in this study, which seeks to understand the nature of flexibility and the methods and implications of its achievement.
To develop causal explanations	Within the acknowledged Critical Realist understanding of causality, a qualitative approach allows investigation of causal powers (whether potential or enacted) to be examined in this study.
To understand unanticipated phenomena	As the topic being explored is not well understood in existing literature, the ability of qualitative approaches to adapt flexibly in order to accommodate the unexpected is a useful capability.

Table 3.6: Motivations for qualitative research
Source: The Author, adapted from Maxwell (1996)

3.5 Selection of research strategies

The research approach described in the previous section identified that this study is principally qualitative, and as a consequence of limited research in this area, broadly exploratory. In this study three distinct strategies are employed (Figure 3.6), through which data are accessed by a number of different methods. The following three sections explain each of the strategies employed, and provide a justification for their utilization in this study. Within each strategy the enabling methods are discussed; these were carefully chosen to most appropriately tackle the different research questions, and a detailed discussion of the rational and justification for these is included in the corresponding subsections.

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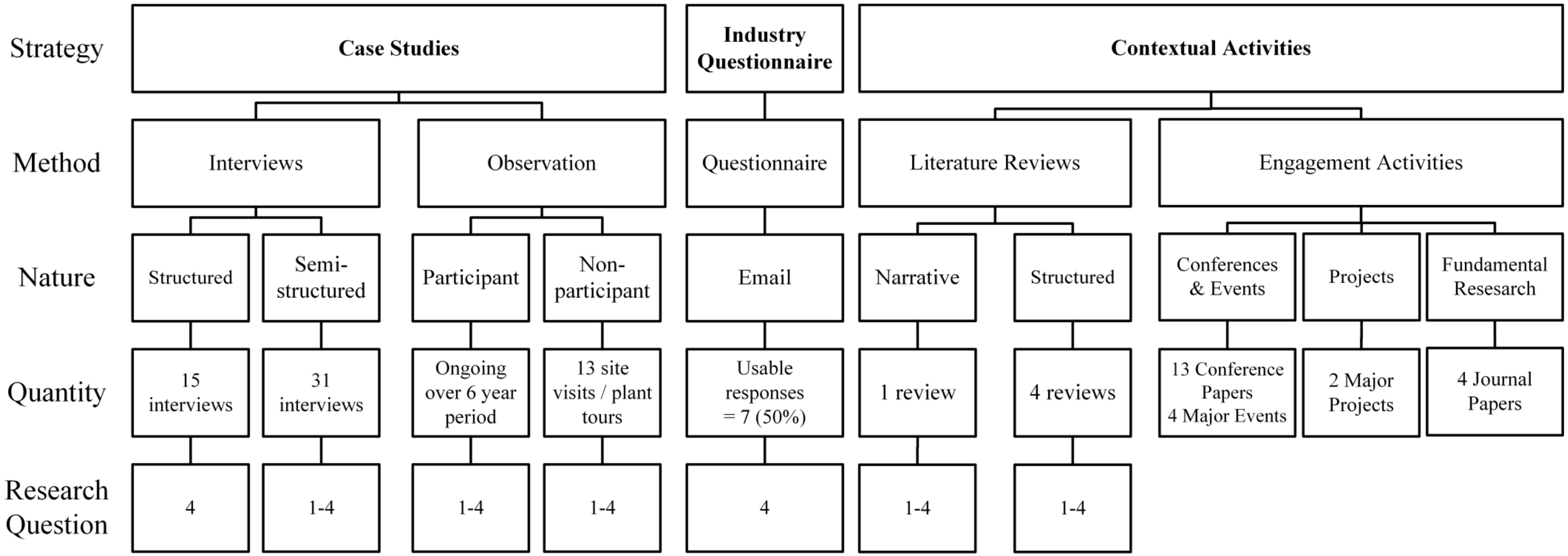


Figure 3.6: Overview of research strategies and methods employed
Source: The Author

3.6 Strategy 1: Case studies

A case study is "an empirical enquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin 2009, p. 18), and is advantageous when asking "how" or "why" questions about contemporary events which are not controllable by the researcher (Table 3.7).

Method	Form of research question	Requires Control of Behavioural Events?	Focuses on Contemporary Events?
Experiment	how, why?	yes	yes
Questionnaire	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

Table 3.7: Situations for different research strategies
Source: Yin (2009)

Case studies are primarily used to develop new theories, often using inductive methods in order to collect primarily qualitative data (Barratt et al. 2011). For Operations Management, McCutcheon and Meredith (1993) suggest that case studies help in the creation of theories to explain the gap between an academic's perception of a concept and how it actually occurs. This is particularly relevant in this study, where perceptions of the implications of Additive Manufacturing for Operations and Supply Chain Management have been evidenced in the literature, but with little empirical data to substantiate these as research findings. Handfield and Melnyk (1998) identify case studies are well suited in the discovery and early theory development stages of research. Case research allows the researcher to access the phenomena and through the application of a number of tools, develop a rich understanding about it. Voss et al. (2002, p. 195) identify case research as "one of the most powerful research methods in Operations Management, particularly in the development of new theory".

It is essential that case study research identifies the appropriate Unit of Analysis which is to be examined. In terms of manufacturing and supply chain management, seminal guidance has focused on the individual product being supplied when considering appropriate strategies (Childerhouse et al. 2002; Fisher et al. 1997; Fisher 1997). Early exploratory work conducted for the current study identified that, in practice, companies focused and organized their manufacturing efforts towards individual product types. Hence, as a result of the research precedent together with empirical observations the Unit of Analysis for this study is considered to be individual product type being produced either in whole or in part by Industrial Additive Manufacturing Systems.

In this research twelve case studies are examined, involving three different Industrial Additive Manufacturing companies and a number of other supply chain entities. A summary of these is provided in Table 3.8 and Appendix A. Each Industrial Additive Manufacturing company has been assigned an alternative name for anonymity:

1. HearingCo, a UK manufacturer of hearing aid devices. This company formerly used conventional manufacturing technologies, but has employed Industrial Additive Manufacturing technologies for 15 years. It is part of a larger group of companies; the UK division has over 150 staff.
2. LittleCo, a UK manufacturer providing outsourced 'bureau manufacturing' services. This company has offered both Industrial Additive Manufacturing and conventional manufacturing technologies for 20 years. It is part of a much larger organization, however the manufacturing division has less than ten staff.
3. BigCo, a multi-national Industrial Additive Manufacturing company that both produces its own products, and also provides outsourced bureau manufacturing services. It has been established for over 20 years, and has offices worldwide employing over 1000 staff.

It is noted that the researcher enjoyed an ongoing relationship with both BigCo and LittleCo for the six year duration of this study, allowing data to be collected and verified at multiple points in time. As shown in Table 3.8 these case studies are additionally informed by the suppliers of machines and raw materials, and for four of the twelve cases data was also achieved from customers of the Additive Manufacturing companies. Notably, when compared to much of the other published supply chain research for Additive Manufacturing (e.g. Khajavi et al. 2014; Ranganathan 2007; Tuck et al. 2007a), this study is relatively unusual in the inclusion of supply chain entities both up-stream and down-stream of the part/product manufacturing activity. As shown in the literature review, most emphasis has been on the individual manufacturer, or alternatively manufacturer-to-customer activities, and has omitted a more extensive consideration of the supply chain. In particular there has been little emphasis on the contribution of machine and materials suppliers in Additive Manufacturing research, and so their inclusion in this study is identified as a relevant contribution.

In Operations Management research the use of multiple case studies is commonplace, and emphasis has been placed on promoting internal validity by using cases which contrast considerably (Stuart et al. 2002). Gerring (2007) identifies these types of case as *diverse*, and these are used within this study to examine variation between cases. 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. Seminal guidance on the number of case studies to conduct indicates that there is no ideal value; instead a balance between having either too much and too little data must be sought – and for this reason (Eisenhardt 1989, p. 545) identified “between 4 and 10 cases usually works well”. Easton (2010) suggests that this guidance is somewhat positivistic in nature, with the assumption being that more cases equate to a better chance of finding confirmatory results. This is somewhat contradictory to the Critical Realist’s viewpoint on causation, where the number of occurrences is not related to what causes it to happen (Sayer 2000). The selection of twelve cases in this study is therefore intended to provide depth for analytical, rather than statistical generalization.

It is acknowledged that diminishing marginal returns may be experienced as case numbers increase, and that resource constraints such as time and money impose practical limitations. As a result, within this study a somewhat pragmatic approach was taken in the selection of cases. Multiple site visits were undertaken with manufacturers, complimented by visits to customers and trade shows. As a result of this iterative approach to case development a number of different potential cases were explored but were rejected from inclusion in this work on the following grounds:

1. Access was inadequate (depth of data available not sufficient to support analysis).
2. Confidentiality constraints leading to insufficient data to report.
3. The cases were identified as irrelevant to the focus of this research.

					Data sources utilized in this study					
Case No.	**Additive Mfr**	**Case Name**	**Product Description**	**Additive Mfg Process**	**Material Supplier**	**Machine Supplier**	**Designer/ Configurator**	**Additive Mfr**	**Customer/ Consumer**	**Primary Comparator Data**
1	Hearing Co	Hearing Aid	In-The-Ear (ITE) Hearing Aid	EnvisionTEC	☑	☑	☑	☑	☑	☑
2	LittleCo	Model Ship	Archaeological reconstruction of model ship	Laser Sintering (LS)	☑	☑	☑	☑	☑	☑
3	LittleCo	Archaeological Models	Archaeological reconstruction of stones	Laser Sintering (LS)	☑	☑	☒	☑	☒	-
4	LittleCo	Architectural Models	Model building (student architecture project)	Laser Sintering (LS)	☑	☑	☑	☑	☑	☑
5	LittleCo	Exhaust Tool	Hydroform tool for exhaust system	Selective Laser Sintering (SLS)	☑	☑	☑	☑	☒	☒
6	LittleCo	LittleCo Fixtures	Inspection fixture for toothbrush	Selective Laser Sintering (SLS)	☑	☑	☑	☑	☒	☑
7	LittleCo	Sensor Tool	Functional prototype of exhaust sensor tool	Laser Sintering (LS)	☑	☑	☑	☑	☑	☒
8	BigCo	Surgical Guides	Guide for surgical applications	Laser Sintering (LS)	☑	☑	☒	☑	☒	-
9	BigCo	Custom Lamps	Customized lighting product designed by customer via website	Laser Sintering (LS)	☑	☑	☒	☑	☒	☒
10	BigCo	Standard Lamps	Standardized lighting product designed by professional designer	Laser Sintering (LS) or Stereolithography (SL)	☑	☑	☒	☑	☒	☒
11	BigCo	Modular Fixture System	Hybrid fixture system customized for user application	Laser Sintering (LS)	☑	☑	☒	☑	☒	-
12	BigCo	Furniture	Designer furniture	Laser Sintering (LS)	☑	☑	☑	☑	☒	☑

Table 3.8: Case studies explored in this research
Source: The Author

The objective of this research is to develop knowledge for operations and supply chain management concerning Industrial Additive Manufacturing, and therefore the ability to generalize some of the findings of this study is beneficial. However, the ability to generalize in quantitative research is contentious; in qualitative research it is even more controversial (Onwuegbuzie and Leech 2010). In terms of Operations Management, Voss et al. (2002) identifies that there are limitations to the generalization that may be drawn from single case studies, and highlights the potential risk of making inferences from single erroneous observations. From this viewpoint multiple case studies are preferable. This perspective tends towards statistical generalization; a perspective which is commonplace in quantitative enquiry, but is often not the goal of qualitative researchers (Onwuegbuzie and Leech 2010). In case research, Yin (2009, p. 43) argues that analytic generalization is appropriate, where the researcher attempts to generalize particular results to broader theory. This technique is employed in this research, and is compatible with the abductive approach taken in the study. Stuart et al. (2002) likens this to "logical extrapolation" in which researchers judge where findings might be valid in other circumstances. Polit and Beck (2010) identify that transferability in the case-to-case approach involves the researcher providing the data with adequate detail that the reader may extrapolate it to other situations.

Yin (2009) identifies that longitudinal case studies examine the same case at two or more different points in time. Voss et al. (2002) found the potential to conduct research over a longer timeframe was beneficial, though researchers may have problems with access as a result. In this study it was possible to develop the case studies for manufacturing companies BigCo and LittleCo over a six year period (2009-14), with multiple visits from the researcher to each company supported by teleconference and email dialogue. Two principal advantages may be identified as arising from this approach.

1. It was possible to appreciate how the implications of Additive Manufacturing changed over time, and how the companies responded to these circumstances. One company grew significantly during the conduct of the study, whilst another waned; this has interesting implications particularly in terms of the flexibility aspect of this research.

2. It was possible to develop trust between the researcher and the respondents as the research developed, with particular benefits of frankness within later interviews.

Construct validity

In order to demonstrate that appropriate procedures have been followed in the conduct of the research, the tactics of Stuart et al. (2002) are followed in the explicit discussion of the methods employed to achieve the data. This approach results in the development of a ‘chain of evidence’ which enables other researchers to achieve the same results from the same base data. Where possible multiple sources of evidence are drawn upon (e.g. process observation to support interview data) in order to confirm individual findings. Results of the research have been verified with contributing companies through multiple methods, including discussions, sharing of process documentation, reviewing of draft texts, and confirmation of case reports.

Internal validity

This applies principally to explanatory or causal studies (Yin 2009), and is therefore less applicable to the exploratory research as conducted in this study. Some principles can be applied, for example Stuart et al. (2002) promotes the use of case studies which are very different in nature to promote internal validity. This is achieved through the selection of products that are produced using a variety of Additive Manufacturing processes for a range of applications.

External validity

Yin (2009, p. 40) emphasises that for external validity, one should aim to “define the domain to which a study’s findings can be generalized”; in other words it is necessary to condition the audience of the research to be aware of how far it can be applied from its original setting. This is apparent for all research methods, not just case studies: for example, the results of a questionnaire on teaspoon inventory shrinkage in one institution (Lim et al. 2005) is unlikely to be generalizable to all types of inventory *per se*. Whilst the current study has been rigorous and thorough in its approach to understanding the focal case studies and associated customers, manufacturers, and suppliers, the exploratory nature of the work does not claim to achieve extensive generalizability, and in Chapter 8 this is discussed in full.

Reliability

It is important that case research demonstrates reliability, for which Yin (2009) has emphasised the importance of other researchers achieving similar results in the conduct of similar studies. In order to demonstrate the ability for replication of the study, a case study protocol was developed and employed, and a case study database was maintained during the conduct of this research. To further support the work, data collected in the form of recorded interviews, interview notes, and email dialogues have been catalogued to allow replication of the study.

3.6.1 Interviews

The use of interviews in this study is justified since the ontological position taken in this research acknowledges opinions of individuals as a valid contribution, and that from an epistemological perspective it is a legitimate means to acquire data. Furthermore, from a pragmatic viewpoint, Saunders et al. (2009, p. 324) observe that where management are involved in responding to a research instrument, they are more likely to participate with an interview than techniques such as surveys/questionnaires since it allows the respondent to understand how their information will be used (addressing trust issues), and also negates the effort associated with writing (for example in the response to a survey).

Semi-structured interviews were used as a technique to inform the case study development. By selecting this approach, the researcher administered questions intended to address the research topics directly, but also allowing opportunity for the development of a more unstructured approach. This was primarily motivated by the exploratory nature of this research, since unstructured interviews can help develop ideas and concepts which are new, either to research as a whole or perhaps just to the individual researcher (Alvesson and Deetz 2000). By combining structure with flexibility, the semi-structured interviews should allow the main topics to be addressed, but also allow responses to be probed by the interviewer (Legard et al. 2003). One of the main motivations for the interview technique is to achieve a depth of understanding. Depth is achieved in such interviews as the interviewee is able to talk about the topic within their own frame of reference, using ideas and concepts with which they are familiar (May 2001). To encourage depth, "open questioning", which discourages simplistic "yes/no" answers is employed, complimented by the use of 'content mining' questions (Ritchie and Lewis 2003).

In Table 3.9 an overview of the semi-structured interviews conducted and included in this study is presented. Five additional interviews (combined with a process tour) were additionally conducted for cases that are not included in this research; whilst these provide some interesting insights they are not used in this study.

Case Study	Mfr	Manufacturer Interviewee	Supporting Interviews	Total
1. Hearing Aid	Hearing Co	Director (1) Production Manager (1) Technician (1)	Senior Audiologist (1) Junior Audiologist (1)	5
2. Model Ship	LittleCo	Production Manager (3) Operations Manager (2) Consultant (1) Technician (1)	Archaeologist (3)	14
3. Archaeological Models				
4. Architectural Models			Architect (2)	
5. Exhaust Tool				
6. LittleCo Fixtures				
7. Sensor Tool			Engineer (2)	
8. Surgical Guides	BigCo	Operations Director (6) Managing Director (3) Technical Director (1) Product Manager (2)		14
9. Custom Lamps				
10. Standard Lamps				
11. Modular Fixture System				
12. Furniture			Designer (1) Conventional Manufacturer (1)	

Table 3.9: Semi-structured interviews conducted in this study
Source: The Author

The interview participants were selected based on their role within the organizations, and were principally middle or senior management. Such ‘key informants’ are a valid means of collecting data, particularly in inter-organizational situations (Kumar et al. 1993), and so is particularly relevant for the supply chain management research within this study. It was recognized these managerial respondents would have knowledge encompassing Industrial Additive Manufacturing, understand its integration within the company, and have some supply chain responsibilities/influence. However, it is acknowledged that seniority does not ensure knowledge; managers may not have the same depth of knowledge as those conducting the focal activity (Kumar et al. 1993), but may have a better understanding of the wider context of the focal topic within the organization and supply chain. To tackle this problem in each interview the responsibilities of the respondent were elicited, and gentle probing undertaken to confirm the extent to which the manager was involved in the focal activity. In repeat interviews responsibilities were re-clarified, and as rapport was developed it was possible to build a better understanding of the manager’s capability to tackle the questions.

Under ideal situations interviews with a number of staff from the organisation may yield an improved quality response (particularly addressing issues of single respondent bias). Practical constraints limit the potential to achieve this: for many of the case studies the size of the companies participating often resulted in only a single informant having the required information for the study. In this research the contribution of multiple respondents (typically 2) was possible for a number of cases as shown in Table 3.9, though it is important to recognize that two techniques were employed:

1. Individual semi-structured interviews were recorded by the researcher using a mixture of field notes and audio recordings. This approach allowed each interview participant to express their contribution individually, with the researcher then creating a synthesis of the multiple interviews afterwards. The challenge with this approach is to ensure that conflicting information is acknowledged, and, where necessary, clarification sought from the respondents.

2. Multiple participants simultaneously contribute to the interview. In this approach a synthesized consensus may be negotiated between respondents, or where there is clear discrepancy in response it will normally be increasingly apparent to the researcher. Group dynamics encourage participants to get involved, speak their minds, and take into account the views of the other group members (Denscombe 2010). It is important to notice that power relations are more likely to prevail in the interviews; within this type of management research the potential for a subordinate to openly disagree with their

superior is lessened. This type of interview is susceptible to bias and group dynamics, and is particularly difficult where there is a lack of consensus within the group (Maylor and Blackmon 2005).

Denscombe (2010) identifies that audio recordings of interviews can accommodate the fallibility of the interviewer's memory when analysing data, however the presence of an audio recording can inhibit the respondent. Interviews were recorded wherever possible, however some respondents expressed a preference not to be recorded and their wishes were observed. Furthermore, where interviews were conducted within the production environment, noise and other disruptions inhibited the practical recording of the interview. In the absence of a recording the researcher made detailed notes, and as soon as practically possible re-wrote these notes in a clearer, structured form in preparation for analysis. Recordings were transcribed by the researcher as soon as possible after the interview had been conducted.

The conduct of interviews for this study was principally in-person at the company sites, resulting in the need for the researcher to travel within the UK to factories and customer premises. Additionally, three European trips were made to collect data from a major Industrial Additive Manufacturing company in central Europe.

Although such fieldwork incurs expense, its importance to this study is justified on three measures:

1. In relationship forming between the researcher and the interview respondent.
2. In the achievement of an increasingly detailed understanding of the phenomena under investigation. This is particularly relevant in such qualitative research, where the researcher and the researched are interactive and inseparable (Sarantakos 1998, p. 54).
3. The ability to observe the operations of the organization, and ask questions in response to such observations.

These in-person interviews were typically 90 – 120 minutes. Complementary follow-up interviews were conducted by telephone, normally of approximately 30 minutes duration. The use of seemingly inexpensive online interviewing techniques such as email was discounted on temporal grounds. As Kivits (2005) reports, email interviews necessitate much time is spent in the establishment and maintenance of a personal relationship in order to access the informant and keep them interested in the research. Additionally, much time is spent waiting for email responses from this asynchronous communication tool.

In addition to the semi-structured interviews, this study utilized fifteen fully structured interviews to elicit information from Additive Manufacturing material and machine suppliers at a trade conference. This is an annual event at which the researcher is frequently in attendance, and was identified in a previous visit as a very good opportunity to collect data from representatives of most of the machine and material suppliers without the requirement for extensive travel to each of the companies.

The trade show consists of many stands at which the companies presented their product range to potential customers. In previous years the researcher identified that companies were willing to enter into discussions on research for 5 – 10 minutes, but were primarily focused on talking with their potential customers. Hence the nature of the event required that data was collected in a short amount of time since respondents would be unlikely to enter into extended discussions. With this constraint in mind, a list of interview questions was developed and evaluated using the four evaluation measures of Ulrich (1999, cited in Flick 2009): relevance, reason, formulation/wording, and positioning. Probes were developed, the questions piloted with a member of the industry, and a summary protocol developed (which included in Appendix D).

Whilst it is acknowledged that the structured nature of this approach constrains the exploration that can be achieved, for the environment it was particularly efficient. In the conduct of the interviews it was observed that respondents were willing to take part in the interviews when the researcher clearly identified the limited number of questions to be asked. Once they had agreed to answer the questions, all respondents participated in the interview through to completion.

Whilst the structured approach does limit the exploratory nature of the research, it did allow the achievement of required information necessary to tackle the research question, and by asking the same questions in the same manner to all respondents, the researcher was able to gain directly comparable data concerning their companies.

3.6.2 Observation (participant and non-participant)

The interviews conducted in this research were complimented by the use of observation methods, for which one of the main benefits is the directness of the approach: instead of asking respondents about their opinions concerning a phenomena, the researcher learns by watching and listening to the actions which occur (Robson 2011). This is particularly relevant for this study since the objective is to understand how Industrial Additive Manufacturing actually affects Operations and Supply Chain Management. Within this research observations were recorded, and these often informed follow-up discussions or interviews. Field notes were made for site visits, using the guidance of Schensul (1999) in the collection of situational data, mappings, and activities of interest in an organized manner that describes activities, records useful quotes, and maintains contextual data including times, dates, and locations.

Lincoln and Guba (1985) found the value of prolonged engagement to support the credibility of research, and for both BigCo and LittleCo observations were made through site visits undertaken over the six year duration of this study. The observational research conducted in this study was both participatory and non-participatory. For HearingCo and BigCo, the researcher acted only as a non-participating observer, making observations and recording notes to inform subsequent discussion and analysis. These observations were made on scheduled site visits, at which the researcher was hosted by the company.

In participatory observation, the researcher is “fully involved with the participants and phenomena being observed” (Collis and Hussey 2014, p. 148). In the context of the LittleCo this included participation in relevant projects being conducted by staff at the organization. Through this approach the researcher could be involved in observing the commercial operations at work, whilst at the same time asking questions of the research participants in their natural setting. This enabled the researcher to observe the practical realities of the operations first-hand, and to see events as they arose, rather than through post-rationalized interviews.

It is acknowledged that there are a number of limitations with observation methods as shown in Table 3.10. One of the most relevant for this study is that by definition only the observable may be observed; the past and future cannot be observed (Sarantakos 1998). As a result, when collecting the data for this study, only the “here-and-now” can be examined, and as a result it was necessary to make multiple visits to a number of the contributing companies in the development of this study.

Source of Error	How do errors arise?	Mitigating actions taken in this study
Lack of ability	Observer inability, tiredness, or disinterest	The researcher is familiar with production environments, and has an inherent interest in this topic.
Observer inconsistency	Inability of observer to maintain consistency in all observations	The breadth of potential observations makes consistency impossible; instead, the researcher shall focus only on process-related observation
	Inter-observer inconsistency	Only a single researcher was involved in making observations.
Non-verbal communication	Influences attitudes and behaviours of the observed	The researcher was mindful of this potential error in their research.
Observer bias	Observer perceives situations according to their own ideology and bias, producing a distorted reality	The researcher acknowledges that their values and bias will affect the work, and there is no one single reality to distort. Pertinent observations were discussed with interview participants.
Deviation	Observer behaves and relates to the observed in a manner not expected or prescribed	The researcher acknowledged this potentiality and made efforts to behave in a consistent manner.
Deception	Observer misleads research participants	The researcher explained clearly the nature of their work and the intentions of their investigation.
Lack of knowledge	Observers are inexperienced or lacking in necessary knowledge to conduct research	The researcher is experienced in production environments, and has conducted upfront research before the observations. Where necessary, the observer sought guidance.
Problems in recording and analysing data	Facts not truthfully recorded Analysis non-systematic and subjective	The researcher acknowledges the importance of maintaining records of their observations, and reporting them appropriately. Follow-up discussions were employed to confirm observations.
Lack of familiarity with observed group	Observer not adequately familiar with the subject to be observed	The researcher acknowledges that in most instances they are an ‘outsider looking in’, and this is likely to affect the observations made. This is lessened for LittleCo observations, where the researcher frequently visited.

Table 3.10: Sources of errors arising from the observer
Source: The Author, adapted from Sarantakos (1998)

3.7 Strategy 2: Questionnaire

3.7.1 Justification for questionnaire

A questionnaire was employed to examine the supply of Industrial Additive Manufacturing machines and materials, and to better understand the operations of upstream manufacturing organizations. This approach was motivated by the wide geographic dispersion of suppliers which made face-to-face interviews with key informants impractical. In the development of the questionnaire the process shown in Figure 3.7 was employed.

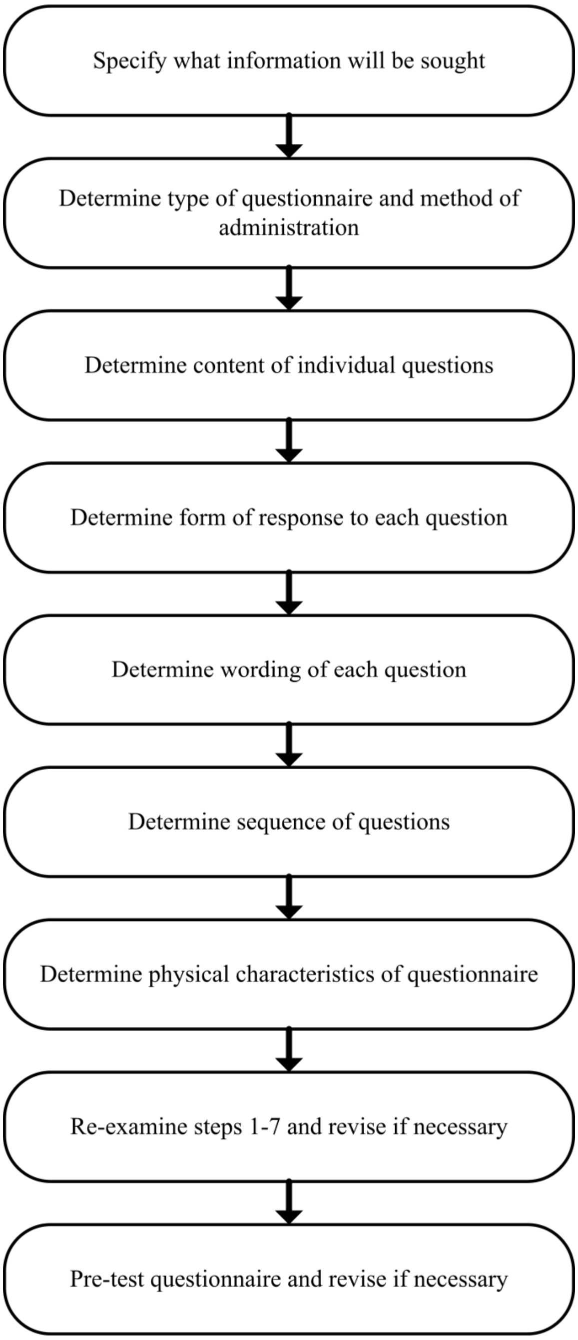


Figure 3.7: Flowchart for development of questionnaire
Source: Churchill Jr (1991)

Step 1: Specify what information will be sought

The purpose of the questionnaire is to learn about the nature of machine and material supplies for Industrial Additive Manufacturing, and particularly to understand the nature of the supply chain. Information is needed concerning the way the machines manufacturers produce and supply machines and materials to their customers.

Step 2: Determine type of questionnaire and method of administration

A mixed mode questionnaire was developed which would be posted to the respondents, and an identical electronic copy sent by email. Respondents would be free to choose which version they completed and returned to the researcher. Each questionnaire would be accompanied by a cover letter or email detailing the purpose of the investigation, and the way in which the data would be used.

Step 3: Determine the content of individual questions

Following a thorough review of the literature, a brainstorming session was conducted and Post-It notes used to cluster and group topics worthy of inclusion in the research. These were drafted, and through an iterative revision process the general content for each question decided. All questions were made optional and the entire questionnaire was anonymous.

Step 4: Determine the form of response to each question

Most questions had a multichotomous element (normally a tick-box), and some had an open element for an explanatory response. This approach was taken to promote consistency in analysis for the closed elements, but with a richer, more detailed qualitative response to aid the researcher’s understanding of the response (and to confirm the research participants understanding of the question).

Step 5: Determine the wording of each question

Each question was carefully worded to avoid jargon or complex terms, and to discuss Industrial Additive Manufacturing in a way that the respondents were most likely to be familiar with. Care was taken to ensure that questions were neither leading, nor making implicit assumptions. As some of the research participants were expected to have English as a non-native language, care was taken to promote clarity in the communication.

Step 6: Determine the sequence of questions

Careful attention was given to the sequencing of the questions to ensure clarity for the reader. The first question was used as a qualifier for the research participant, and directed them to complete the appropriate section(s) of the questionnaire (these were colour-coded for ease of reference). Questions of a more sensitive nature were included later in the sequence, which Churchill Jr (1991) identify is likely to make them less objectionable to the research participant. The intention was not, however, to mislead or coerce the respondent to complete a question that they did not want to, and it was made clear that all questions were optional.

Step 7: Determine physical characteristics of questionnaire

The questionnaire was designed in such a manner than each section filled one page of A4. This was motivated by a desire to enable the research participant to have a clear understanding of the number of questions that they would be asked to complete, and to enable them to browse the questionnaire before deciding whether to participate.

Step 8: Re-examine steps 1 – 7 and revise if necessary

The questionnaire was developed through four iterations of this procedure in order before being released for pilot testing.

Step 9: Pre-test questionnaire and revise if necessary

The questionnaire was reviewed carefully for general errors (typographical, numbering, grammar etc) before being piloted with an Industrial Additive Manufacturing machine supplier known reasonably well to the researcher. No revisions were identified as being necessary as a result of this external pilot. A copy of the questionnaire sent to manufacturers, together with associated literature is included in Appendix B.

3.7.2 Selection of research participants

The annual "Wohlers Report" provides an up-to-date review of the nature of the Additive Manufacturing industry, and of the main events arising each year. Within this publication, an annually updated chart provides a cumulative count of the total number of installed Industrial Additive Manufacturing Systems worldwide by manufacturer, and Wohlers (2008) was therefore utilized as a means to identify suitable research participants; subsequently Wohlers (2012) was consulted to ensure continued validity of these earlier choices.

The small size of the industry is acknowledged to yield a very small population from which to draw a sample, and some of the companies listed have ceased trading, or have been bought/merged with other companies and no longer exist as separate entities. Furthermore, some of the companies have sold very few (or zero) machines which limit their applicability to this research and they were excluded on these grounds. Existing flexibility research (Dixon 1992) has, however, asserted that single industry studies afford focus and do not have the requirement for larger sample sizes found in multi-industry research.

Where the researcher already knew an appropriate contact in the company, a telephone conversation was instigated to establish their willingness to participate before issuing the survey.

Where the main contact was not known, efforts to identify an appropriate respondent were made using the "LinkedIn" social networking tool. In the event a suitable contact could not be identified in this manner, an enquiry email was sent to the company to request a contact name. Once the potential respondent's willingness and suitability to participate was established, the questionnaire was sent by email and post. 14 questionnaires were sent, and 8 received representing a response rate of 57%; of these 7 were sufficiently complete to be used in this study (50%).

The respondents were able to respond anonymously by post, however all but one chose to use email. The researcher was therefore aware of which companies had responded, but has not linked these details to the responses made as anonymity was assured to the respondents. However, as the respondents included some of the major suppliers to the market, it can be asserted that the companies responding represent over 90% of the production machines that have been sold as identified by Wohlers (2012). Hence, despite the small overall population of companies to survey, this research has been able to achieve a good response rate for an internet or postal survey (Dillman et al. 2009), and whilst the issue of non-respondent bias is acknowledged, the responses are believed to be representative of the current marketplace.

3.8 Strategy 3: Contextual activities

The two principal research strategies were complimented by a number of other activities that inform the researcher's overall understanding of the topic, and contribute to the academia and industrial knowledge on the topics. A third strategy concerns 'contextual activities' that support the study, either directly in the form of literature reviews, or indirectly through the related activities undertaken by the researcher.

3.8.1 Literature review

The literature review is a fundamental part of any scholarly research, requiring the researcher to engage and critique previous studies and "strike a balance that simultaneously displays criticality with regard to the assumptions, theories, and methods used whilst at the same time acknowledging the insights and strengths of the studies" (Easterby-Smith et al. 2012, p. 102). Literature reviews, when used by experienced researchers, enable the identification and refinement of questions about a topic, rather than answers to what is known about it (Yin 2009, p. 14). Literature reviews therefore serve to both inform their reader of the current state of knowledge, but importantly support the development of new knowledge. White (2011) identified that *conducting* a literature review is different to *writing* a literature review, and set out five skills that the researcher must possess (Table 3.11).

Skill required	Author comment for this study
Identify what is meant by 'literature'	This is contextualized in the literature review regarding the specific areas to which the author refers.
Locate literature	Electronic databases, books, theses, trade-publications are considered as valid sources of literature (though differences in the quality of these are acknowledged).
Critically appraise literature	Data extraction forms are used to summarize principal findings in the research, allowing for quick retrieval and review of papers as the work progressed.
Manage/Organize literature during writing revisions	Literature was read from paper to aid comprehension in this task-based activity with electronic copies stored and managed using EndNote bibliographic software.
Integrate the literature	Two distinct literature reviews are provided, and their findings are revisited throughout the empirical chapters.

Table 3.11: Skills required in the conduct and writing of the literature review
Source: The Author, adapted from White (2011)

In the conduct of this research, ongoing iterations were made between data collection and analysis and the established literature base. The extended time period over which doctoral research is conducted, together with the increasing popularity of Additive Manufacturing in media and research leads to a dynamic and rapidly evolving literature base. Through continual reference to the literature the author was able to ensure that the current study utilizes the most relevant current knowledge, whilst simultaneously evaluating the novelty and contribution made.

3.8.2 Engagement with industry and academics focused on Additive Manufacturing research

A number of activities were undertaken in the course of this research which led to the achievement of 'tacit knowledge' that supported and enabled the achievement of the study. Often such activities are not reported in Business research, however these activities provided knowledge and understanding to support the 'main' strategies of case studies and questionnaire and are therefore included in this section. This inclusion is supported by Wolfinger (2002), who has previously identified tacit knowledge as being the most important consideration in understanding what research observations are worthy of inclusion in research. Understanding context and importance is essential for the researcher to ask the most relevant questions, or note the most pertinent observations. In qualitative studies where the 'knower' and the 'known' are interactive and inseparable (Sarantakos 1998), it is therefore appropriate to acknowledge the other main activities undertaken by the researcher that have informed the work:

- Attendance at industry-focused conferences (e.g. multiple years of the UK Additive Manufacturing conference), at which research was discussed with other academic and industrial participants. This allowed the researcher to make a useful network of industrial contacts that have been consulted as the research progressed.

- Participation in academic research events. The author attended various research calls by funding bodies (e.g. TSB, EPSRC), during which it was possible to establish alignment between the current study and current research requirements. He also chaired a session at an ESRC research scoping event in Bath, the results of which are published in Smith (2012).

- Participation in annual academic Operations Management conferences (EurOMA, LRN, ICPR) to present and disseminate the results of this study as it developed. This allowed the researcher to formally establish ideas in published literature, and also to gain the feedback of academics in support of the work.

- Providing guidance and support in applications of Industrial Additive Manufacturing as an Academic Investigator on a £27m industry-academia collaborative project (http://www.astutewales.com/en/), and for projects with Cardiff School of Engineering. These activities provided additional access to companies and potential case studies, which although not presented in the current work, heightened the confidence of the researcher in the findings of this study.

- Conduct of fundamental research in Industrial Additive Manufacturing process and materials technologies. This allowed the researcher to better appreciate the basic principles governing the operation of the machines and limitations on their capabilities. Similarly, additional research has examined potential implementation models utilizing e-commerce technologies. These works have yielded four peer-reviewed journal papers, one of which is published in the International Journal of Advanced Manufacturing Technology, and the second in Polymer Testing, the third in Assembly Automation. The fourth paper has been accepted for publication in Manufacturing Technology Management.

3.9 Analysis of data

The conduct of this research through a mixture of methods yielded a wealth of data, for which the challenge for the researcher is to ensure an accurate evaluation to identify true and meaningful findings that satisfy the research questions. This is a particularly pertinent challenge for qualitative data (Silverman 1997), and is a common issue for management researchers (Easterby-Smith et al. 2012). Harding (2013) identified that there is no accepted consensus on how to evaluate the validity of qualitative data analysis, but that reflexivity is an essential element requiring the researcher to appreciate the choices they have made in analysis, and the role of the researcher in the construction of research findings.

A useful overarching approach to the analysis of qualitative data was proposed by Miles and Huberman (1994), in which qualitative data analysis consists of three principal activities:

1. Reduction (or condensation) to sharpen, focus, and organizes data in such a way conclusions can be drawn and verified.
2. Display of the data through visual techniques such as matrices, tables, charts etc.
3. Conclusion drawing and verification to identify regularities, patterns, and explanations.

This approach was followed in this study, where data gained through different methods was condensed to be manageable, displayed through tables and diagrams, and conclusions drawn using these. Using this commonly adopted approach also helps 'show' the process to the reader, which is an important technique employed to help build confidence in the findings of research. In line with Edmondson and McManus (2007), the focus for the analysis of such qualitative research was on the identification of patterns between cases, which is a technique often employed in the analysis of case studies (Yin 2014).

In the satisfaction of the research questions the analysis of data from several methods is used, which not only helps to satisfy the questions but in many instances helps triangulate the findings. To promote consistency and reliability in this work all data collection and analysis was performed by the researcher. The techniques employed in each are explored in the remainder of this section, with the integration of these data described in detail in Section 3.10.

3.9.1 Analysis of interview data

Interviews typically generate a large volume of qualitative data, for which the interpretation and analysis activities are often complex and require the researcher to have a detailed appreciation of their content. One particularly important aspect of the analysis of interview data is the researcher's immersion in it; through re-playing recorded interviews, re-reading transcripts and notes, and effectively re-living the interview. In doing so, the researcher has increased confidence that the analysis does not omit any of the detail originally collected (Harding 2013). This was particularly important for this research, where data was collected over an extended time period, and where successive interviews with informants built on data collected in prior interviews.

The focused nature of the fifteen structured interviews afforded a relatively structured approach to their analysis. The responses to each question were coded to in a data reduction exercise, through which the principal themes could be identified through tabulation to afford subsequent assessment for patterns in support of conclusions. In addition, each interview was summarized in terms of its conduct and any pertinent notes to support these (e.g. demeanour of respondent, notable opportunities for development etc).

In the analysis of the semi-structured interviews it was important that the analysis did not lose the richness and depth afforded by this technique. Interviews were allowed to run to extended lengths (up to three hours), leading to the achievement of much qualitative data for analysis and the researcher was careful to ensure that this was diligently recorded and analysed in this research. Where interviews were recorded each was carefully transcribed by the researcher as soon as reasonably possible after the interview, and the transcription checked for accuracy by playback of the original recording. Such use of transcription is commonplace in qualitative research, though the researcher is in agreement with Kvale (1997) that the process of moving between speech to words leads to a loss of data relative to the original encounter due to the interpretative nature of the transcription activity. As highlighted in Section 3.6.1 as a result of practitioner or practical constraints not all interviews were recorded, and so these could not be transcribed. Instead, detailed notes were made in the interviews (including any pertinent quotes), and these were written up carefully as soon as reasonably possible afterwards.

Using the transcriptions and supporting notes interview data was summarized and categorized to identify pertinent responses, and particularly to explore alignment and disjunction between different respondents on a range of topics. Harding (2013) identified that this comparative approach is an effective way to move between a large volume of interview data to a more succinct and manageable amount of data. This approach allowed for a more concise means by which to display the data, from which subsequent analysis through thematic coding was employed. It is, however, acknowledged that where interviews could not be recorded, coding based on the actual discourse could not be employed. As coding is but *one* way (not *the* way) to analyse qualitative data (Saldaña 2013), this limitation is acknowledged but is not critical to this work. Such practical constraints instead required the researcher to maintain detailed notes of interviews, and to base analysis on these.

To support the analysis of the interviews, and to covey the data to the reader this work also makes use of quotations. Using quotations is a well-established technique to support the explanation of the research findings; whilst this can promote interest and make a study more compelling to the reader, as Cameron and Price (2009) note care has to be taken to avoid confirmatory bias through 'selective' quotation. Within this thesis a selection of quotations has been employed to support the narrative of the researcher.

3.9.2 Analysis of observational data

Observational data was identified as being a particularly valuable contributor to this study, and was achieved through the site visits undertaken in the conduct of this research. There is much overlap between observational methods and ethnography, and a useful means of conducting observation is the ongoing production of observational notes and findings rather than relying on the fallibility of the human memory. To support these field notes the researcher was permitted to take photographs at LittleCo and at some of its customer operations, and some of these are included in this thesis to support the analysis.

DeWalt and DeWalt (2011) highlight that for observational data there is much value in reading and re-reading field notes as part of a process of reducing and evaluating data for subsequent write-up, and this was useful in supporting the analysis and communication of this research. As much of the observational data concerned the manufacturing systems at work, it was possible to use some techniques widely used in operations management as a means to analyse and effectively communicate the observational data. Wu (1994) advocated the achievement of simplicity in the assessment of the complex manufacturing system concept as being advantageous. One such useful tool applied in this research is IDEF0 process modelling, which enjoys relative speed in implementation, together with a strict language and the ability to identify both data and control through its diagrammatic approach (Aguilar-Savén 2004). It is an established means of analysing manufacturing systems (Williams 1988), for which very detailed guidance on the tool has been provided by NIST (1993), and a detailed appraisal of its prevalence within research has previously been provided by Kim and Jang (2002). It enables a multi-levelled evaluation of a system, from the uppermost level of strategic planning to the fundamental operational levels (Nicholson 1991), and four principal capabilities of IDEF0 are given by Buede (2000):

1. Demonstrates how transformation of inputs to outputs is achieved by the system.
2. Establishes definite systems boundaries on a context diagram.
3. Has a single viewpoint from which the system is observed.
4. Combines graphical and natural languages to form a co-ordinated set of diagrams.

In application, Drake et al. (1998) identified that IDEF0 is particularly suitable for application in environments where dedicated systems engineering departments do not exist. In the context of the current study, recent relevant examples arise from Beckett (2003) who has used IDEF0 to explore systems and subsystems in Virtual Enterprises, Wagner et al. (2014) who used IDEF0 diagrams to compare conventional and changeable manufacturing systems, and the work of ElMaraghy et al. (2014) in the development of a tool to evaluate layout in manufacturing systems. In terms of customization, Cullinane et al. (1997) presents a useful evaluation of a generic Mass Customization production system through IDEF0, whilst for Additive Manufacturing Meteyer et al. (2014) used IDEF0 to explain binder-jetting processes, and Tuck et al. (2008) demonstrated the stages of production for 3D customized parts.

3.9.3 Analysis of questionnaire data

As identified in Section 3.7, a questionnaire was employed to gain data in a structured manner from senior management in companies supply Industrial Additive Manufacturing machines and materials. The limited number of potential and actual respondents led to a relatively small amount of data to be analysed, which was achieved manually by the researcher.

Data from all respondents was collected and recorded in Microsoft Excel, and any annotations/notations made by respondents noted separately for subsequent consideration. As none of the questions mandatorily required a response it was necessary to identify null values, and where commonality across respondents could be noted this is acknowledged in Chapter 7. The data was tabulated and analysed using descriptive statistics and a supporting narrative, and these findings are presented in detail in Chapter 7.

3.9.4 Analysis of archival and company data

Several of the companies involved in this research shared process data and confidential company information with the researcher, complimented by secondary data sourced from websites and trade publications. Analysis of this data is specific to the type of data provided; for example details of process activities were used in the development of process maps and in support of IDEF0 diagrams. Similarly, historic details of individual builds (e.g. Figure 6.3) supported the development of some of the case studies in this research.

3.9.5 Ensuring confidence in the analysis of data

Irrespective of the approach taken in the analysis of data, it is important to recognize that there will be some interpretation activities undertaken by the researcher. To help evaluate the accuracy of these interpretations, in this study a five stage approach was taken as the research progressed (Figure 3.8).

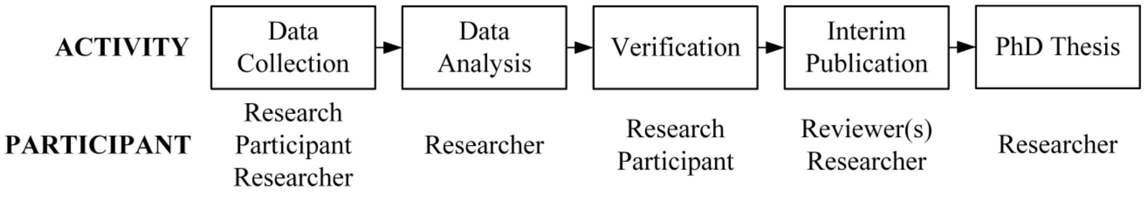


Figure 3.8: Process to enhance confidence in research findings
Source: The Author

This process provides a distinct verification stage in which the findings of the data analysis were verified with the research participants before being published in interim conference papers. Research participants were consulted about the analysis, and where an on-going relationship existed, were sent copies of the proposed publication for their comments. At conference presentations, details of the data and analysis were discussed, and feedback used to help ascertain whether any further analysis was required.

This approach recognizes the knowledge and experience of the research participants, but at the same time acknowledges that their ability to evaluate the analysis of the research is likely to be influenced and ultimately constrained by their own capabilities to appraise research. By exposing the research to a wider academic audience it was possible to gain additional perspectives that could be used to support the development of this work, improving confidence in the findings.

The limitation of this approach is that not all aspects of the research have been published in advanced of the preparation of this thesis. For these sections of the work it is not possible to 'close the loop' in this formal way. Instead, where possible feedback discussions have been employed to highlight the findings of the research with relevant participants.

3.10 Working with multiple methods

3.10.1 Integrating multiple methods in the collection and analysis of data

As described in the preceding sections, a number of different methods are employed in the collection of data for this research, and in Figure 3.6 the linkage between methods and research questions is identified. The rationale for the selection of each research method has been shown; however it is acknowledged that these methods are not implemented in isolation in this study, and that there is much benefit that may be achieved through their combination. In particular, much emphasis has been placed upon the utilization of multiple methods to enhance confidence in findings relative to mono-method research (Bryman 2004), and it is noted that multi-method studies are increasingly common for case study research (Yin 2009).

The systematic combining approach described in Section 3.4 is identified by Dubois and Gadde (2002, p. 556) as promoting the combination of multiple sources of data to "revealing aspects unknown to the researcher, i.e., to discover new dimensions to the research problem", and in their work they demonstrate this to be achieved using a range of methods including interviews, observation, and archival data. For case research multiple sources are important, since without them "an invaluable advantage of the case study strategy will have been lost. Worse, what started out as a case study may turn into something else [as a result of over-reliance one method leading to insufficient attention to data achieve through other sources" (Yin 2009, p. 118). Systematic combining acknowledges the complexities of case research, and the tacit knowledge with which such research is conducted (Dubois and Gadde 2013), and this approach is followed in the current study using multiple methods of a principally qualitative nature to collect data from a variety of different sources. As shown in Figure 3.9, these methods may be subdivided into two groups:

1. Methods that contribute primarily to collecting data from the empirical world to develop the case.
2. Methods that contribute primarily to collecting data from the theoretical world to contribute develop the theory.

The systematic combining approach aids the integration of these methods, promoting the iteration between different methods in the collection of different types of data, and then in analysis through matching, direction & redirection. It is, however, acknowledged that such an approach requires much caution as it is essential to carefully evaluate the compatibility of different methods (Dubois and Gadde 2013), and since this is consistent with any multi-method study, in the design and conduct of this research this requirement was monitored by the researcher.

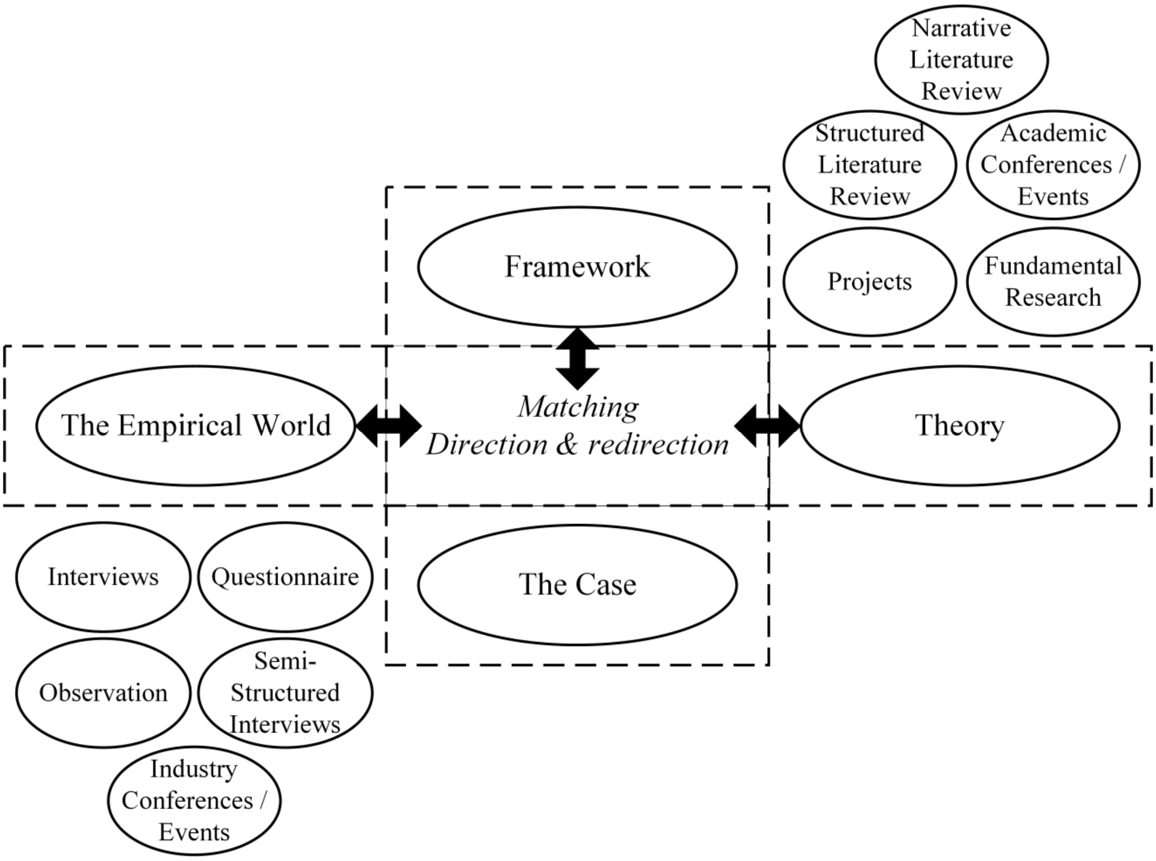


Figure 3.9: Integrating methods using Systematic Combining
Source: Adapted from Dubois and Gadde (2002)

3.10.2 Triangulation through multiple methods

The application of multiple methods promotes methodological triangulation (Bryman 2004), whereby different methods are used to tackle the same problem. Denzin (1978) refers to this specifically as 'between-methods triangulation', which is a type of triangulation is particularly important in promoting validity, and can also be a useful aid to the integration of multiple methods in the research.

As identified in Figure 3.6, during the collection of data the researcher sought evidence from multiple sources; for example using observations in process-tours to identify consistency (or otherwise) with previously collected interview data. Similarly, the focus of the structured interviews and surveys was intentionally designed to have appropriate overlap that would enable triangulation between these methods. As noted by Jick (1979) methodological triangulation offers the potential to expose data to which a mon-method approach would be 'blind'; for such exploratory qualitative research the importance of on-going triangulation during the data collection process is therefore important in the shaping and direction of the subsequent research activities. In final analysis and dissemination of the research through this thesis, triangulation of data is demonstrated in the content and narrative of this thesis, with alignment and disjunction reported accordingly.

It is, however, acknowledged that triangulation is not a panacea for the conduct of good research. It has long been identified that the application of multiple methods will not lead to the strengths of one method counteracting weaknesses in another (Jick 1979), nor does it provide an easy or well-trodden route to a demonstration of a method’s validity (Mason 1996) or opportunity for consistency or replication in qualitative research (Patton 1980). The author is mindful of these constraints when consideration methodological triangulation in the current study.

3.11 Acknowledging the role of the researcher in the research

The critical realist approach taken in this work acknowledges that the individual researcher is intertwined in the conduct of the study and its results; unlike positivistic approaches no attempt is made to separate the researcher from the researched.

Much emphasis is made in research methods texts on the skills of the researcher to undertake their work, particularly in the social sciences and in qualitative studies (Collis and Hussey 2014; Robson 2011; Rubin and Rubin 1995). The educational and industrial experience of the researcher is therefore important in such work, particularly in terms of ability to understand and relate to the manufacturing environment.

In recognition of this observation, it is stated that the researcher is a Charted Engineer, and holds undergraduate and postgraduate degrees in Engineering. He has been employed in technical and managerial roles in manufacturing firms, and is currently a Lecturer in Manufacturing Systems Management. As an academic, the author continues to work closely with industry, and has led a number of engagement projects with manufacturing companies in Wales. The author has published a number of conference and journal articles based on qualitative and quantitative methods related to Industrial Additive Manufacturing, and in preparation for this doctoral study achieved an MSc in research methods.

3.12 Chapter summary

This chapter has presented the ontological and epistemological positioning of this study, along with a justification of the research instruments used to gather and assess the data. Evaluations have been provided for the advantages, disadvantages, and implications of these decisions. It is acknowledged that emphasis on the design of research, particularly with regards to methodology is not always a priority in Operations Management. Indeed, Schmenner et al. (2009) complain “methodology is not knowledge”, and argue more attention should be paid to creativity and understanding, and less on these seemingly wasteful pursuits. To a limited extent the author is in agreement with these established Operations Management academics; it is easy to spend too much time thinking about how research might be conducted, at the expense of its actual conduct. However, by extension, the author argues there is little purpose in conducting research if the resultant methodological limitations serve to undermine the outputs. High quality research must be the objective for the Operations Management researcher, typically linked to industry practice, and achieved through an appropriate design (Karlsson 2008).

The interaction between these tools and the critical realist philosophical stance taken by the author has been identified as an appropriate approach to the research process. In adopting a qualitative, exploratory approach to the research it is acknowledged that the author is deviating from the Operations Management tradition, but in doing so is able to get closer to a ‘reality’ than can be otherwise achieved:

> “... artificial reconstructions of reality and people’s perceptions of reality (primarily through surveys) account for 84 percent of OM research efforts published in 2003. This, in essence, may be interpreted to mean that OM scholars are still “not leaving their offices” as they develop their research. However, it is becoming more important that we, as scholars, directly observe the reality that we wish to study, especially for developing rather than testing theory. As an applied discipline, OM scholars cannot fully capture the complexity of these phenomena through “remote” methods such as artificial reconstruction and/or surveys. Our results do show movement toward more direct observation of the phenomenon being studied, but we need to expand these efforts through such research methods as case and field-based studies, action research, and experiments.”
>
> *Craighead and Meredith (2008, p. 723)*

Chapter 4 The Concept of an Industrial Additive Manufacturing System

Chapter Aims

1. Establish the activities, mechanisms, and controls in contemporary Industrial Additive Manufacturing practice.
2. Define the structure of an Industrial Additive Manufacturing System.
3. Identify control architectures in Industrial Additive Manufacturing Systems.

4.1 Chapter overview

The purpose of this chapter is to combine established manufacturing systems theory with empirical observation of Industrial Additive Manufacturing at three different companies to define an Industrial Additive Manufacturing System. As shown in Figure 4.1, this chapter therefore follows the earlier Literature Review that provides the theoretical foundations, together with the Research Method which explains approaches to the conduct of the research.

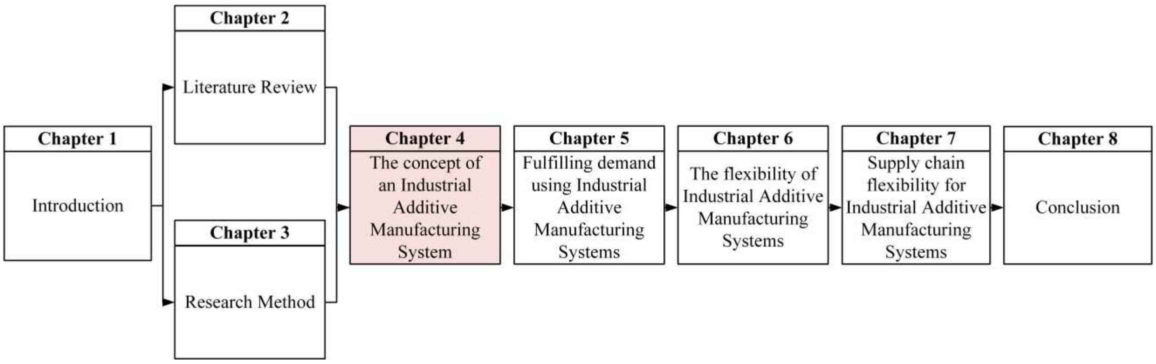


Figure 4.1: Thesis structure
Source: The Author

In Section 2.2 it was demonstrated that a manufacturing systems perspective is well-established in literature, and also accepted in industrial practice. Within this review the general transformative manufacturing system was presented, and the merits of a systems approach outlined. Emphasis was placed on the works of John Parnaby and Denis Towill, in which demand is satisfied by a range of controlled resources operating in spite of uncertainties that are internal and/or external to the system.

By comparison, in Section 2.8 it was demonstrated that existing research has predominantly considered Additive Manufacturing from the perspective of individual *technologies*, rather than in terms of a manufacturing *system*. Although early implementations of the technologies focused solely on prototyping capabilities in laboratory environments, many contemporary commercial installations are employed in the competitive production of a range prototypes, tools, and end-use parts. In Section 2.9 it was shown that they are often promoted for customized, low volume demand, which for conventional manufacturing was shown in Table 2.4 as traditionally introducing uncertainty and complexity in operations as a whole.

These observations suggest there is merit in considering Industrial Additive Manufacturing as a manufacturing system, and the purpose of this chapter is to examine contemporary Industrial Additive Manufacturing in the context of Parnaby's manufacturing system concept. Specifically, it provides a detailed exploration of the structure of an Industrial Additive Manufacturing System, developing the limited existing literature with new research to propose a concept that underpins the subsequent chapters of this thesis. This chapter therefore tackles **Research Question 1: How is an Industrial Additive Manufacturing System structured?**

To support this chapter, Appendix C contains an introduction to the concept of Industrial Additive Manufacturing, providing a detailed statement of the terminologies used in this study, an overview of applications in which Additive Manufacturing is employed, and up-to-date data on the nature of the industry. This technical component is a necessary consideration of this management study, since Additive Manufacturing technologies approach the fabrication process in different ways, which may have consequences for their application and management in industrial environments. In the context of this study, the rationale for the inclusion of a process-focused section to this work is more formally justified by the guidance of Hopp (2011), who identified the necessity of understanding fundamental low-level process elements of any supply chain in order to understand the chain as a whole.

4.2 Method overview

In Chapter 2, the concept of a manufacturing system was developed based on established literature, and was defined as "a structured collection of manufacturing resources that are organized and controlled in order to transform input resources into useful outputs to satisfy market requirements". Individual manufacturing technologies such as Additive Manufacturing are therefore contributors to the focal system, and are subject to and influenced by the other components of the system. The complexity of manufacturing systems requires several actions to be taken to make their assessment both manageable and practical, and these are shown in Figure 4.2.

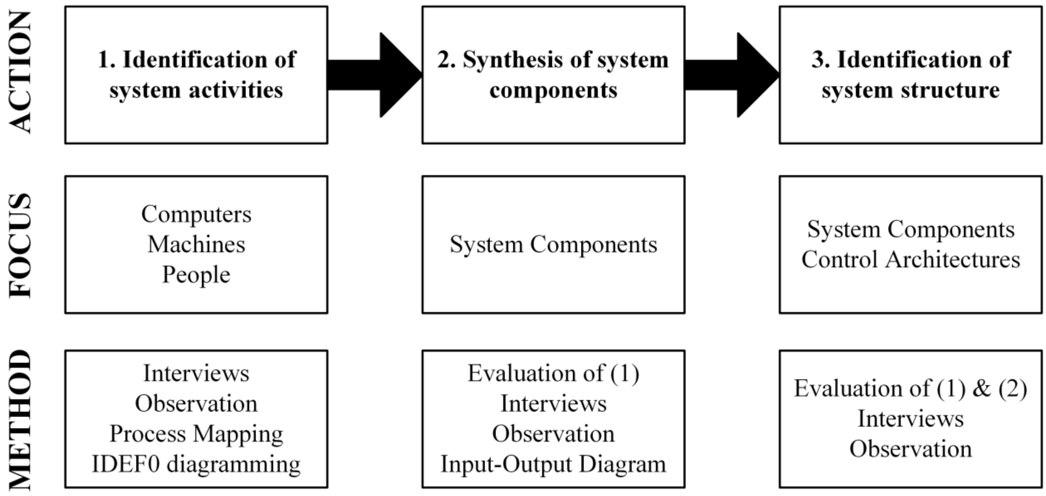


Figure 4.2: Stages of evaluation for an Industrial Additive Manufacturing System
Source: The Author

1. To understand the nature of an Industrial Additive Manufacturing System, this study examines the *activities* undertaken in the fulfilment of demand for each of the twelve case studies. Previous work has prescribed generic process chains for Additive Manufacturing (Dotchev et al. 2009; Eyers and Dotchev 2010; Gibson et al. 2010), however these are developed conceptually rather than empirically, and emphasize machines rather than the manufacturing system. By understanding what is being undertaken (functions), and the way these are performed (through mechanisms & controls), it is possible to understand the elements of the system that are relevant for consideration. To achieve this understanding, the researcher used interview and observation methods at site visits with each of the three Industrial Additive Manufacturers, together with process data provided by some of these companies. To delimit the focal system from other systems and the wider environment, it is necessary to understand system boundaries particularly in terms of activities undertaken by the customer. To achieve this, visits to the customer premises were undertaken and in cases where such visits were not possible, information from the manufacturer concerning the customer's activities was sought. Based on this investigation, IDEF0 diagrams were produced for all twelve case studies.

2. The second phase of system assessment is the identification of system *components* to define the totality of activities in a manageable manner. Manufacturing systems are complex, and may be comprised of multiple sub-systems (Wu 1994). Within an IDEF0 model, each box represents the boundaries of an activity (Kim and Jang 2002); therefore by grouping multiple

boxes a logical assignment of activities to system components may be achieved. This is achieved through functional and logical assessments and contributes to the definition of a general system structure, within which the resources exist. It is, however, important to recognize that whilst from a structural perspective a system may be divided into smaller components, from a functional perspective this is not the case; when divided some of the essential properties or characteristics are lost from the overall (Ackoff 1997). To mitigate this issue, it is therefore essential to understand the interface between identified boundaries. These can be thought of as the interconnections that hold the various elements together (Meadows 2009), for which Parnaby (1987) advocated the usage of input-output diagrams in exploration and explanation. Through this approach the principal components of an Industrial Additive Manufacturing System can be identified, enabling the generalization of the research in the development of a conceptual model of an Industrial Additive Manufacturing System based on empirical observation.

3. Having identified the components of the manufacturing system, attention turns to the system *controls* within which these operate. Parnaby (1979) identified that system control is attainable by careful design and a professional approach in the execution of the system, and as described in the literature review, Dilts et al. (1991) presented four over-arching models for the control of automated manufacturing systems. Although it is not the intention of this research evaluation to examine control engineering *per se*, from a management perspective it is valuable to understand the approach taken in the co-ordination of the Industrial Additive Manufacturing System to achieve control. Using case data through this evaluation, the structure of an Industrial Additive Manufacturing System is defined and evaluated (as shown in Figure 4.3)

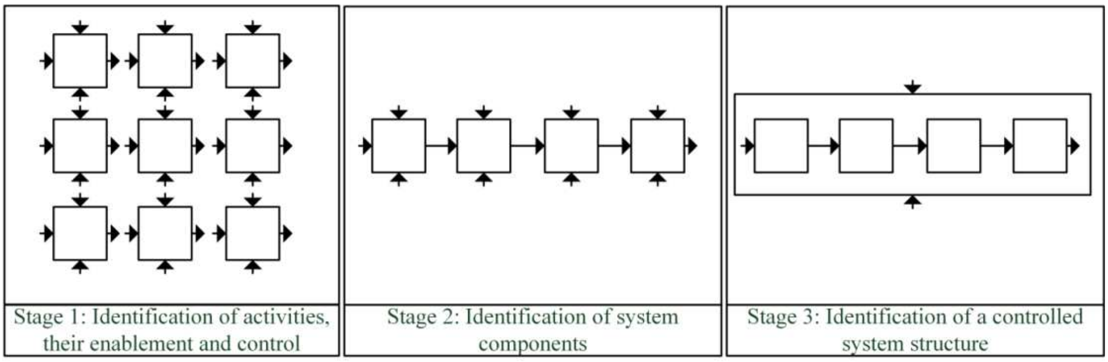


Figure 4.3: Progression of the development of an Industrial Additive Manufacturing System
Source: The Author

Developing an understanding of an Industrial Additive Manufacturing System demonstrates the abductive approach taken in this research. By combing the limited existing literature theory with the findings of the individual case studies, it is possible to identify alignment and disjunction, leading to the development of the manufacturing system concept informed by existing theory, but which also makes a contribution to new theory. To assist the reader in the interpretation of the following sections, a summary of the case studies is repeated in Table 4.1 and extended to identify the distinct Additive Manufacturing concept (Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacturing (RM)) as defined in Appendix C.

Case No.	Additive Mfr	Case Name	Product Description	AM Concept	Additive Mfg Process
1	HearingCo	Hearing Aid	In-The-Ear (ITE) Hearing Aid	RM	envisionTEC
2	LittleCo	Model Ship	Archaeological reconstruction of model ship	RM	Laser Sintering
3	LittleCo	Archaeological Models	Archaeological reconstruction of stones	RM	Laser Sintering
4	LittleCo	Architectural Models	Model building (student architecture project)	RM	Laser Sintering
5	LittleCo	Exhaust Tool	Hydroform tool for exhaust system	RT	Selective Laser Sintering
6	LittleCo	LittleCo Fixtures	Inspection fixture for toothbrush	RT	Selective Laser Sintering
7	LittleCo	Sensor Tool	Functional prototype of exhaust sensor tool	RP	Laser Sintering
8	BigCo	Surgical Guides	Guide for surgical applications	RM	Laser Sintering
9	BigCo	Custom Lamps	Customized lighting product designed by customer via website	RM	Laser Sintering
10	BigCo	Standard Lamps	Standardized lighting product designed by professional designer	RM	Laser Sintering or Stereolithography
11	BigCo	Modular Fixture System	Hybrid fixture system customized for user application	RT	Laser Sintering
12	BigCo	Furniture	Designer furniture	RM	Laser Sintering

Table 4.1: Summary of case studies explored in this research
Source: The Author

4.3 Managerial perspectives on the nature of Industrial Additive Manufacturing Systems

The scope of a manufacturing system is subject to interpretation by the designer or analyst, and as such it is acknowledged that there are different perspectives on the delimitation of systems from their sub-systems and individual components. There is no single definition of a manufacturing system (Parnaby 1979), and through the structured literature review (Section 2.8) it has been demonstrated that Additive Manufacturing is most commonly considered from the perspective of the individual machines, rather than the manufacturing system. A focus on the manufacturing technologies in the literature is perhaps unsurprising, since it is the additive nature of the manufacturing processes that is the emphasis of most academic research on Additive Manufacturing. In many research articles, consideration of the way in which these operate within a wider systems perspective is outside the natural remit of the paper. However, from the earliest interviews conducted in this research it was evident that managers considered the machines to be but one component of their overall manufacturing operations. When a semi-structured interview became increasingly focused on the contribution of the machines in the fulfilment of customer orders, the managerial research participant exclaimed:

> "so you're *just* interested in that *one* machine, not the rest of what we do?"
>
> *Operations Manager, HearingCo*
> *Emphasis added to reflect dialogue*

For this respondent, Additive Manufacturing machines were recognized as being a contributor to flexible production at their factory, but not solely responsible for its achievement. Instead, a range of different manufacturing processes involving both machines and labour in a number of different activities were identified as contributing to the output of the line and satisfaction of individual orders.

A similar perspective was demonstrated by the Operations Director at the largest Additive Manufacturing company, BigCo. Noting the 1000+ staff employed, it was emphasized that the majority of effort for the company was in the design preparation and post-processing activities, in which the majority of the workforce are engaged. Whilst this organization has the most comprehensive set of Additive Manufacturing technologies in the world, it was apparent that most interviews on the realization of customer orders focused not on the machines, but on the related activities undertaken outside of the machine build chamber.

These senior staff emphasized Industrial Additive Manufacturing machines as but one part of the overall process, and took an increasingly holistic view on the nature of manufacturing systems. Such findings highlight the need to consider the contribution of Additive technologies, but also the other elements that comprise the Industrial Additive Manufacturing System.

4.4 Identifying the activities undertaken by Industrial Additive Manufacturing Systems

4.4.1 Identifying functions in Industrial Additive Manufacturing Systems

By examining twelve case studies across three manufacturing companies, a wide number and range of activities were identified as being undertaken in the fulfilment of demand. Through interviews and observations it was possible to identify that these may be grouped into three principal categories:

1. Primary activities that either directly add value to the manufactured part, or are necessary for manufacture but not directly adding value. These are the focus of this study.
2. Secondary activities that provide support for manufacturing. Activities undertaken by the manufacturer that are not directly linked to the production of the product, but performed by resources of the system. This includes activities such as stock-takes and routine maintenance, which whilst essential to the firm are not core activities in the immediate satisfaction of demand. To afford focus, these activities are not examined in this study.
3. Unrelated activities that are undertaken by resources of the manufacturing system, but for which no relevance to the manufacturing system or the products produced. These activities are not examined in this study.

Through observation (participant and non-participant) and interview methods, for each case study multi-level IDEF0 diagrams were developed to explore the way in which focal parts were created. An example may be found in Appendix D. In order to support comparative analysis of these twelve cases, a common terminology was used to define each activity undertaken. In Table 4.2 an overall summary of activities undertaken is provided based on the IDEF0 data. It is evident that there are many commonalities that exist between the different cases, irrespective of the technology employed or the organization implementing them. For example, CAD model generation, capacity planning, machine setup, and quality assessment activities can be observed as occurring in almost all cases, and for all manufacturers. By contrast, many of the activities undertaken are not consistently employed for each case study, which required the researcher to evaluate their inclusion within the definition of a manufacturing system.

	Case Reference											
Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Create design idea				☑			☑		☑			☑
Select item to scan	☑	☑	☑		☑			☑				
Prepare item for scanning	☑	☑	☑		☑			☑			☑	
Scan item	☑	☑	☑		☑			☑			☑	
Review pointcloud		☑	☑		☑			☑			☑	
Inverse existing CAD design						☑						
Create 3D CAD model	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑
Conduct Virtual Prototyping			☑	☑			☑	☑				☑
Conduct Physical Prototyping		☑	☑	☑			☑					
Design optimization	☑						☑	☑			☑	
Prepare STL file	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Check STL file quality	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑
Evaluate part manufacturability		☑	☑	☑	☑	☑	☑	☑			☑	☑
Evaluate feature manufacturability		☑	☑	☑	☑	☑	☑	☑			☑	☑
Prepare final production STL	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑
Batch STLs for simultaneous production	☑	☑		☑	☑	☑	☑	☑	☑	☑	☑	☑
Identify accuracy requirements		☑	☑	☑	☑	☑	☑				☑	☑
Configure build layout	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Determine optimal build parameters		☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Finalize build configuration	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Identify production capacity	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Identify production priorities	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Produce production plan	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Perform machine setup	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Photocure resin	☑									☑		
Laser Sinter powder		☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Drain build	☑									☑		
Cool build		☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Disassemble build & material recovery	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Remove excess powder / Clean	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Perform oven processing					☑							
Perform quality assessment	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Perform part collation / ordering		☑		☑				☑				☑
Perform part colouring										☑	☑	☑
Assemble parts	☑				☑	☑	☑		☑	☑	☑	
Additional processing					☑							

Table 4.2: Summary of activities undertaken by the manufacturing systems
Source: The Author

4.4.2 Identifying mechanisms in Industrial Additive Manufacturing Systems

To understand the nature of the manufacturing system it is necessary to appreciate the way in which the functions undertaken are achieved. Within the definition of a system using IDEF0, mechanisms are defined as the resources by which a function is performed. In Section 2.2 it was identified that manufacturing system resources may be physical (e.g. machines or labour), or non-physical (e.g. information). In evaluating a manufacturing system, Slack (1987) differentiated between structural and infrastructural resources. In the current study, infrastructural resources are taken to extend to overarching resources such as factories and warehouses, whereas structural considerations include resources such as machines, equipment, information systems, and people/labour involved in manufacturing.

The current study identifies a range of different mechanisms through which the system functions are achieved, with considerable commonality across the different cases. A coding schema was employed to identify the different enabling mechanisms (Table 4.3). Using this technique a summary of the principal mechanisms for each of the cases is shown in (Table 4.4 - Table 4.6).

Labour / People		**Machine / Equipment**		**Computer / Information Processing**	
A	Skilled Labour	Z	Automated Machine	G	General Software
B	Semi-Skilled Labour	Y	Semi-automated Machine	S	Product Specific Software
C	Unskilled Labour	X	Manual machine/handtools	T	Process Specific Software
				D	Document

Table 4.3: Coding schema for IDEF0 mechanism analysis
Source: The Author

4.4.2.1 Labour resources

For each activity undertaken, Table 4.4 provides an evaluation of the nature of the labour involved in its satisfaction. These capabilities were coded in terms of three skill levels:

A. **Skilled:** Possessing high technical competency in a role, and/or high flexibility in the capability to perform activities. Highly trained (to degree level or equivalent), autonomous, experienced resource that is difficult to substitute. Typically involved in complex areas of design or management roles.

B. **Semi-skilled:** Trained in the achievement of a narrow variety of tasks and capable of achieving these to a high standard, but operating with close managerial supervision. Typically performing technical but routine operations.

C. **Unskilled:** No training or experience in the task undertaken, easily substituted, close managerial supervision required.

	Case Reference											
Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Create design idea	-	-	-	B	-	-	A	-	B	-	-	A
Select item to scan	B	A	A	-	A	-	-	A	-	-	-	-
Prepare item for scanning	B	A	A	-	A	-	-	A	-	-	A	-
Scan item	B	A	A	-	A	-	-	A	-	-	A	
Review pointcloud	-	A	A	-	A	-	-	A	-	-	A	-
Inverse existing CAD design	-	-	-	-	-	A	-	-	-	-	-	-
Create 3D CAD model	B	A	A	A/B	A	A	A	*	*	-	A	A
Conduct Virtual Prototyping	-	-	A	A/B	-	-	A	A	-	-	-	A
Conduct Physical Prototyping	-	A	A	A	-	-	A	-	-	-	-	-
Design optimization	B	-	-	-	-	-	A	A	-	-	A	-
Prepare STL file	*	A	A	A	A	A	A	*	*	A	A	A
Check STL file quality	*	A	A	A	A	A	A	A	*	-	A	A
Evaluate part manufacturability	-	A	A	A	A	A	A	A	-	-	A	A
Evaluate feature manufacturability	-	A	A	A	A	A	A	A	-	-	A	A
Prepare final production STL	B	A	A	A	A	A	A	A	*	-	A	A
Batch STLs for simultaneous production	B	B	-	B	B	B	B	A	A	A	A	A
Identify accuracy requirements	-	A	A	A	A	A	A	-	-	-	A	A
Configure build layout	*	A	A	A	A	A	A	A	A	A	A	A
Determine optimal build parameters	-	A	A	A	A	A	A	A	A	A	A	A
Finalize build configuration	B	A	A	A	A	A	A	A	A	A	A	A
Identify production capacity	B	A/B	A/B	A/B	A/B	A/B	A/B	A	A	A	A	A
Identify production priorities	B	A/B	A/B	A/B	A/B	A/B	A/B	A	A	A	A	A
Produce production plan	B	A	A	A	A	A	A	A	A	A	A	A
Perform machine setup	B	B	B	B	B	B	B	B	B	B	B	B
Photocure resin	*	-	-	-	-	-	-	-	-	*	-	-
Laser Sinter powder	-	*	*	*	*	*	*	*	*	*	*	*
Drain build	*	-	-	-	-	-	-	-	-	*	-	-
Cool build	-	*	*	*	*	*	*	*	*	*	*	*
Disassemble build & material recovery	B	B	B	B	B	B	B	B	B	B	B	B
Remove excess powder / Clean	B	B	B	B	B	B	B	B	B	B	B	B
Perform oven processing	-	-	-	-	*	-	-	-	-	-	-	-
Perform quality assessment	B	A	B	B	A	B	B	B	B	B	B	B
Perform part collation / ordering	-	B	-	B	-	-	-	B	-	-	-	B
Perform part colouring	-	-	-	-	-	-	-	-	-	B	B	B
Assemble parts	A	-	-	-	A	B	B	-	B	B	B	-
Additional processing	-	-	-	-	B	-	-	-	-	-	-	-
*- = Not evidenced * = Not required A = Skilled B = Semi Skilled C = Unskilled*												

Table 4.4: Summary of functions and their enabling labour resources
Source: The Author

For some activities a clear delimitation was not evidenced, with staff of differing skill levels performing the task. In such examples both skill levels are recorded. Where a hyphen is recorded, this activity is not undertaken; therefore it is only the activities where an asterisk is shown that do not have a demonstrated requirement for labour.

Although much enthusiasm has been extended in research for Additive Manufacturing to significantly reduce labour in the production of parts (e.g. Tuck et al. 2007a), the results of this study shown in Table 4.4 highlight that labour represents an important contribution to the overall manufacturing system's capability to fulfil demand. Within the remit of the activities presented in Table 4.4, HearingCo employed approximately 100 staff, LittleCo 2 staff, and BigCo approximately 800 staff. For each company this direct labour for manufacturing represented the bulk of their workforce, highlighting the need for human involvement in manufacturing.

The data presented in Table 4.4 demonstrates the need for labour to be involved in the majority of activities undertaken within the manufacturing system. Furthermore, this assessment particularly emphasizes the involvement of skilled labour, which is inconsistent with the viewpoint of Nyman and Sarlin (2012) that Additive Manufacturing is "zero skill manufacturing". The analysis shows that the manufacturing system is reliant on a variety of skills, ranging from skilled design capabilities through to manual skills in material movement and machine loading. No examples of unskilled labour could be identified in any of the twelve cases.

Each of the three manufacturers identified the benefits of a multi-skilled workforce, and this was evidenced in practice through the process tours.

- For HearingCo (Case 1), staff were trained in to undertake many different roles in order to accommodate daily fluctuations in demand. For example, staff involved in scanning hearing aid moulds would, later in the same shift, be involved in the assembly of the final devices.
- For LittleCo (Cases 2-7), the small scale of the operations required staff to be skilled in multiple capabilities, but also to be adaptable to new demand requirements. For the focal cases, despite the differences in product, a single member of staff performed all design evaluation and configuration activities. Likewise, despite the differences in the size, shape, quality, and applications requirements of each case, another member of staff performed all machine unloading, part finishing, cleaning, and assembly activities.
- For BigCo (Cases 8-12), the scale of the operations demonstrated enabled staff to work in team-based activities that promoted specialism. For example, focused teams of medical design staff worked only on medical products (e.g. Case 8), which was enabled by the predictable demand volumes and similarity of activities required.

Using Table 4.4 it is possible to identify the activities undertaken that require no labour (highlighted with a *). Common to all cases it is demonstrated that Industrial Additive Manufacturing machines have no requirement for human intervention, as in normal operation they are fully automated and each of the companies demonstrated their abilities for unattended operation. Likewise, the post-manufacture activities of draining or cooling are achieved by the machines. It is this capability to physically fabricate that is typically reported in literature as eliminating the labour requirement in Additive Manufacturing: it is, however, noted that the same unattended operation is achieved in an oven-processing activity for Case 5; this is a 'conventional' manufacturing technology that exhibits the same abilities to conduct its process without human intervention. When questioned, LittleCo identified the similarity of unattended automation for a number of conventional technologies and Additive Manufacture as "ironic", noting the emphasis placed in the Additive Manufacture literature on this capability.

The process tours evidenced that all of the companies operated multiple Industrial Additive Manufacturing machines simultaneously, with fabrication achieved in unattended operation. However although labour was not needed for the manufacturing activity, in processes of longer build durations (e.g. LS and SL), periodic observation of the machine was performed by technicians to assure continued operation, and to make any necessary interventions in the event of build failure. Typically a single technician oversaw the operation of multiple machines. This supports the earlier postulation by Walter et al. (2004) of the potential for cost reduction in a multi-machine environment through labour sharing. This human observation of processes was particularly employed with LittleCo, since their machines provided no electronic feedback from the manufacturing processes to the controller. At the commencement of this research, similar behaviour was exhibited by BigCo, however having recognized the limitations of this manual approach, the company invested in the integration of process monitoring tools to increase real-time feedback to controllers and to support automation in the management of processes.

Through comparison between the cases several examples for which activities are achieved without labour as a result of substitution with software tools are identified. This is shown to be prevalent where part designs are similar, and adequate production volumes exist to justify the costs of software development and maintenance. Case 1 provides a good example of this, where specialist software is employed to support much of the design activity. Since all hearing aids are approximately the same overall size and have the same quality requirements, production of the STL and its evaluation are achieved by automated software. Similarly, since overall part sizes are predictable, batch layouts can be readily planned by software to achieve simultaneous production of multiple devices (Figure 4.4).

Figure 4.4: Hearing aid batch
Source: Eyers and Dotchev (2010)

Software is also used to aid the design-elicitation process, by providing customers with assistive tools with which to specify their parts. Such use of configurators has been widely cited as supporting customization strategies (Forza and Salvador 2002; Trentin et al. 2011), and was demonstrated in Cases 8, 9 and 11 to aid customers in the design of their products. This capability is explored in more depth in Chapter 5.

4.4.2.2 Machine Resources

By its definition in Section 4.2 Additive Manufacturing utilizes machines in the fabrication of parts; however in a variety of supporting activities undertaken within the system other machines and equipment were identified as being employed. From Table 4.5 these can be identified as used in the elicitation of design through scanning as part of a reverse engineering process, or in the support of the design process through virtual prototyping. Similarly, for all cases machines are used in the manufacture of the part, but since finishing activities are required for all parts the use of additional equipment for these activities is commonplace.

Within this study, equipment used is delimited by the nature of human involvement required whilst they are operating: whether fully automated (no involvement), semi-automated (some involvement), or manual (hand tool or requiring continual involvement). These machines may be employed in pre-production activities (e.g. scanning equipment used in Reverse Engineering), or post-production (e.g. in measurement and testing activities).

	Case Reference											
Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Create design idea	-	-	-	*	-	-	*	-	*	-	-	*
Select item to scan	*	*	*	-	*	-	-	*	-	-	-	-
Prepare item for scanning	*	X	*	-	X	-	-	X	-	-	Y	-
Scan item	Y	Y	Y	-	Y	-	-	Y	-	-	Y	-
Review pointcloud	-	*	*	-	*	-	-	*	-	-	*	-
Inverse existing CAD design	-	-	-	-	-	*	-	-	-	-	-	-
Create 3D CAD model	*	*	*	*	*	*	*	*	*	-	*	*
Conduct Virtual Prototyping	-	-	*	*	-	-	*	*	-	-	-	*
Conduct Physical Prototyping	-	Z	Z	Z	-	-	Z	-	-	-	-	-
Design optimization	*	-	-	-	-	-	*	*	-	-	Y	-
Prepare STL file	*	*	*	*	*	*	*	*	*	*	*	*
Check STL file quality	*	*	*	*	*	*	*	*	*	-	*	*
Evaluate part manufacturability	-	*	*	*	*	*	*	*	-	-	*	*
Evaluate feature manufacturability	-	*	*	*	*	*	*	*	-	-	*	*
Prepare final production STL	*	*	*	*	*	*	*	*	*	-	*	*
Batch STLs for simultaneous production	*	*	-	*	*	*	*	*	*	*	*	*
Identify accuracy requirements	-	*	*	*	*	*	*	-	-	-	*	*
Configure build layout	*	*	*	*	*	*	*	*	*	*	*	*
Determine optimal build parameters	-	*	*	*	*	*	*	*	*	*	*	*
Finalize build configuration	*	*	*	*	*	*	*	*	*	*	*	*
Identify production capacity	*	*	*	*	*	*	*	*	*	*	*	*
Identify production priorities	*	*	*	*	*	*	*	*	*	*	*	*
Produce production plan	*	*	*	*	*	*	*	*	*	*	*	*
Perform machine setup	*	X	X	X	X	X	X	X	X	X	X	X
Photocure resin	Z	-	-	-	-	-	-	-	-	Z	-	-
Laser Sinter powder	-	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
Drain build	Z	-	-	-	-	-	-	-	-	Z	-	-
Cool build	-	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
Disassemble build & material recovery	X	X	X	X	X	X	X	X	X	X	X	X
Remove excess powder / clean	X	X	X	X	X	X	X	X	X	X	X	X
Perform oven processing	-	-	-	-	Z	-	-	-	-	-	-	-
Perform quality assessment	Y	Y	*	*	Y	*	*	*	*	*	*	*
Perform part collation / ordering	-	*	-	*	-	-	-	-	-	-	-	*
Perform part colouring	-	-	-	-	-	-	-	-	-	X	X	X
Assemble parts	X	-	-	-	X	X	X	-	X	X	X	-
Additional processing	-	-	-	-	X	-	-	-	-	-	-	-
- = *Not evidenced* * = *Not required* X = Manual Y = Semi Automated Z = Automated												

Table 4.5: Summary of functions and their enabling manufacturing machine resources
Source: The Author

Examples of resources identified in this study include:

Automated hardware (Category Z)

- ***Additive Manufacturing Machines*** are employed in the production of parts for all cases, and are discussed in detail within Appendix C.
- ***Ovens*** are used in post-processing of some Additive Manufactured parts, and were used in Case 5 for bronze infiltration of the part. This equipment is used to improve the material characteristic of the part through indirect tool manufacture, and once loaded runs unattended.

Semi-automated hardware (Category Y)

- ***Optical scanning tools*** such as 3D scanners are used extensively in the elicitation of designs for Reverse Engineering, and were evidenced in Cases 1-3, 5, 8, and 11. These tools capture the geometry of an existing artefact, and produce a digital representation for subsequent manipulation.
- ***Measurement & Test Equipment*** are used for all cases in the verification of parts to ensure that they have achieved the required quality parameters, and includes measurement systems (from mechanical rulers to sophisticated CMM equipment), as well as tools for destructive and non-destructive assessment.

Manual hardware (Category X)

- ***Hand tools*** are used in the finishing processes for all cases by labourers, and include a range of resources such as paintbrushes, air blasters, screwdrivers etc.
- ***Material recovery tools*** are used to recover material used in Additive Manufacturing that may be re-used in future manufacturing activities. In the Laser Sintered powder-based cases (2-12) this constitutes scoops and shovels; for resin-based processes (1, 10) liquid collection receptacles are used.

4.4.2.3 Computers & Information Processing

Parnaby (1987) explicitly noted the importance of computers within the manufacturing system, and today computers are ubiquitous in most production environments including Additive Manufacturing facilities. Each of the three manufacturers made use of conventional desktop PC's within their operation, however their utilization varied dependent on the software, which may be delimited as follows:

- ***General Software*** includes conventional 'office' tools such as spreadsheets to serve administrative functions within the manufacturing process. Whilst each of the companies used these tools in their office functions, in terms of manufacturing only LittleCo demonstrated their application as part of the manufacturing system, particularly for use in planning.
- ***Process-specific Software*** includes Additive Manufacturing specific tools such as Materialise 3-matic^{STL} and Materialise Magics, which are used in the design and configuration of parts for Additive Manufacture. These tools were demonstrated in all cases as performing a range of tasks, particularly in the activities leading up to the utilization of the Additive Manufacturing machine.
- ***Product-specific Software*** has been developed for a number of products that are typically customized, but produced in high volume (e.g. for the design of ITE Hearing Aid Shells or Surgical Guides). The repeatability of work justifies initial expenditure on software that makes the design and manufacture process more efficient. Similarly, web-based configurators are also employed to support customers in the design of products within bounding constraints (for example in the selection of options in the manufacture of custom lamps).

In addition to the computer resources, it was noted that paper-based documents may be used to enable many different activities within the manufacturing system. Where these of particular importance they were recorded in the IDEF0 model and subsequent analysis.

- ***Documents*** are typically paper-based resources that are used in the fulfilment of demand. This could include a work order, design/assembly schematic, or a physical build plan that is used in part identification post-manufacture.

	Case Reference											
Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Create design idea	-	-	-	D	-	-	-	-	*	-	-	-
Select item to scan	D	D	D	-	D	-	-	D	-	-	-	-
Prepare item for scanning	D	*	D	-	*	-	-	D	-	-	D	-
Scan item	*	*	*	-	*	-	-	*	-	-	*	-
Review pointcloud	-	T	-	-	T	-	-	T	-	-	*	-
Inverse existing CAD design	-	-	-	-	-	T	-	-	-	-	-	-
Create 3D CAD model	S	T	T	T	T	T	T	S	S	*	*	T
Conduct Virtual Prototyping	-	-	T	T	-	-	T	S	-	-		T
Conduct Physical Prototyping	-	D	D	D	-	-	D	-	-	-	-	-
Design optimization	S	-	-	-	-	-	T	S	-	-	S	-
Prepare STL file	S	T	T	T	T	T	T	S	T	T	T	T
Check STL file quality	S	T	T	T	T	T	T	S	T	-	T	T
Evaluate part manufacturability	-	TD	TD	TD	TD	TD	TD	SD	-	-	TD	TD
Evaluate feature manufacturability	-	TD	TD	TD	TD	TD	TD	SD	-	-	TD	TD
Prepare final production STL	S	T	T	T	T	T	T	S	T	-	T	T
Batch STLs for simultaneous production	S	T	-	T	T	T	T	T	T	T	T	T
Identify accuracy requirements	-	TD	TD	TD	TD	TD	TD	-	-	-	TD	TD
Configure build layout	S	T	T	T	T	T	T	T	T	T	T	T
Determine optimal build parameters	-	D	D	D	D	D	D	T	T	T	T	T
Finalize build configuration	S	T	T	T	T	T	T	T	T	T	T	T
Identify production capacity	T	G	G	G	G	G	G	T	T	T	T	T
Identify production priorities	T	G	G	G	G	G	G	T	T	T	T	T
Produce production plan	T	G	G	G	G	G	G	T	T	T	T	T
Perform machine setup	*	*	*	*	*	*	*	*	*	*	*	*
Photocure resin	*	-	-	-	-	-	-	-	-	*	-	-
Laser Sinter powder	-	*	*	*	*	*	*	*	*	*	*	*
Drain build	*	-	-	-	-	-	-	-	-	*	-	-
Cool build	-	*	*	*	*	*	*	*	*	*	*	*
Disassemble build & material recovery	D	D	D	D	D	D	D	D	D	D	D	D
Remove excess powder / Clean	-	D	D	D	D	D	D	D	D	D	D	D
Perform oven processing	-	-	-	-	*	-	-	-	-	-	-	-
Perform quality assessment	-	D	D	D	D	D	D	D	D	D	D	D
Perform part collation / ordering	-	D	-	D	-	-	-	D	-	-	-	D
Perform part colouring	-	-	-	-	-	-	-	-	-	*	*	*
Assemble parts	D	-	-	-	D	D	*	-	*	*	*	-
Additional processing	-	-	-	-	*	-	-	-	-	-	-	-

*- = Not evidenced   * = Not required   G = General   S=Products Specific   T=Process Specific   D=Document*

Table 4.6: Summary of functions and their information processing resources

Source: The Author

4.4.3 Identifying activity controls in Industrial Additive Manufacturing Systems

Activities that are enabled by their mechanisms also need controls which guide or regulate the individual activity as it is undertaken, and as Cullinane et al. (1997) demonstrated these can be wide-ranging in their nature, including organizational policies and environmental influences. By evaluating the cases presented in the current study, five principal controls and their typical nature can be identified:

1. Product design controls. These are mainly *product*-specific, and may reflect industry norms concerning the approach to be taken in the design. For example, in the design of an architectural part (Case 4), conventions for aesthetic and mechanical properties are well-established and applied in design. Similarly, in the development of custom fixtures (Case 11), standard interfaces to connect the part to its modular beam are essential, and design controls exist for these. Additive Manufacturing has been acknowledged to remove many constraints concerning 'Design For Manufacturing' (Hague et al. 2003a), which support this observation.
2. Preparatory controls. These are typically *process*-specific, and concern the application of established procedures to achieve requisite part performance in manufacture. For example, controls exist to promote accuracy in the production process in the layout and orientation of parts within a build chamber. Much research has explored the various options to achieve optimal preparation of parts for manufacture (e.g. Franco et al. 2010; Gibson and Shi 1997; Soe and Eyers 2014), and although the different manufacturers have their own approaches in the execution of these controls, in general commonality exists for each process.
3. Controls in manufacture. These are mainly *process*-specific attributes of individual manufacturing machines, and are intended to ensure that the manufacturing process achieves its requirements. For the twelve cases, the controls observed related to the focal machines, and were instigated by the machine manufacturers.
4. Controls in post-manufacture processing. These combine both *product* and *process*-specificity, for which the purpose is to prepare the manufactured part for finishing activities. For example, process-specific controls for Laser Sintered parts concern effective material recovery for recycling. Product-specific controls are typically associated with post-manufacturing operations involving cleaning and finishing, where the individual products have specific requirements to be observed.
5. Controls in assembly and testing. These are mainly *product* specific, and exist to finish a part to meet the requirements of the customer.

A notable distinction concerning the sophistication of these controls can be identified relative to the repeatability of the activity. For example, in Case 1 the design of the hearing aid shell is achieved through the pouring of a silicon mould and subsequent reverse engineering. Whilst each part design is different the method is identical and controls to regulate the activities are standardized. Likewise, for surgical guides (Case 8) the repeatability of production leads to the development of standard controls that may be documented and adherence measured. In new applications of Industrial Additive Manufacturing, the nature of the controls for design activities was identified as being developmental. For Model Ship (Case 2), whilst the archaeologists were experts in the processes for recording and producing a 2D model ship using conventional approaches in cardboard, they were unfamiliar with the different activities to be undertaken for reverse engineering and development of CAD models for Additive Manufacturing. Development of controls concerning these activities was demonstrated as an iterative process, achieved by ongoing collaboration between the archaeologist designer and the manufacturer.

For process-specific controls, commonality between cases exploiting the same Industrial Additive Manufacturing technology is more evident. For example, different manufacturing processes require different preparatory activities (e.g. support structure generation for SL, powder recycling for LS), but for each activity the controls are largely unchanged irrespective of the nature of the demand. However, different manufacturers are identified as having different sophistication in their controls; for example in material management for LS BigCo demonstrated a far more sophisticated approach than LittleCo in terms of material traceability and recycling policies. Similarly, approaches to production planning differ for each of the three manufacturers, but within the individual organizations their control is standardized for each process.

It is also identified that despite Additive Manufacturing being recognized as a technological approach to manufacturing, many of the controls which underpin its operation lack technological sophistication. The increasing competency of computing resources has meant that emphasis in the literature has long prescribed the application of computers in the production and control process, without which control would be “inconceivable” (Kochhar et al. 1995, p. 411). Various approaches to computer-based control have been proposed as technologies have increased in competency, however all aim to satisfy the same basic problem of how to marshal and allocate resources to best achieve the transformative process:

- LittleCo operated the least sophisticated computer-based system in terms of manufacturing control, relying on spreadsheet tools to produce basic manufacturing plans and with no computer control within the manufacturing system.
- HearingCo implemented an ERP system to control the order processing and production scheduling aspects of its operations, however there is no overall computer control evident within the defined manufacturing system.

- BigCo implemented a bespoke production control system which integrated order processing, engineering design, production planning, manufacturing execution, and assembly procedures. For some of the newer machine technologies feedback from process control systems was integrated in to the overarching production control system.

4.5 Identifying the components of an Industrial Additive Manufacturing System

Section 4.4 demonstrated a multitude of activities that are undertaken by Industrial Additive Manufacturers in the fulfilment of customer orders. Whilst this provides a detailed appraisal of the way in which parts are achieved through Industrial Additive Manufacturing, it is both product and process specific. In the development of a general concept for an Industrial Additive Manufacturing System, it is necessary to identify those principal activities that can be identified as common to the entire system concept. This section therefore defines the system structure from these empirical observations.

This definition was achieved through three stages:

1. A logical assignment of activities was performed based on the identified activities in Section 4.4. Despite the parts being produced having a number of differences (e.g. size, application, material type), many commonalities are evident in their manufacture. Through a clustering exercise these are grouped in order to ascertain the principal components of the system at a higher level of abstraction.
2. An examination of the functional assignment of activities observed within the three Industrial Additive Manufacturing companies was performed. Consideration was given to the layout of operations, the assignment of resources (e.g. machines and labour), and to organizational structures that affected the way in which activities were achieved.
3. The functional and logical assignments were compared and combined to identify the general concept of an Industrial Additive Manufacturing System that is informed by practice, but is neither product nor process technology specific.

As a result of this activity, the four identified components of an Industrial Additive Manufacturing System are presented in Figure 4.5, and discussed in the remainder of this section.

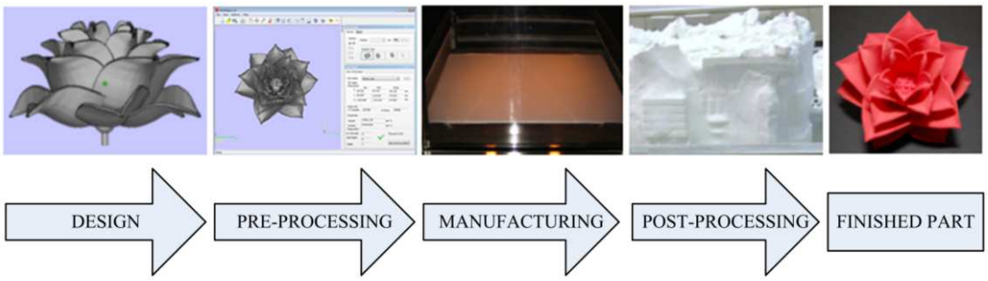


Figure 4.5: Four identified components of an Industrial Additive Manufacturing System
Source: The Author

4.5.1 System Component 1: Design

Design in Industrial Additive Manufacturing Systems represents all activities from the inception of the original idea, to being ready to produce an initial STL file. This definition acknowledges that the traditional boundaries of the manufacturer and external customer overlap; the use of Additive Manufacturing as part of a co-design or co-creation strategy has been discussed (ElMaraghy et al. 2013), in which collaboration arises between the customer and manufacturer in the achievement of a design, typically to promote customization. Depending on the nature of the product and customer, the Additive Manufacturer may be involved from the outset, or later in the design process, and Table 4.7 provides an overview of the nature of this activity identified in each of the twelve cases

	Case Study											
Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Initial design idea development				☑			☑		☑			
Configurator provision								☑	☑		☑	
Reverse Engineering	☑	☑			☑						☑	
CAD Design		☑	☑	☑	☑	☑	☑	☑			☑	☑
Virtual Prototyping			☑	☑			☑	☑				
Physical Prototyping		☑	☑	☑			☑					

Table 4.7: Manufacturer involvement in the co-creation of products
Source: The Author

4.5.1.1 Elicitation of original design

Although there is currently enthusiasm for customers to design their own products (Anonymous 2011a), the difficulty of eliciting customer design for Additive Manufacturing is well established in the literature (Ariadi et al. 2012), and cases evidenced in this project highlighted a significant involvement of manufacturers in the process. Four approaches to design were evident:

1. Manufacturers conduct all aspects of design initiation on behalf of the customer.
2. Manufacturers provide a basic design, from which the utilization of configurator software is utilized to finalize the customer design. This approach does not require such advanced design skills on the part of the customer, and can be used for the customization of existing designs.
3. Reverse Engineering through 3D scanning of an existing artefact. This process is relatively quick, through requires specialist hardware and often needs manual intervention to correct issues.
4. Design (or customization of an original design) using CAD. This process is typically time consuming and requires much skill on the part of the designer.

4.5.1.2 Design Prototyping

Prior to committing a design for manufacture, the ability to perform prototyping may be required. Two types of prototyping are evidenced from the cases:

1. Virtual prototyping arises where designs are iteratively prototyped on-screen. This approach allows a designer to evaluate a design, and make ongoing changes before committing to manufacture. This approach has been shown as advantageous by Dodgson et al. (2006), particularly in the reduction of product development costs.
2. Physical prototyping may be undertaken to make a trial-run of the intended part, or to produce a sample part for evaluation. This was evidenced for cases 2, 3, 4, and 7 to assist both the customer and manufacturer understand the opportunities to produce parts through Additive Manufacturing, and best means to achieve this.

4.5.2 System Component 2: Pre-Processing

Section 2.9 demonstrated that many literature sources advocate the ability for Additive Manufacturing machines to produce directly from a 3D design, however in the current study the activities identified through the twelve cases suggest this to be an oversimplification. In practice, each manufacturer demonstrated the evaluation of designs to consider the best approach to manufacture them, and related activities of production planning to determine how best to manage the manufacturing system.

4.5.2.1 Assessment of manufacturing feasibility

Although much enthusiasm exists for Additive Manufacturing machines to produce almost any part (e.g. Anonymous 2011a), cases from both BigCo and LittleCo demonstrated a range of activities that needed to be undertaken to evaluate the potential capability and suitability of a part for manufacture.

1. To ensure the successful manufacture of a part, the Industrial Additive Manufacturers all validated the STL files before their use. Errors in the received STL file were identified by production managers as a principal cause of build failure for both BigCo and LittleCo, and much emphasis was made by these companies to validate the incoming design files. The companies employed software and human-based techniques to evaluate the incoming files to ensure they were as-expected, complete (no holes found), and without any obvious identifiable corruption. If necessary, and where possible, the manufacturers typically repaired damaged files on behalf of the customer.

2. Overall ability to manufacture a given part is assessed to examine whether the design is suitable for the selected manufacturing process. For example, this may include fundamental considerations such as the physical size of the part to be produced. The build chamber size is finite and so parts of a greater size must be produced in sections (for subsequent joining). In the example of the exhaust tool (Case 5), such limitation required the part to be split into three sections as it could not be produced as a whole. Notably, where production is of similar parts (e.g. ITE Hearing Aids in Case 1), as a result of prior experience the requirement for this assessment is lessened.

3. Feature assessment is performed to ensure that all required features are reproducible using the focal manufacturing technology. As discussed in Appendix C, each Additive Manufacturing process has minimum operational limits within which it can operate, and some Industrial Additive Manufacturing technologies are better than others at reproducing fine details. As with the previous stage, this activity was identified as

particularly important where prior experience of manufacturing the part (or a similar part) did not exist.

4. Generation of STL files was performed for all cases to enable manufacture of the part.

4.5.2.2 Build Preparation

Once the design has been confirmed, and the STL files built, preparation for the Additive Manufacture of the part may commence. Whilst in principle the part may be produced directly from the STL model, in practice further configuration is needed by the manufacturer to optimize production.

1. Collection of multiple parts to build. Whilst Additive Manufacturing can make one-of-a-kind manufacturing economically feasible (Hopkinson et al. 2006b), all companies involved in this research identified this was only viable with a ‘full build’. Such simultaneous manufacture has already been shown as offering cost advantages by amortizing the expense of the machine and its setup over a range of products; for example see Ruffo and Hague (2007) in terms of Laser Sintering.
2. Identifying requirements for accuracy. Approaches to accuracy differ between processes, and may incur trade-offs in terms of processing time and/or cost. It was identified by both BigCo and LittleCo that different parts had different accuracy requirements, and as a result this needed to be considered in the preparation stages.
3. Identifying optimal build parameters to meet the requirements of each build. Many of the cases use LS, for which build parameters include considerations such as recycling ratio, part orientation, scan spacing, and wall temperatures which affect the manufactured part.

4.5.2.3 Production Planning

Mellor et al. (2014) identified that little research has been conducted into the planning of production for Additive Manufacturing, save only for efforts by Munguia et al. (2008). Within the current study, the companies demonstrated emphasis on two principal activities: loading and scheduling. Each of the companies took a different approach to this activity.

- As a result of much uncertainty in demand, on a daily basis HearingCo experienced very high variations of demand making daily production planning for same-day despatch very difficult. The Production Manager identified that planning was instead possible on a monthly horizon, where demand was much more predictable. Work was typically sequenced first-in-first-out (FIFO), unless priority orders were received. Multi-skilled labour resources are reallocated through the manufacturing system as required.

- As LittleCo has only one instance of each technology type, all work for that type is simply loaded to the individual machine to be produced. The order of work is sequenced principally by customer requirement date, however to maximise utilization any excess space in the build chamber will be filled with smaller future orders. The other enabling resources of the system (e.g. technicians, post-processing equipment) have no plan for loading or scheduling; technicians self-allocate to work, and use the other resources however required.
- BigCo has a number of instances of the same technology, allowing the allocation of work to different machines based on availability. By extension, labour was allocated to different parts of the factory based on demand, with this flexibility made possible by a multi-skilled workforce.

4.5.3 System Component 3: Manufacturing

Upon completion of the preparatory activities, the final production STL model is transferred to the Industrial Additive Manufacturing machine for fabrication. Whilst the operation of the individual manufacturing processes is process specific and is performed according to the principles detailed in Appendix C, the overall outcome of this activity is the direct fabrication of the required part. The machines operate in an unattended mode for the duration of the build, and this time is principally determined by the speed of the individual machine and the size of the build being performed. Various simulations of build time taking this into account have been developed (Pham and Wang 2000; Ruffo et al. 2006a). During this time the cases indicate no requirement for labour in the production process, however for processes of a longer duration (e.g. LS and SL), demonstrated practice for BigCo and LittleCo was for labour to be involved in the monitoring of production systems for faults.

4.5.4 System Component 4: Post-processing

The final stage component of the manufacturing system is post-processing, which encompasses all the finishing activities for parts produced using Industrial Additive Manufacturing. As evidenced in Section 4.4, all of the cases demonstrated a need for a variety of different activities to be performed after the Additive Manufacturing machine-based processes. From this research, five distinct activities are identified:

4.5.4.1 Removal of build contents from machine

The build is removed from its machine, and taken to a dedicated area for further processing. For all companies and technology types this activity was achieved by the technician, using manual lifting equipment to carry the load. A demonstration of this activity is provided in Figure 4.7 (Stages 1 & 2).

4.5.4.2 Identification and extraction of parts from build

All three companies demonstrated the simultaneous manufacture of multiple parts in their Industrial Additive Manufacturing machines, which has previously been identified as reducing individual part costs by amortizing setup and depreciation costs (Atzeni et al. 2010; Ruffo and Hague 2007). Figure 4.6 demonstrates a typical multi-part build at LittleCo for Laser Sintering, which the technician needs to remove from the overall build and correctly identify each part. To aid in part identification, LittleCo and BigCo provide technicians with copies of the build plan, allowing them to identify parts based on the location within the build. In Figure 4.7 (Stage 3) the beginning of the removal process is shown.

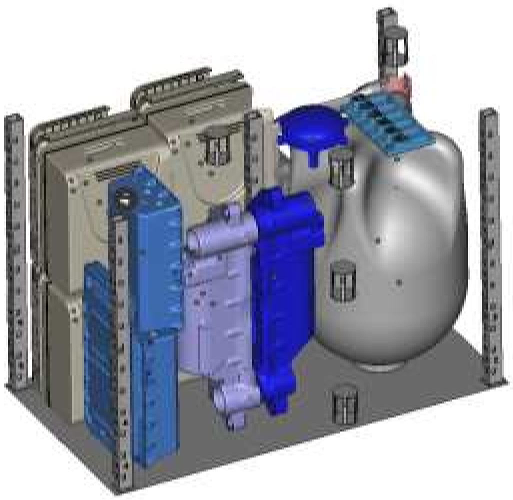


Figure 4.6: Contents of a LS build chamber for simultaneous manufacture of parts
Source: LittleCo

4.5.4.3 Material recovery for recycling or disposal

For every build there is the need to remove excess material and/or support structures before the part can be finalized. Depending on the Additive Manufacturing technology employed and material selected, it is possible to recover unused materials for recycling, thereby lessening production and disposal costs. For the focal cases in this study, recycling was performed for LS and SLS by manual recovery of some of the unused power (see Figure 4.7, (Stage 4) and Dotchev and Yusoff (2009) for a detailed appraisal).

1. Completed LS build for EOS P700 machine

2. Transportation of build

3. Extraction of part(s) from build in dedicated facility

4. Material recovery

Figure 4.7: Initial stages in post-processing for Laser Sintering at LittleCo
Source: The Author

4.5.4.4 Quality inspection

Three principal approaches to quality inspection were identified within the focal companies, with each chosen based on the requirements of the customer:

- Visual inspection and comparison to expected design
- Measurement of conformance to design
- Functional testing to assess mechanical characteristics

One of the main challenges in quality assessment was identified by LittleCo, who identified a "best-effort" approach to quality assessment was sometimes taken:

> "You must have an idea of the design to understand the customer needs. The trouble is, we never really know the [intended] application – sometimes we can't even recognize the potential of the part – but we always have to ensure we get the right quality. We always need to check the part out before we finish"
>
> *Production Technician, LittleCo*

4.5.4.5 Finishing & Assembly

Once the part has been verified as being adequately fabricated it may either be despatched to the customer, or may have further activities performed in finishing and assembly. This may include aesthetic aspects such as colouring, or further processing such as polishing or infiltration. As a result of these activities further evaluations of quality may also be necessary.

4.5.5 Summary of system components

Section 4.5 has shown how, though the detailed analysis of observed practices in commercial manufacturing systems, a number of different activities take place in the satisfaction of the demand. These activities have been noted as being a combination of product and process specific, and in this section commonalities between the twelve cases have been identified and summarized into four general components of an Industrial Additive Manufacturing System, as shown in Figure 4.8

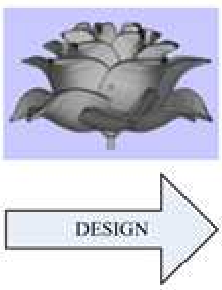
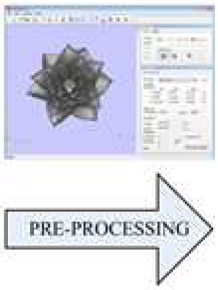
Component	 	 	 	
Activity	Create design idea Select item to scan Prepare item for scanning Scan item Review pointcloud Inverse existing CAD design Create 3D CAD model Conduct Virtual Prototyping Conduct Physical Prototyping Design optimization	Prepare STL file Check STL file quality Evaluate part manufacturability Evaluate feature manufacturability Prepare final production STL Batch STLs for simultaneous production Identify accuracy requirements Configure build layout Determine optimal build parameters Finalize build configuration Identify production capacity Identify production priorities Produce production plan	Perform machine setup Photocure resin Laser Sinter powder Drain build Cool build	Disassemble build & material recovery Remove excess powder / Clean Perform oven processing Perform quality assessment Perform part collation / ordering Perform part colouring Assemble parts Additional processing

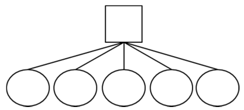
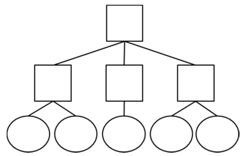
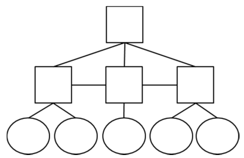
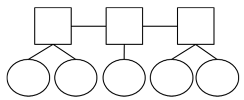
Figure 4.8: Components of an Industrial Additive Manufacturing System
Source: The Author

4.6 Identifying the control architectures of an Industrial Additive Manufacturing System

The preceding sections have demonstrated the development of a general understanding of an Industrial Additive Manufacturing System from literature and empirical research. The activities undertaken together with the individual mechanisms and controls have been demonstrated, from which clustering has allowed the general system components to be developed. This has enabled a systems perspective to be adopted, and in this final section the integration of these findings in a holistic model to include the organization of control for the entire system as shown in

Figure 4.3, leading to the definition of the structure of an Industrial Additive Manufacturing System.

Dilts et al. (1991) identified that control architectures concern the coordination of control information and system operation, and proposed four generic architectures that were evaluated in Section 2.2. This conceptual understanding is applied in this research to understand the possible ways an Industrial Additive Manufacturing System may be controlled. Using data from the twelve case studies and three Industrial Additive manufacturers, this section demonstrates the application of each of the control architectures, and examines the implications of these. The work of Dilts et al. (1991) is particularly applicable in this thesis, since the focus of their four principal forms of manufacturing control system architecture is intended for application in the context of automated and flexible manufacturing systems. It is shown in this chapter that Industrial Additive Manufacturing Systems have some degree of automation during the ‘manufacture’ stage, and in Chapter 6 some types of flexibility are evidenced. However, Dilts et al. (1991) focus on the role of computers to co-ordinate the control of the manufacturing system; within the current study it is acknowledged that computers will form part of the control, but it is a more general understanding of the principles of control that are of most interest, and their technological enablement a secondary consideration. The assessment is structured around the characteristics that have previously been synthesized in Section 2.2 and are summarized in Figure 4.9.

Additive Manufacturer	Control Architecture	Reconfigurability	Extensibility	Fault Tolerance	Mfg Autonomy
LittleCo	**Centralized Form** 	Low	Low	Low	Low
HearingCo	**Proper Hierarchical Form** 	High	Medium	Medium	Medium
BigCo	**Modified Hierarchical Form** 	High	Medium	Medium	Medium
BigCo Collaborative	**Heterarchical Form** 	High	High	High	High

Control component □ Manufacturing entity ○ Control interrelationship

Figure 4.9: Identified control architectures for focal manufacturing systems

Source: The Author

4.6.1 Centralized Form: LittleCo

LittleCo is a small Additive Manufacturing bureau, with a range of different machines and three permanent staff to perform all activities associated with manufacturing. A single manufacturing facility exists, with labour and infrastructure resources shared between each of the different manufacturing process types. Within this system, planning and co-ordination of all operations is performed centrally by the commercial manager, representing a central control element in the system. Such a configuration is typical in small Additive Manufacturing bureaus, wherein a few machine resources are controlled by a single control entity.

At the cell level decision making is minimal, and is largely based on the established procedures implemented by the central controller. Examples of cell-level decision making typically focused on approaches to achieve effective finishing of parts. Manufacturing autonomy is therefore low. Parts are produced according to the instructions of the controller, and established relationships between the controller and manufacturing entities are tight and long-term. As there is no electronic feedback mechanism, feedback arises from the human operators rather than through the Additive Manufacturing process resources, and is therefore manual, ad-hoc, and typically informal in nature. This leads to identified difficulties in planning and scheduling of work, and as a result the controller does not plan for full utilization of the system's resources.

The system comprises of individual instances of Industrial Additive Manufacturing machines, with no redundancy in the event of component failure. Similarly, there is little opportunity to interchange resources. The system has no defined options for expandability or reconfiguration, and does not collaborate with any other manufacturer. This has negative implications for the company which were demonstrated during this research when an extended period of machine downtime was observed for one of the manufacturing processes. During this time LittleCo was unable to satisfy customer orders, and as a result some orders were delayed and some orders lost to other companies. Similarly, during this research the amount of work for the system decreased significantly, yet there was no reconfiguration of system control in reflection of this change.

4.6.2 Proper Hierarchical Form: HearingCo

As a member of a larger group of companies, the manufacturing operations of HearingCo operate relatively autonomously from other group companies, but within the overall control of a central control entity. As a result, from a single UK manufacturing site the company fulfils demand for UK and Western Europe, with a dedicated production line producing customized ITE Hearing Aids. A management hierarchy oversees the facility, with dedicated production planners managing the planning and co-ordination of all operations. Control is therefore delegated hierarchically through the operations, with individual elements of the operations under control of local controllers.

Large variability in order volumes on a daily basis requires reconfiguration of labour within the manufacturing system to optimize its usage. Multi-skilled staff move between order processing, design, manufacturing, and assembly activities as required to maximise their utilization. This is controlled centrally by the production manager, and can also be reliant on individual team-leaders in execution. A clearly defined production process, together with a factory layout promoting series-based production means that work moves between workstations independent of the controller; however there is very little feedback of in-process activity. Unless a manual request for feedback is instigated, controllers have little awareness of the state of a given entity of the manufacturing system.

The system comprises of multiple instances of machine and labour resources that can be interchanged in the event of component failure, however there is no excess capacity for redundancy. In the event of a major failure of the system the ability exists to reallocate work to a different system within the network, however this is neither seamless nor desirable. In the event of this occurrence, manufacturing control is delegated to the alternate system.

It is identified that expansion of the system may be achieved using additional components; however the ability of the central controller to manage increasing numbers of manufacturing entities constrains the extent of such extension. During the conduct of this research there was no demonstration of this capability.

4.6.3 Modified Hierarchical Form: BigCo

BigCo splits its manufacturing systems into specialist facilities (for medical device production), and generalist facilities for all other production requirements. It employs two sites for its most specialized medical applications, in Europe and in the US. This second US based site provides additional production capacity for specialised medical components, local to demand for US customers. Each manufacturing system has assigned resources for the four manufacturing system components; these are specialized and are not typically shared between systems. Overall control of the multiple systems occurs at the European headquarters.

Each system is under the responsibility of a single director, and is distinctly controlled by production planners who schedule work using the company's planning software. Control is therefore delegated hierarchically through the operations, with individual elements under control of local controllers. An individual system comprises of multiple instances of machine and labour resources that can be interchanged in the event of component failure, however there is no excess capacity for redundancy. Compared to the Proper Hierarchical form, the principal difference observed in this example is the inter-relationship between manufacturing systems. Work and resources can often be switched within manufacturing systems without major penalty, and this is frequently employed to achieve load-balancing across the entire company's demand. Notably this is constrained by some of the specialist applications requiring particularly high quality production (e.g. medical parts), where dedicated systems are essential in promoting both quality and repeatability.

4.6.4 Heterarchical Form: BigCo Joint Venture

True heterarchical form requires that a manufacturing system has no overall supervisor, with entities self-configuring in the achievement of manufacturing. It is noted that in the context of Additive Manufacturing a similar notion was proposed by Berlak and Webber (2004a) in 'competence networks', however in this system a definite controller coordinates the product fulfilment process.

Within the current study it is identified that several companies in the Additive Manufacturing industry have joined together in a heterarchical-like form, and BigCo is a participant member. As demand is placed upon the system, individual companies take work based on their competencies, capacity, and potential responsiveness (the latter often dictated by production location relative to demand). Each manufacturer controls its own production, and therefore has a high degree of autonomy in manufacturing. Similarly, there exists some redundancy in the system, since the system is able to draw upon the capabilities of a distributed network of major manufacturers. Communication within the system is identified as good, with most information shared using the internet. The focal heterarchical system is a closed system; members are fixed and so unlike a marketplace there is little movement in-and-out of the system. Nevertheless, relative to the other control architectures, relationships within the system are loose and transient.

4.7 Discussion

Building on the preceding sections of this chapter in conjunction with Appendix C, the purpose of this section is to address the first research question posed in this study: *Research Question 1: How is an Industrial Additive Manufacturing System structured?*

In Section 2.8 it was evidenced that research emphasis has concerned the capabilities of Additive Manufacturing machines to achieve production objectives, with little emphasis on contribution made by other manufacturing resources. Whilst Section 2.2 demonstrated a long-established systems perspective exists for general manufacturing, such a consideration has not been extended to the specific context of Industrial Additive Manufacturing. To address this research gap this chapter has explored the activities, mechanisms, and controls that are demonstrated in three different commercial manufacturers that utilize Industrial Additive Manufacturing technologies in the production of twelve different products (Section 4.4).

An important finding presented in this chapter concerns the nature of the activities undertaken within the manufacturing system, highlighting the need for a 'systems' rather than 'machine' perspective. It has been demonstrated that current industrial practice is poorly aligned to prophesies for 'just click print' production, with 36 distinct activities identified in the case research. It has been shown that many activities are undertaken in the design of parts, and these have been shown to differ based on the means of elicitation (e.g. original design or reverse engineering), with differing levels of involvement from the manufacturer. Likewise a number of activities are undertaken in preparation for manufacture, and in the post-processing of parts which have often been overlooked in evaluations of Additive Manufacturing.

The way in which these activities are achieved has received a detailed consideration in this study. In the fulfilment of demand it has been shown that a range of different resources are necessary to achieve production objectives in addition to the Industrial Additive Manufacturing machines. Whilst the technologies of Additive Manufacturing might offer a range of potential advantages, they are shown to be incapable of entirely satisfying demand independent of other system resources. Only two activities directly involve the Industrial Additive Manufacturing machine, and through a detailed investigation it has been shown that a multitude of labour, machine, and computer/information processing resources are utilized in production. These are the manufacturing system's resources which need to be effectively managed; by focusing only on the individual machine these are neglected. The importance of labour resources within the manufacturing system has been demonstrated in the empirical work in this chapter, and this is noted to be contrary to observations made in several conceptual papers. It has been shown that labour is not eliminated from the manufacturing system, and is needed for many of the activities undertaken in the achievement of production. Whilst the Industrial Additive Manufacturing machines are able to operate without direct labour involvement, the absence of feedback from the machines and the criticality of their activities was shown to result in labour being employed in the monitoring of machines through observation.

Whilst it is demonstrated in this chapter that activities (and therefore the consumed resources) may differ according to specific product or process requirements, by considering twelve case studies and three different manufacturers, identified commonalities support generalization. This has led to the proposal of four general system components in Section 4.5: **design, pre-processing, manufacturing, and post-processing,** and the identification of the three principal resources of **labour, machines, and information processing** resources by which these components are enabled.

These important findings both justify the consideration of Industrial Additive Manufacturing in terms of a manufacturing system, and are used to inform the way in which its structure has been identified. Based on the findings presented in this chapter, in Figure 4.10 the empirical observations drawn from the twelve cases are combined with the concept of Parnaby's manufacturing system to provide a general framework for an Industrial Additive Manufacturing System. The four principal components are identified and (within the dotted lines) shown to be within the domain of an overall control architecture, and Section 4.6 has demonstrated alignment to different architectures, and the implications of each of these. The resources of the manufacturing system (structural and infrastructural) have been explained in this chapter.

This framework satisfies the fundamental requirements of a manufacturing system, and serves to consolidate and extend some of the relevant Additive Manufacturing literature. It presents a manufacturing system which is driven by demand, enabled through resources, and affected by disturbances (such as uncertainty). It aligns to the top-down input-transformation-output perspective (de Neufville and Stafford 1971; Parnaby 1979), and is comprised of component subsystems that facilitate focus at different parts of the system (Bhattacharya et al. 1996). Recognizing the importance of control in a manufacturing system (Parnaby 1979; Parnaby and Towill 2009b), within this chapter approaches to control of individual activities, subsystems, and the entire system have been demonstrated.

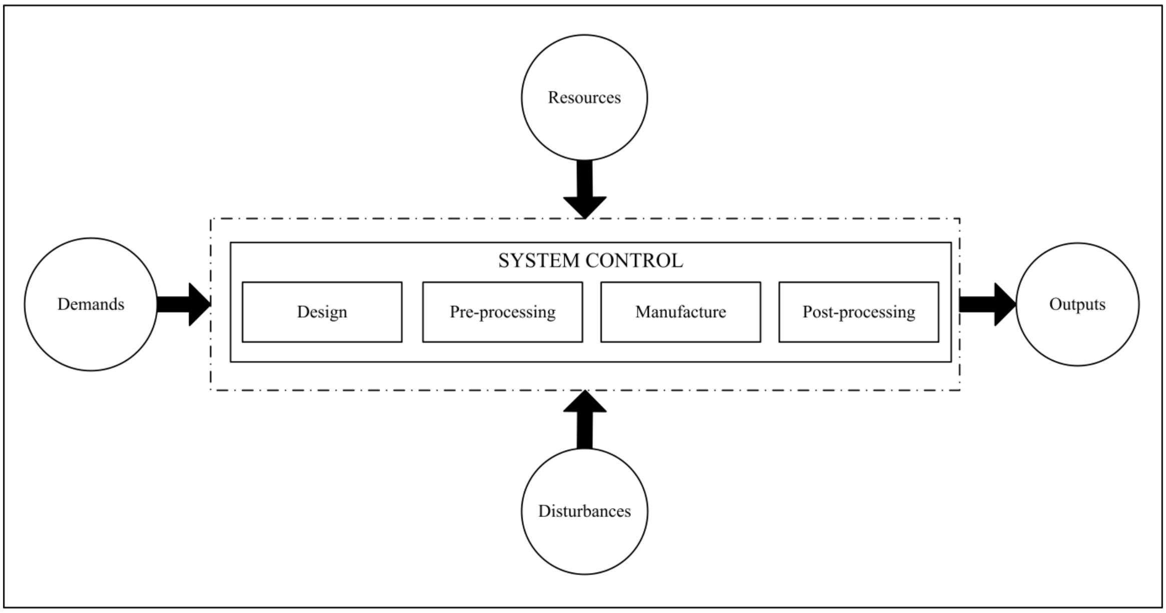


Figure 4.10: The concept of an Industrial Additive Manufacturing System
Source: The Author

4.8 Chapter summary

This chapter has evaluated the nature of Industrial Additive Manufacturing Systems, and has provided an up-to-date and detailed appraisal of contemporary commercialised technologies leading to the development of a novel typology of Industrial Additive Manufacturing technologies. Combined with Appendices C & D, this exploration contributes to the overall thesis through the presentation of relevant technical details that are requisite in understanding of how different Industrial Additive Manufacturing processes fulfil demand.

The chapter has explored the nature of Industrial Additive Manufacturing Systems in satisfaction of Research Question 1. Through the evaluation of activities undertaken in the production of both component parts and whole products in Industrial Additive Manufacturing Systems, commonalities and differences in terms of activities, components, and controls have been highlighted. It has been demonstrated that some current research which generalizes the management implications of Additive Manufacturing from a theoretical perspective has omitted to consider the implications that can only be identified through functional analysis based on empirical research. Based on the work of Parnaby (1979) in the development of the manufacturing system concept, and Dilts et al. (1991) in terms of manufacturing system control architectures, this empirical research has led to the development of the Industrial Additive Manufacturing System concept that underpins much of the research undertaken in the remainder of this study.

Chapter 5 Fulfilling Demand through Industrial Additive Manufacturing Systems

Chapter Aims

1. Examine the nature of demand experienced by Industrial Additive Manufacturing companies.
2. Demonstrate how Industrial Additive Manufacturing Systems fulfil demand for products.
3. Examine the alignment of Industrial Additive Manufacturing Systems to established manufacturing theory.

5.1 Chapter overview

The purpose of this chapter is to explore how Industrial Additive Manufacturing Systems are employed in commercial practice to fulfil customer demand. In Section 2.9 it was shown that existing literature has much enthusiasm for the manufacturing *technologies* to produce a wide range of products for many different applications, however there was little demonstration of this in applied commercial manufacturing *systems*. It is acknowledged that recent works have begun to focus implementation strategies for Additive Manufacturing (Mellor et al. 2014), however a research gap remains in understanding *how* manufacturing systems satisfy demand.

As shown in Figure 5.1, this chapter builds upon the work of Chapter 4 in which the concept of an Industrial Additive Manufacturing System was developed, and is a precursor to subsequent chapters that provide a detailed evaluation of the nature of flexibility in both the manufacturing system and wider supply chain. In doing so, this chapter tackles **Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?**

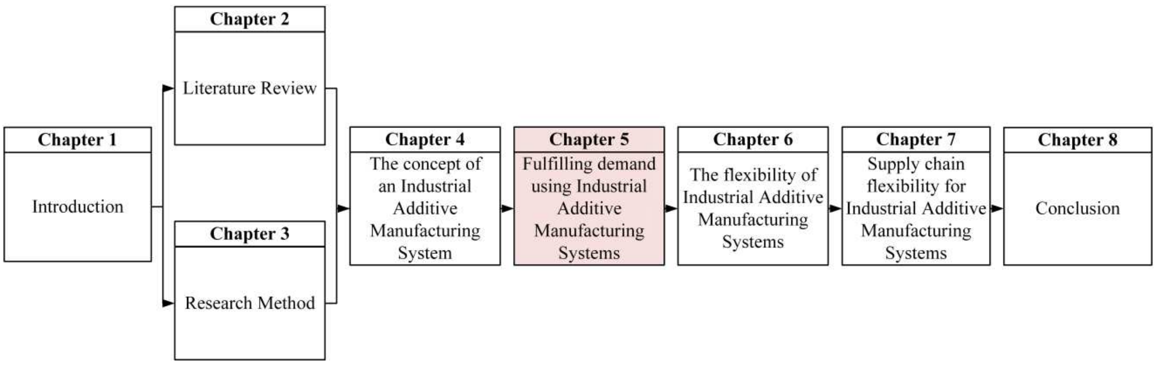


Figure 5.1: Thesis structure
Source: The Author

To satisfy this research question and address the aims of this chapter, as shown in Figure 5.2 three activities are undertaken:

1. An assessment of overall demand placed upon the manufacturing operations of the focal Industrial Additive Manufacturing companies is made (Section 5.3), establishing the context in which the individual cases exist.
2. An analysis of three case studies is performed (Sections 5.4 – 5.6) to achieve a detailed understanding of how demand is satisfied for given products.
3. An assessment in terms of Hayes and Wheelwright's product-process matrix is provided (Section 5.7) using all twelve cases, identifying alignment of the focal Industrial Additive Manufacturing Systems to established manufacturing systems theory and potential configuration strategies.

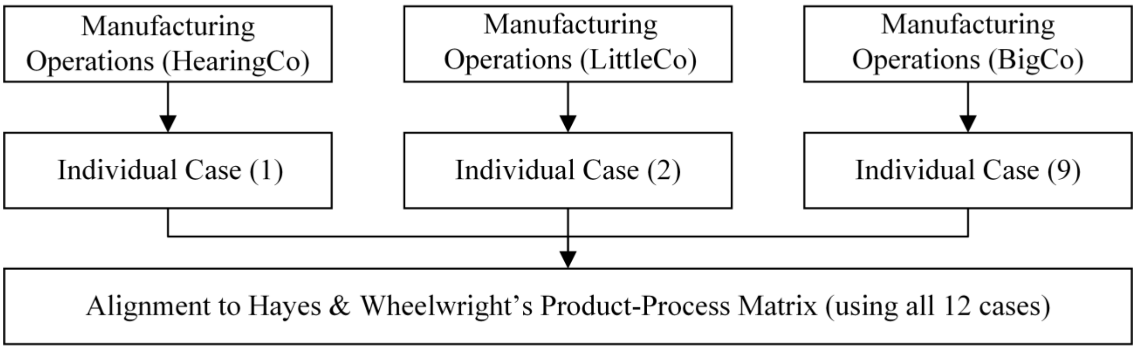


Figure 5.2: Investigation undertaken in Chapter 5
Source: The Author

This third activity is motivated by a conceptual note by Tuck et al. (2008) in the context of Rapid Manufacturing *technologies*, which suggested that future developments and the elimination of labour in manufacturing would enable the efficient production of high variety products at all levels of production volume. A similar proposition has more recently been suggested by Helkiö and Tenhiälä (2013), who identified a lack of specificity in the technologies as supporting the production of complex products. This would be in conflict with the established product-process matrix prescribed by Hayes and Wheelwright (1979), whereby decisions on process choice are aligned to demand requirements placed upon the system. In essence, Tuck et al. (2008) suggests the potential to achieve total flexibility, and to fully overcome volume-variety trade-offs through Additive Manufacturing. Such a capability could be a valuable asset, and would clearly distinguish Additive Manufacturing from many other types of manufacturing system, however as a conceptual proposition it has not been examined empirically, thereby motivating this investigation.

5.2 Method overview

The purpose of this chapter is to report identified commercial practice, and in the achievement of its objectives a qualitative investigation is undertaken. Such an approach is intended to provide a rich understanding of the nature of some Industrial Additive Manufacturing Systems, emphasizing the *how* and *why* concerning manufacturing operations.

In Section 5.3 the overall nature of demand experienced for each of the three Industrial Additive Manufacturing companies is presented, based on managerial interviews and observational data collected during site visits. This section draws upon data from senior staff, and contributes to an overall understanding of the operations of the manufacturers.

Sections 5.4 – 5.6 provide a detailed account of how demand is satisfied through three in-depth case studies (Table 5.1), with one case selected for each of the focal manufacturers. The case reports are written to explain the implications arising from choices made, and in doing so identify demonstrated current practice in manufacturing. The writing of these case study reports is structured to the linear-analytic style as defined by Yin (2009); this is akin to the 'scientific approach' defined by Robson (2011) which supports cross-case comparison. A full discussion of case study methods used in this research may be found in Chapter 3.

Building on the previous work, Section 5.7 considers the alignment of the manufacturing system to the traditional product-process matrix (Hayes and Wheelwright 1979) using data gathered from all twelve case studies through observation, managerial interviews, and supplementary company data. This section provides an empirical evaluation of Tuck et al. (2008), and demonstrates different approaches Industrial Additive Manufacturing Systems may take to satisfy demand.

Section	Case	Additive Mfr	Research Method	Data sources
5.4	Hearing Aid (Case 1)	HearingCo	Interviews	Audiologists[1] (2) Director (1) Production Manager (1) Technician (1)
			Process Observation	Production site tour (1)
			Document analysis	Process data from company
5.5	Model Ship (Case 2)	LittleCo	Interviews	Archaeologist/Project Manager (3) Production Manager (2)
			Participant Observation	Customer site tour (2) Production site attendance
5.6	Custom Lamps (Case 9)	BigCo	Interviews	Production Director (3) Technical Director (1) Product Manager (1)
			Process Observation	Production site tour (3)

Table 5.1: In-depth case studies examined in this chapter
Source: The Author

[1] These customers represent a major UK retail organization which supplies approximately 60,000 units annually, representing one quarter of all digital hearing aids privately purchased in the UK. The UK marketplace is split between private vendors and public provision by the National Health Service (NHS). Hearing-aid manufacturers supply both markets, however this study does not have ethical approval to conduct research in the domain of the NHS and therefore constrains its investigation to the private sector only.

5.3 Understanding the nature of demand experienced in Industrial Additive Manufacturing companies

The unit of analysis in this case research is the individual product type being produced, however it is acknowledged that the manufacturing systems that produce these exist within the wider manufacturing organization. The three Industrial Additive Manufacturers examined in this study serve a wide range of customers, consistent with the industry as a whole (Munguia et al. 2008; Wohlers 2012), and this section therefore explores the overall demand facing Industrial Additive Manufacturing companies.

In Section 2.2 it was shown that manufacturing systems exist to fulfil a demand, whether external or internal to the system. The nature of this demand can, at its most basic, be delimited in terms of its variety and volume, from which Hayes and Wheelwright (1979) proposed the manufacturing system should be appropriately configured. Unless overall demand increases proportionately, increasing variety and customization will reduce the volume of any given product variant, and in Section 2.3 it was shown that increasing variety can lead to a number of characteristics detrimental to the effective performance of the manufacturing system.

To understand the nature of demand facing manufacturing organizations, four attributes are explored in this section:

1. Total volume of different parts or products required.
2. Variety / customization requirements.
3. Requirements for responsiveness in the satisfaction of demand.
4. External uncertainties faced in satisfying demand.

By recognizing demand facing the firm to be multi-faceted, this approach is consistent with previous techniques employed in Operations Management (e.g. Childerhouse et al. 2002). Confidentiality dictates that some data in the following assessment has been omitted, and production volumes given with less precision than obtained in the conduct of the research.

5.3.1 HearingCo

HearingCo is the UK manufacturing division of HearingCo Group, which has operations around the world. HearingCo has a single UK manufacturing site, at which products are made and supplied to a network of audiologist customers. HearingCo only produces its own range of devices, and does not produce products that are not related to audiology.

Production Volume

HearingCo produces tens of thousands of ITE devices every year in response to orders from audiologists. Most individual orders are for one or two identical devices, and normally these will be batched on a daily basis by audiologists.

Variety / Customization in ordering

HearingCo has an established range of hearing aid devices to suit a range of patient requirements, for which the ITE Hearing Aid device is the only unit produced using Industrial Additive Manufacturing technologies. The ITE device offered is customized to the requirements of the customer. A series of configuration options is provided for each device (Figure 5.3), and the outer shell of the device is customized to the shape of the individual wearer (described in detail within Section 5.4).

Requirement for responsiveness

HearingCo stressed the importance of their devices as contributing to the quality of life for the end customer, and the market requirements for quick response manufacturing. The production manager identified that the company needed to satisfy the majority of its orders same-day, which (when combined with 2-3 days total transport time), meant that for each device design elicitation, manufacturing, and delivery should be achieved within five working days. From interviews with audiologists such a schedule was observed to be consistent with other companies in the industry.

Uncertainties in demand

HearingCo identified that on a daily basis it experienced much uncertainty concerning the volume of orders that it would receive, or the mix of these from its product range. It was identified that demand for individual devices was subject to the requirement of the patient:

> "[it] is impossible to forecast for each day what devices we will need to make, but we have to be able to make them regardless."
>
> Operations Manager, HearingCo

The company receives orders from a network of hundreds of audiologists, with each placing orders based on the patients presenting at their clinics. HearingCo identified that they envisaged little ability from the audiologists to forecast daily requirements for different device types; through interviews with audiologists this was confirmed. It was identified by the Production Manager that the difference between 'busy' days and 'quiet' days equated to "300% variability" which posed challenges for the operation in the satisfaction of demand.

HearingCo identified that despite considerable fluctuation in daily demand, on an annual basis the requirements for different device types were largely predictable. In practice, it identified the use of historic monthly production data as being a useful source for longer-term planning; the Operations Director defined overall demand for ITE device as enjoying a small degree of growth annually, with month-on-month requirements largely consistent and without notable deviation arising from issues such as seasonality.

Brand	A		B		C		D		E		F	
Models	5		3		5		5		9		5	
Ear (Left/Right)	L	R	L	R	L	R	L	R	L	R	L	R
Size	1	1	1	1	2	2	2	2	1	1	1	1
General Options	4	4	4	4	6	6	6	6	6	6	6	6
Faceplate Colour	3	3	3	3	3	3	3	3	3	3	3	3
Faceplate Option	2	2	2	2	2	2	2	2	2	2	2	2
Shell Colour	4	4	4	4	4	4	4	4	4	4	4	4
Wax Prevention	7	7	7	7	7	7	7	7	7	7	7	7
Vents	5	5	5	5	5	5	5	5	5	5	5	5
Manual Assist	4	4	4	4	4	4	4	4	4	4	4	4
Shell Option	3	3	3	3	3	3	3	3	3	3	3	3
Engraving text	1	1	1	1	1	1	1	1	1	1	1	1
Remote control	0		1		9		9		9		9	

Figure 5.3: Configuration options for ITE Hearing Aid device
Source: Adapted by the author from an original HearingCo document

5.3.2 LittleCo

LittleCo is a UK based manufacturing bureau providing outsourced manufacturing services for a wide range of industrial customers. It offers capabilities in LS, SLS, SLA, and envisionTEC technologies, together with post-processing and tooling capabilities. It accepts orders from a range of customers, and one of its specialisms is project-based activities, where it undertakes consultancy for design, prototyping, and development.

Production Volume

LittleCo produces hundreds of different products each year, mainly using its LS and SL technologies. Individual orders can constitute single unit requirements, or may extend to several hundred similar or identical parts. Total production volume for all machines was estimated by the Production Manager to be less than 10,000 parts per annum.

Variety / Customization in ordering

LittleCo has no product range of its own, instead providing outsourcing capabilities to produce parts on behalf of other firms, for many industries including automotive, aerospace, construction, scientific, and education. Observed examples include models for city planning, prototype parts for aerospace applications, gifts for marketing activities, prototype engine parts, and replica automotive parts. LittleCo produces prototypes (RP), tool patterns for investment casting (RT), and some end-use parts (RM).

Requirement for responsiveness

The company has a split between short lead-time parts, and longer and more complex project-based work. Some short lead-time work was identified as being 3-5 days for fulfilment, whereas longer projects could be many months in their completion.

It was identified that timescales are agreed between the customer and company at the point of quotation, which took into account expected workloads for LittleCo. However, it was recognized by the Production Manager that the timing of actual demand was often uncertain, leading to difficulties in effective production planning.

Uncertainties in demand

LittleCo identified that demand was very unpredictable in both short and long-terms, and that a combination of a diverse range of customers together with little visibility of demand posed challenges for the manufacturer. In addition to temporal uncertainties, LittleCo also identified challenges arising from uncertainties in the nature of the parts demanded. For some short lead-time items, LittleCo had little involvement in the design process, and often did not know the purpose or requirements of the product being produced. Such uncertainty provided challenges particularly in the pre-processing and configuration stages of production, where parameters influencing part quality and performance are decided.

> "We build stuff for a lot of different people, and they don't always know when they are going to need it. Sometimes this works for us but sometimes it doesn't and that can lead to upset customers or they go [to another provider]."
>
> *Production Manager, LittleCo*

5.3.3 BigCo

Of the three Additive Manufacturing companies participating in this study, BigCo is identified as being the largest, with significantly more staff, products, production capacity, and annual growth than either of the other firms. It serves a broad range of customers that were defined by the company as 'medical', 'industrial', and 'consumer'.

The work performed by BigCo may be categorized in two ways:

1. As a manufacturer of its own products. BigCo provides its own product range of medical and consumer products, most of which are offered in a form for further customization to meet the customer requirements. These products tend to be for end-use (Rapid Manufacturing).

2. As a provider of outsourced manufacturing for other companies (as a manufacturing 'bureau'). The applications of these products varies (Rapid Prototyping, Rapid Tooling, and Rapid Manufacturing) and is not always apparent to the manufacturer.

BigCo has two principal manufacturing sites; one in Europe (which is the focus of this study), and a recently opened, smaller unit in the US. The company utilizes multiple distribution channels:

- Direct sales enabled via the internet
  - Customers upload their designs directly for manufacture.
  - Customers customize existing designs online for subsequent manufacture.
- Indirect sales via supply chain intermediaries
  - A network of sales offices in America, Asia, and Europe.
  - A network of independent agents and retailers.
  - A small network of its own retail stores.

The manufacturing systems are organized and managed in two ways, and the nature of demand is explored in this section in line with these:

1. Specialist production, where dedicated production lines are established for high volume, repetitive production of the same products (albeit with customized characteristics)
2. Generalist production, where resources of the manufacturing system are shared amongst the production of a wide variety products at a range of production volumes.

5.3.3.1 BigCo Specialist production

Production Volume

A large proportion of the specialist production undertaken by BigCo concerns medical devices, most of which are used as part of surgical operations. BigCo produces tens of thousands of medical devices each year for a worldwide market, and demand for these was identified as consistently growing strongly each year.

Variety / Customization in ordering

BigCo offers a small range of medical devices to be produced using its LS processes and specialist post-processing techniques. These devices are chosen by surgeons based on the application requirement, and customized by surgeons and experienced medical designers to meet the individual patient requirements. Multiple configuration options can be selected by the designer, which is complimented by the ability to achieve geometric customization in order to be of an appropriate shape for the patient.

Requirement for responsiveness

BigCo identified that individual medical components typically had a three week lead-time, with the majority of effort arising in the design component of the manufacturing system. The physical production and finishing of individual products was shown to normally represent three days of this total leadtime.

Uncertainties in demand

The Production Manager identified that whilst "each and every device is different" and required iterative development with the commissioning surgeon, the overall volume of parts to be produced was largely predictable. The company also observed that the three week lead-time provided some visibility of orders to be produced using Industrial Additive Manufacturing machines. This allowed them to plan manufacturing to better optimize machine utilization. Hence whilst uncertainty existed over the specific customization to be made, from the perspective of the manufacturing system demand volumes were identified as being stable, predictable, and growing on an annual basis.

5.3.3.2 BigCo Generalist production

Production volume

Generalist production at BigCo constitutes a large [confidential] proportion of the company's total output, and accommodates demand from a wide number and range of different customers. The overall production volume is split across a number of different Industrial Additive Manufacturing Technologies, with LS, SL, and FDM being the principal contributing technologies.

BigCo identified that requirements for individual parts varied considerably, from single unit production through to thousands.

> "The largest unit we made was 10,000 off. That was a [physically] small part."
>
> *Operations Director, BigCo*

Variety / Customization in ordering

The generalist approach to manufacturing is intended to support a very wide range of different product requirements.

- Most of the work for the manufacturing system arises from the outsourcing of work to BigCo. It is therefore unique to the individual customer, typically as a wholly new design submitted for manufacture. In outsourcing, the company does not offer a standard 'range' of products, rather the capability to manufacture the individual requirements of the customer.

- A smaller amount of work for the manufacturing system arises from the manufacture of BigCo's own product range of consumer goods. These are defined products, listed in the company's catalogue range, and are typically customized to meet individual customer requirements.

Where BigCo provides an outsourced manufacturing capability, there is typically a high degree of variety observed, with little commonality in parts produced. This was evidenced in practice by process tours undertaken by the researcher, where a plethora of different products was shown to be in production simultaneously. It was observed that parts ranged considerably in size, shape, and materials and required a variety of different post-processing operations (e.g. painting, cleaning, assessment etc). Some identifiable applications included automotive and aerospace, but in many instances the purpose of the part was unclear to the observer.

By comparison, the company's own product range was more readily identifiable in the process tour. These consumer products were typically customizable in terms of geometry, material choice, and finishing operations, all of which were predefined by BigCo.

Requirement for responsiveness

BigCo identified that the generalist production involved many different customers, from a diverse range of backgrounds and with different requirements for responsiveness in the fulfilment of orders.

- Short lead-time products (1-2 days fulfilment) were noted as arising frequently, and the ease of satisfying these requirements typically depended on the workload and available manufacturing resources at the time of production.
- Longer lead-times were negotiated with some customers, and were identified as assisting with production planning within the organization. For products from their own range the company typically defined standard lead-times for products, however interviews and observation highlighted difficulties for the manufacturer in matching its timeliness of order fulfilment with the requirements of the customer:

> "in the beginning [for consumer products] we thought – everybody thought – we can let them wait a little longer, because if we work for automotive sometimes that's two days and the thing has to be there. Initially we were looking at terms of two weeks to consumers… we can do it faster but just to be safe if there's too much complaint."
>
> *Technical Director, BigCo*

The availability of some slack provided both a buffer to the company, and also helped with the batching and scheduling of work. However, it was identified that the nature of some goods attracted customers with specific responsiveness requirements:

> "Depending on products of course because in customisation we see you have a very big market – for example gifts for holidays or birthdays, and it's always the way that people take on that two days or five days before the anniversary. That's always the same."
>
> *Technical Director, BigCo*

In the context of its own product catalogue and customizable products for consumer markets, the informant at BigCo identified the need for responsiveness to be achieved in order to compete with bricks-and-mortar distribution channels:

> ".. if you look at the overall online internet business I believe we have to work, I believe we have to make it faster anyway because even consumers are very impatient: if they go to a shop and they want a cell phone they pay and they get it. If you want to compete from an online way it is very important that they choose a cell phone and you send it to them the day after and they receive it the day after. It's got to be competitive."
>
> *Technical Director, BigCo*

Likewise, for industrial B2B customers the need for responsiveness was echoed by other staff in the organization as being an important consideration for the company:

> "we have a very short horizon on what we produce, and customers have a short, efficient time for buying our product."
>
> *Operations Director, BigCo*

> "We have to make it when they [the customer] want it – not later or we're not in the game."
>
> *Product Manager, BigCo*

Uncertainties in demand

BigCo identified that for its generalist production, uncertainty was a major challenge for its operations. A most succinct but informative quote from an interview highlights the challenge for the firm in terms of the uncertainty it faced, and a desire to increase repeatability of production:

> "If I exclude the [specialist products], then I would say that 95% [of demand] is short term, unpredictable…. repeat business will not solve everything, but it will give us a certain stability."
>
> *Operations Director, BigCo*

This uncertainty in demand inhibited some planning operations, and was identified by the Operations Director as requiring the company to hold stocks of raw materials and surplus capacity for production. As a result, this was identified as limiting the ability of the company to achieve full utilization of its manufacturing assets, leading to strategies being employed to stimulate demand:

> "So what we see, and apply, is that you have a certain number of planned buyers. If we see, and can predict a couple of days – if the workload is getting down we broadcast an email to the internal sales team 'these are the technologies with free capacity', so you can [take confidential action]. So we have mechanisms to cope with it [uncertainty] – but then yesterday I heard that we turned down some order from some customers because we just can't produce them. And that is really bad because in a week from now we may have free capacity."
>
> *Operations Director, BigCo*

5.3.4 Summary findings

Sections 5.3.1 – 5.3.3 have demonstrated that each of the manufacturing companies experiences a wide variation in demand requirements, which have been explained in terms of their volume, variety/customization, responsiveness and external uncertainty characteristics and are summarized in Table 5.2. Although there is commonality in some aspects of the demand nature, the three companies can be observed to have taken different strategies:

- HearingCo has a narrow product range and employs a number of constraints on customization to limit the range of options available.
- LittleCo produces for a wide range of different customers, and as a result of the high degree of uncertainty does not plan for full utilization of its resources.
- BigCo has split its operations into two functional divisions. Similar to HearingCo, the specialist division produces high volume customized products that have a limited number of configuration options. A second generalist division accommodates the more uncertain demand, producing a wide range of volumes and varieties in response to market requirements.

		HearingCo	LittleCo	BigCo Specialist	BigCo Generalist
Volume	**Typical range per part (units)**	1 - 2	1 – 1000	1 off	1 – 10,000
	Total production per annum (units)	Very High – tens of thousands	Medium – up to ten thousand	Very High – tens of thousands	Very High – tens of thousands
Variety	**Nature of variety or customization**	-	Variety in new products	Customization of geometries	Variety in new products
	Nature of customization	Customization of geometries Customization of functionality	-	Customization of geometries	Customization of geometries
Responsiveness	**Typical production lead time**	1 day	Varies	3 weeks	Varies
	Importance	Critical, contractual	Varies	Critical, contractual	Varies
Uncertainties	**Nature**	Daily volumes unpredictable	Daily volumes unpredictable	Some uncertainty over daily production volumes	Daily volumes unpredictable
	Mitigation techniques	Workforce flexibility Process flexibility	Workforce flexibility Excess capacity Process flexibility	Process flexibility	Workforce flexibility Capacity management Process flexibility

Table 5.2: Nature of demand for focal Industrial Additive Manufacturing companies
Source: The Author

Within this overall context, the following three sections explore in more detail how each of the manufacturers satisfies demand for an individual product type.

5.4 Case Study 1: Production of hearing aid shells

5.4.1 Case overview

This case concerns the manufacturer of hearing aid devices by HearingCo. Hearing aids are used by individuals with impaired hearing to provide some degree of correction. Figure 5.4 illustrates a range of alternate hearing aid device types that may be used dependent on the patient's requirement. In the UK, laws govern the sale of hearing aids, limiting their supply to authorised professionals (known as audiologists), and principal manufacturers include GN Resound, Oticon, Phonak, Siemens, and Starkey. Audiologists may be independent providers, work for one of the larger retail chains (e.g. Boots or Specsavers), or be employees of the NHS. It is commonplace for audiologists to purchase hearing aids from multiple suppliers.

The ITE hearing aid is a particular type of device which is widely used for both children and adults with higher degrees of hearing impairment. It fits entirely within the ear canal, selectively amplifying noises from outside the ear. The ITE device consists of an outer shell, within which a number of modular electronic components are held, including a microphone, and a Digital Signal Processor (DSP) which is used to process the external sound and convey it to a speaker. It is a customized product, with the outer shell manufactured to the shape of the individual ear, and the modular electronics within the device configured to the individual hearing loss profile.

The ITE hearing aid product was identified by both the audiologist and manufacturer as having important implications for the quality of life for the wearer, and so where new or replacement devices are required, responsiveness in supply is required. HearingCo identified that it almost always satisfied its target of same-day production and despatch of ITE Hearing Aid devices.

HearingCo is part of a multi-national group of companies that supplies over 300,000 hearing aids annually, and has utilized Industrial Additive Manufacturing technologies in the fabrication of the hearing aid shells for over 12 years. Within the HearingCo factory, the Industrial Additive Manufacturing system is integrated within the overall manufacturing operations, in which shells and electronic components are assembled to form the device. Hearing aid shells are produced as part of the overall line-based process, and labour resources are multi-skilled to allow them the flexibility to move between functions in the shell manufacture and assembly processes.

Figure 5.4: Different types of hearing aid
Source: Crystal Hearing Limited

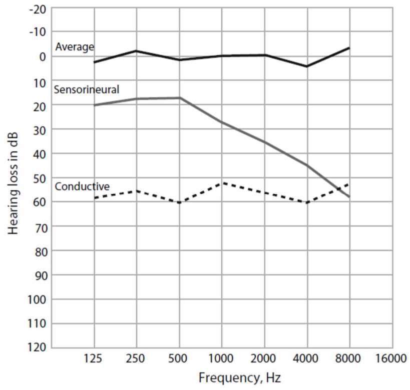


Figure 5.5: Sample audiogram
Source: Persad et al. (2007)

Figure 5.6: Production of hearing aid shells
Source: envisionTEC GmbH

5.4.2 Design elicitation

Each ITE hearing aid is configured to the requirements of the individual client. This necessitates a customised hearing aid shell to fit the individual ear, and a customised configuration of the internal electronics to match the hearing-loss profile. The configuration process is normally initiated by the client visiting the audiologist for an assessment of their hearing. A standard process is performed at the assessment, where the client will respond to a series of tests of their hearing. If the demonstrated hearing capability falls short of an expected standard, a hearing aid device may be suggested. The device will be chosen based on a number of factors, including the extent of hearing loss, the client's age, and their lifestyle. A profile of the hearing loss (known as an audiogram) is recorded and used to configure the hearing aid electronics during manufacture (Figure 5.5). Where an ITE hearing aid device is to be utilised, the geometry of the individual ear needs to be captured with which the shell can be constructed. In ITE devices it is particularly important that this matches the shape of the overall ear, since poorly fitting devices are less effective, uncomfortable and will potentially fall out of the ear whilst being worn. In such devices a characteristic whistling noise is often present, which is uncomfortable for the client and those around them.

A common technique to elicit the ear shape is the pouring of silicon into the ear, where it is allowed to set for a few minutes before being removed. From this silicon mould an inverse representation of the human ear can thus be identified, which is used to shape the hearing aid device. This mould, the audiogram, and an order form detailing other configuration details (including colours, wax prevention systems, vent options and accessibility aids) is batched with other orders, and are sent daily via Royal Mail post to the manufacturer.

HearingCo receives daily deliveries of hearing aid moulds from all parts of the UK, and has standardized the order processing and manufacturing process (Table 5.3). Deliveries are opened at the manufacturer and entered as jobs within the planning system. The audiologist's mould is scanned using a 3D non-contact scanner to obtain a reverse engineered digitised representation which will be the basis of the manufactured part. To finalize the design, the Materialise Rapid Shell Modelling (RSM) software is used by a technician to correct and configure the part. The software tool has been developed especially for this product to enable the technician to identify potential pressure points that would cause discomfort, and to correct any defects in the scanned item. It also can simulate the placement of the various electronic components, and perform quality checks on the proposed build. As a result, the finalizing of the design for manufacture takes about five minutes per shell.

5.4.3 Pre-processing

The company has standardized its manufacturing technology, and all parts are configured for a single machine type. Every hearing aid is produced with the same machine parameters, and so in pre-processing there is no requirement to consider either orientation or optimization issues. The main activity undertaken is collecting of orders to (normally) 24 units, which is a full build for the envisionTEC machine. Once a full build is ready for production, a technician uses the RSM software to configure the production process. As this software is optimized for the application and focal machine type, this activity requires only limited intervention from the technician.

5.4.4 Manufacturing

The physical dimensions of the hearing aid shell are unique to the patient, however the overall small nature of the shell means that their production can be achieved relatively quickly. The production of hearing aid shells is performed using one of HearingCo's four envisionTEC machines, and takes between 1 and 2 hours to complete. The selection of machines that could achieve the production of small batch sizes (Figure 5.6) relatively quickly was identified by HearingCo as being optimal, since prior experience with larger capacity machines had disrupted flow during the batching process.

The individual machines are employed in the repetitive production of hearing aid shells, and do not make any other products. As a result, their configuration is optimized and maintained for this application. With the exception of loading materials, the manufacturing process is largely unattended.

5.4.5 Post-processing

On completion of shell manufacture, labour is required to identify and split individual hearing aid shells from the build, and minimal post-processing may be performed to clean the device prior to the conduct of a quality assessment procedure. HearingCo identified that overall the Additive Manufacturing process was very reliable, achieving good surface characteristics and consistently high quality parts that needed little work in post-processing.

Once the hearing aid shell is complete, it is matched to the correct order and then enters the rest of the production system, where component modules including microphones and DSP's are added by skilled technicians to finalize the product. All devices are tested, then packed and despatched by courier to the audiologist for subsequent fitting for the customer.

#	Task Description	Time	Operation	Inspection	Transport	Storage	Delay	VA	NNVA	NVA
		Units								
		Minutes	○	□	⇦	▽	D			
1	Create audiogram	20-30	✓					✓		
2	Pour silicone mould	5	✓						✓	
3	Wait for mould to set	5-10					✓		✓	
4	Complete customisation sheet	5	✓						✓	
5	Complete order form	5	✓						✓	
6	Package items	5	✓						✓	
7	Wait for Royal Mail collection	Up to 600					✓			✓
8	Deliver to manufacturer	1 day			✓				✓	
9	Unpack items	5	✓						✓	
10	Enter order on SAP	5-10	✓						✓	
11	Scan mould	5	✓						✓	
12	Configure and fix using RSM software	10-30	✓	✓					✓	
13	Collate 24 units						✓			✓
14	Configure job	20	✓						✓	
15	Load resin and prepare machine	20	✓						✓	
16	Manufacture	60	✓					✓		
17	Unload machine	10	✓						✓	
18	Identify individual shells	10	✓						✓	
19	Transport to assembly line	1			✓				✓	
20	Add electronics		✓					✓		
21	Configure electronics		✓					✓		
22	Quality Assurance & testing			✓				✓		
23	Pack goods for shipment		✓						✓	
24	Wait for courier	Up to 480					✓			✓
25	Deliver to retailer	Overnight			✓				✓	

Table 5.3: ITE hearing aid process map
Source: The Author

5.5 Case Study 2: Production of a model ship

5.5.1 Case overview

This case examines the process of archaeological model-making in an Industrial Additive Manufacturing System, in which a 15th Century medieval ship was recreated from individual 'timbers' manufactured by LittleCo. Overall, over 2,000 individual wooden timbers were recovered from the original sunken ship, for which each is unique in terms of its physical dimensions, surface profile, and the location of individual 'clinker holes' that originally contained iron nails or wooden treenails. The project required approximately 700 scale timbers, intended to form an accurate representation of the hull of the sunken medieval ship, originally of an estimated 30 metres in length.

The ship had spent hundreds of years in riverbed sediment, and it was identified that attempts had previously been made to dismantle it. As a result, the timbers were distorted and warped, making conceptualisation of the original size and shape difficult to evaluate. Specifically, it was difficult to appreciate the shape of the original hull. The purpose of the project was to faithfully reproduce these individual timbers at 1:10 scale, and through the assembly of each timber, better understand the construction and shape of the original ship. Each of the timbers to be produced ranged from 20 - 450mm in length, with the average width being 25mm.

Archaeological model-making is commonly applied in the context of ships to provide a scaled reconstruction of the original hull-form, and traditionally this would be achieved through careful measurement and tracing of the original timbers, before being reproduced in cardboard or wood. This approach has a number of limitations affecting its suitability, including the functional and mechanical characteristics of the materials, the high-labour requirement for measuring and cutting materials, and the limitations in accuracy that can be conveyed through craft approaches.

5.5.2 Design elicitation

To acquire a digital representation of the model, each timber was scanned by the archaeologist team over a two-year period using FaroArm co-ordinate measuring machines (Figure 5.7) and non-contact laser scanning systems. This activity was identified as slow and labour-intensive, and at its peak, 15 staff worked on the Reverse Engineering task. As each timber was completed, 3D data was assembled using a general purpose software package.

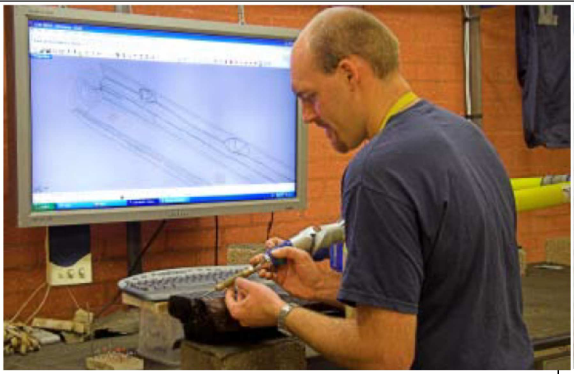


Figure 5.7: Geometry capture process
Source: Soe et al. (2012)

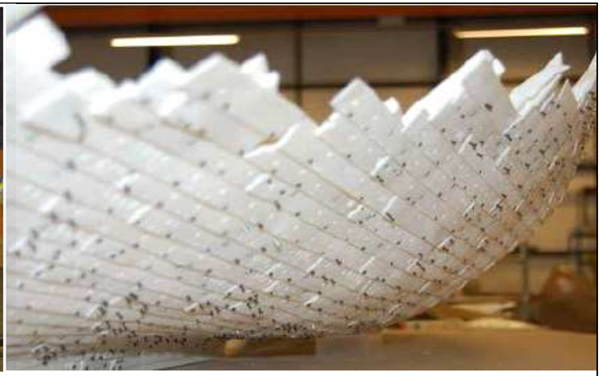


Figure 5.8: Partial ship hull in assembly
Source: The Author

The archaeology team were not aware of any previous attempts to reproduce a ship using Industrial Additive Manufacturing, and whilst they were familiar with 3D scanning techniques they had no previous experience of producing designs for Additive Manufacture, and acknowledged that the initial stages constituted a great deal of learning for them about how to appropriately create part designs that were suitable for manufacture. Similarly, whilst the LittleCo manufacturer had much experience in model-making, they had little experience of this type of archaeological application and so the initial stage constituted a 'learning experience' for them both.

As part of the design stage, meetings occurred between ModelShip and LittleCo, in which requirements for the physical characteristics of the parts were developed. The archaeologists had limited awareness of the characteristics of different products or processes, and so in the initial discussions there was a need for LittleCo to provide appropriate explanation of the options and their implications, and as result of explorations propose a suitable selection of machine and material for the application. It was also necessary to conduct a 'prototyping' phase, with design samples being sent to LittleCo for evaluation, where an experienced designer evaluated them using a combination of software tools and his prior experience in the manufacture of other products. From these initial parts, the designer identified a number of characteristics that made the parts unsuitable for manufacture, including file-format errors and incomplete designs (with data missing leading to holes). This initially labour-intensive process therefore helped the archaeologist develop best practices in the achievement of the original design from the timbers.

In addition to the practicality of achieving a 3D design, it was shown that much labour effort was needed to ensure that it was manufacturable. One of the largest challenges for the designer and archaeologists was the achievement of 'scaling' within the production model, since although the 3D model could be accurately displayed on a computer screen, it was identified that very small details would not be reproduced in the manufacturing process. Just as a reducing photocopier may lose some of the smallest details in its actions, so too may this be a problem in the manufacture of models created from scanned artefacts.

The archaeologists involved in the project were particularly keen to understand how the positioning of the nails would bend the timbers, thereby recreating the shape of the hull as shown in Figure 5.8. Through reverse engineering, the location of the holes could be accurately determined, together with their respective sizes. Each original hole was different, ranging from 10 to 40mm in diameter. The process of scaling these was straightforward, and initial modelling identified they could be replicated in the 1-4mm range. Notably however, for the model (which employs screws, rather than nails), the practicalities of sourcing 1mm screws for assembly required minor deviation from this scale on the grounds of functional practicality. It was therefore found that for each part, a review of its ‘manufacturability’ was needed, and manual interventions made to ensure all required features would be reproduced in the physical parts

Additionally, as part of the design it was necessary to evaluate the desired mechanical properties of the physical parts. It was identified that the individual timbers needed a limited degree of flexibility, to allow them to bend slightly when assembled to form the ship’s hull. The LittleCo designer explored three possible approaches to this (part hollowing, part hollowing with lattice, parametric change), and manufactured prototypes for the customer to identify the best approach.

5.5.3 Pre-processing

The choice of Industrial Additive Manufacturing process was made as part of the design process, and with an EOS P700 machine justified on build chamber size capability, processing capability, and its ability to fabricate without support structures. Of the available materials, polyamide 12 was selected based on its mechanical performance characteristics and relatively low cost.

The need for accuracy in the production of these parts meant that process parameters needed to be held constant over the extended duration of the project (18 months in total, but in intermittent builds). Since the machine and materials would be reconfigured many times between builds to satisfy orders from other customers, LittleCo needed to carefully plan for repeatability in builds. To do this, the production manager ensured that the same machine was planned for each batch, and that all of the machine-specific settings such as laser power and scan speed were held constant between builds. To mitigate thermal inconsistencies between builds, each were configured to contain only the model ship parts, arranged in approximately the same part of the build chamber. In doing this, LittleCo were not fully utilizing the capacity of the machine, significantly increasing the costs of production.

In ideal circumstances, using the same material batch promotes increased consistency in production however as ten builds were produced over an eighteen month period, storing the material was unfeasible. Instead, best efforts were made to keep the ratio of recycled to virgin material constant.

5.5.4 Manufacturing

To produce each batch, the virgin and recycled polyamide material was manually loaded into the two storage tanks by a technician, and production commenced according to the planned build parameters. Once the manufacturing process had started, there was no labour involvement and the machine operated in an unattended mode to manufacture the parts through laser sintering. Once sintering was complete, the build was left to cool from its production temperature (approximately 177°c) to an ambient temperature. LittleCo use a rule-of-thumb approach for this process, allowing the build to cool for the same amount of time that processing occurred. This process was repeated for all of the ten builds.

5.5.5 Post-processing

For each build, the need existed for basic post-processing activities to be undertaken in preparation of the parts for the customer. With the assistance of mechanical aids, a technician removed the build from the machine and emptied it onto a breakout table. The objective of the technician is to remove the parts from the build, whilst at the same time recovering the maximum amount of recyclable material. Although the sintering process should sinter just the part, the material immediately surrounding it is heated in the process, and as a result it becomes degraded and unsuitable for recycling. The technician must therefore carefully extract the parts to preserve as much material as possible, but at the same time ensure that all parts are successfully removed.

For each of the individual parts, hand-finishing was performed by the technician. To remove excess powder, each part was brushed using a soft paintbrush before compressed air was delicately used to remove any stubborn or hard-to-reach powder. A sample of parts was quality inspected, and all parts packed for despatch to the customer.

5.6 Case Study 9: Production of custom lamps

5.6.1 Case overview

The ability to produce highly complicated geometries has led to the application of Industrial Additive Manufacturing technologies in the production of a wide range of artistic and design applications. One such example is that of lamps, which comprise of a base with stem, a light-fitting, a bulb, and an Industrial Additive Manufactured lampshade that features a textual message.

BigCo identified that customer awareness of the issues involved in the design of customized products was limited in terms of several important aspects. It was observed that many potential customers were unfamiliar with 3D design tools, and that the current complexity of these meant that for many customers, the ability to create their own innovative designs that could be manufactured using Industrial Additive Manufacturing machines was significantly constrained by their technical abilities.

These limitations also extended to the customer's awareness of general product development issues. For example, it was recognized that customers would not typically be aware of how their design would best dissipate light, and safety issues regarding the required distance between their design and the heat-generating light bulb.

Whilst the company provides support to a range of customers to support their design of products this labour represents a cost to the company, which if applied to the lamp product could make it uncompetitive. Additionally, it was noted that for many customers, simpler customizations were adequate, as they did not require anything more complex than a simple personalization of their product, and nor did they want to interact with the company in the achievement of a design.

5.6.2 Design

BigCo offer two different styles of lamp which are then customized by the customer to meet their requirements. Although the components of base, stem, light fitting, and light bulb are standard to all lamps, it is possible to change several aspects of the lampshade. Design is elicited via BigCo's website, which allows customers to customize their own lampshade in several ways. It is possible to choose from three different surface finishes, and to embed a short piece of text into the design of the lamp, with a choice of three typefaces.

By constraining the overall shape of the design, and reducing the customization to configuration options and text, the ability is offered for customers to quickly and easily to create their own unique design directly on the website, without the need for interaction with 3D design tools.

One notable implication of this approach to design is the ability for automatic conversion from the web-based design representation into a production ready STL file, without the need for manual verification of the design. Since both of the lamp styles are already verified as production-ready, and their surface finishes pre-tested, it is only the text that changes the overall geometry of the product. This customization has no implications for the verification of the design file, leading to quicker and simpler production of verified designs for production.

5.6.3 Pre-processing

This approach to configurator-based design also provided opportunities to lessen the activities normally undertaken in pre-processing for custom designs. Many of the decisions involved in the pre-processing stage concerning accuracy, build orientation, and machine parameters are already well-defined for the standard product, and the nature of the customization does not affect these.

In preparation for manufacture, the customer order is entered into BigCo's computerised planning system alongside all other production orders. A resource planner allocates the work to a specific Laser Sintering build, manually configuring its location within the build chamber based on established conventions.

In terms of production planning, the customized nature of the lampshade requires that it is produced in response to an individual customer order (MTO), rather than as a stock based item (MTS). If capacity is constrained, this can have implications for the prioritization of work overall within the system and therefore production planners prioritize work accordingly.

5.6.4 Manufacturing

In the Industrial Additive Manufacturing machine, there is no difference in the way the custom lampshade is processed relative to a standardized version. The nature of the customization makes no difference to the way in which the machine builds the parts, nor to the costs incurred in its production.

Custom lampshades are produced using a Laser Sintering machine, which is manually loaded by an operator with virgin and recycled materials. In normal circumstances, these custom lamps will be fabricated as part of a larger build in order to fully utilize the build capacity of the machine.

Production is performed on general purpose machines, and lamps will be produced in a simultaneous build, often with other types of component requiring the same material configuration and build parameters. Once the machine begins operation, manufacturing is unattended, with the build time based on the individual machine, its configuration, and the size of the build being produced.

5.6.5 Post-processing

Parts created in the Laser Sintering process need several post-processing activities to be undertaken once the manufacturing activity and build cooling are complete.

With the assistance of mechanical aids, a technician removes the build from the machine and empties it onto a breakout table. The technician manually removes all parts from the build, and in doing so carefully identifies potential powder that may be recycled for future use. Material control policies in the organization promote traceability and quality, and so material recycling is performed particularly carefully to ensure conformance with these internal requirements.

To remove excess powder lampshades are gently cleaned using handtools or compressed air, and the quality of the part is confirmed. As the overall shape of the product will be consistent with all other customized lamps of this type, technicians are familiar with the expected shape that they will be processing, offering potential benefits for standardization and repeatability of operations.

5.7 Identifying potential strategies to satisfy demand

The qualitative case studies presented in the preceding sections have demonstrated the way in which the three different Industrial Additive Manufacturing Systems satisfy different demand types. All of these companies are producing parts that have unique requirements, either as a result of a variety of new products (Case 2) or in terms of customization of an existing one (Cases 1 and 9). These observations support the general claims in the literature (Table 2.11) that Additive Manufacturing technologies support the ability to effectively produce customized products as a result of their geometric processing capabilities.

Based on the capabilities of the individual machine, Tuck et al. (2008) proposed the hypothetical position that Rapid Manufacturing could support high variety manufacture at different production volumes, facilitated by the elimination of labour from processes as a result of tooling and automation. In this section this proposition is explored in an empirical observation of how Industrial Additive Manufacturing Systems may be configured in practice to accommodate such demand.

5.7.1 A product-process evaluation for Industrial Additive Manufacturing Systems

Although not acknowledged in their paper, Tuck et al. (2008) effectively propose a version of the Hayes and Wheelwright (1979) product-process matrix, but for which the same process type is able to achieve high variety, but without any penalty at different production volumes. Such a system would enjoy high process flexibility, but without any holding cost of that capability.

Hayes and Wheelwright characterise demand through qualitative “low” and “high” rankings for each axis of the product process matrix. Whilst this approach is sufficiently generic to promote transferability to different industries, it lacks the necessary specificity to facilitate empirical assessment. In the current study, increased focus in terms of industries and manufacturing technologies enables the researcher to be more explicit in defining these attributes:

Volume is considered in terms of the annual demand placed on the system as informed by the focal manufacturers. It concerns the total number of units of a product that are produced (or expected to be produced) on an annual basis.

Variety is considered in terms of the degree of variety or customization in the focal case product.

- High customized products are mainly customized to meet an individual customer requirement. This customization is usually important to the customer.
- Medium customized products have some degree of customization, but also a number of standardized attributes.
- Low customized products are either standardized, or have such little customization that it does not constitute a major factor in the customer’s decision to purchase.

The twelve case studies explored in this study are presented in the context of the product-process matrix for an Industrial Additive Manufacturing System as shown in Figure 5.9 and Table 5.4. On the vertical axis, each case has been evaluated for its variety/customization categorization in terms of a high/medium/low scale. Classifying degrees of variety and customization is a complex activity outside the scope of the current study. Each case is therefore plotted in the centre of its categorization, and within the same category no attempt is made to indicate whether one case is more or less customized that others in the category. On the horizontal axis, each case has been evaluated in terms of its annualized volume and plotted on a logarithmic-like scale. This scale was developed through analysis of the overall demand placed on the manufacturing system for each of the three companies (as explored in Section 5.3). Space constraints require cases 2, 5, 6, and 12 to overlap; each has a volume of 1.

Using the descriptors of Hayes and Wheelwright, the original four process types (job, batch, line, continuous) are mapped to the matrix based on the characteristics given in Table 2.5.

- Job based processes exist for 1-off and low volume production, using general machines and standard configurations. Setups are frequent, run lengths are short, and overall process speeds tend to be quite slow. Job based processes typically have a large requirement for labour, which is often skilled. This is particularly evident for cases where much work is needed in the design and pre-processing stages, where decisions are needed to understand the best way to produce parts.
- Batch based processes produce higher volumes than job counterparts, but still employ general machines and fairly standard configurations. The nature of batch processing has fewer specific setups than job processing, and run lengths are longer, with some efforts to reduce labour requirements (through standardization of activities or substitution through software tools).
- Line based processes are used at high volumes, and have dedicated machines that are setup especially for long runs of the focal product type. Setups are infrequent and run lengths long, with efforts made to reduce labour requirements. Flow is rigid and well-established, and the speed of production is faster as a result of specialisation.
- Continuous processes are included in this matrix, but were not demonstrated in the focal cases. Such approaches are intended for very high production volume, with almost no setups and no relative inflexibility in terms of production volume.

Project-based processes were not included in the original definition by Hayes and Wheelwright (1979), and are thus subsumed within job processes in this study.

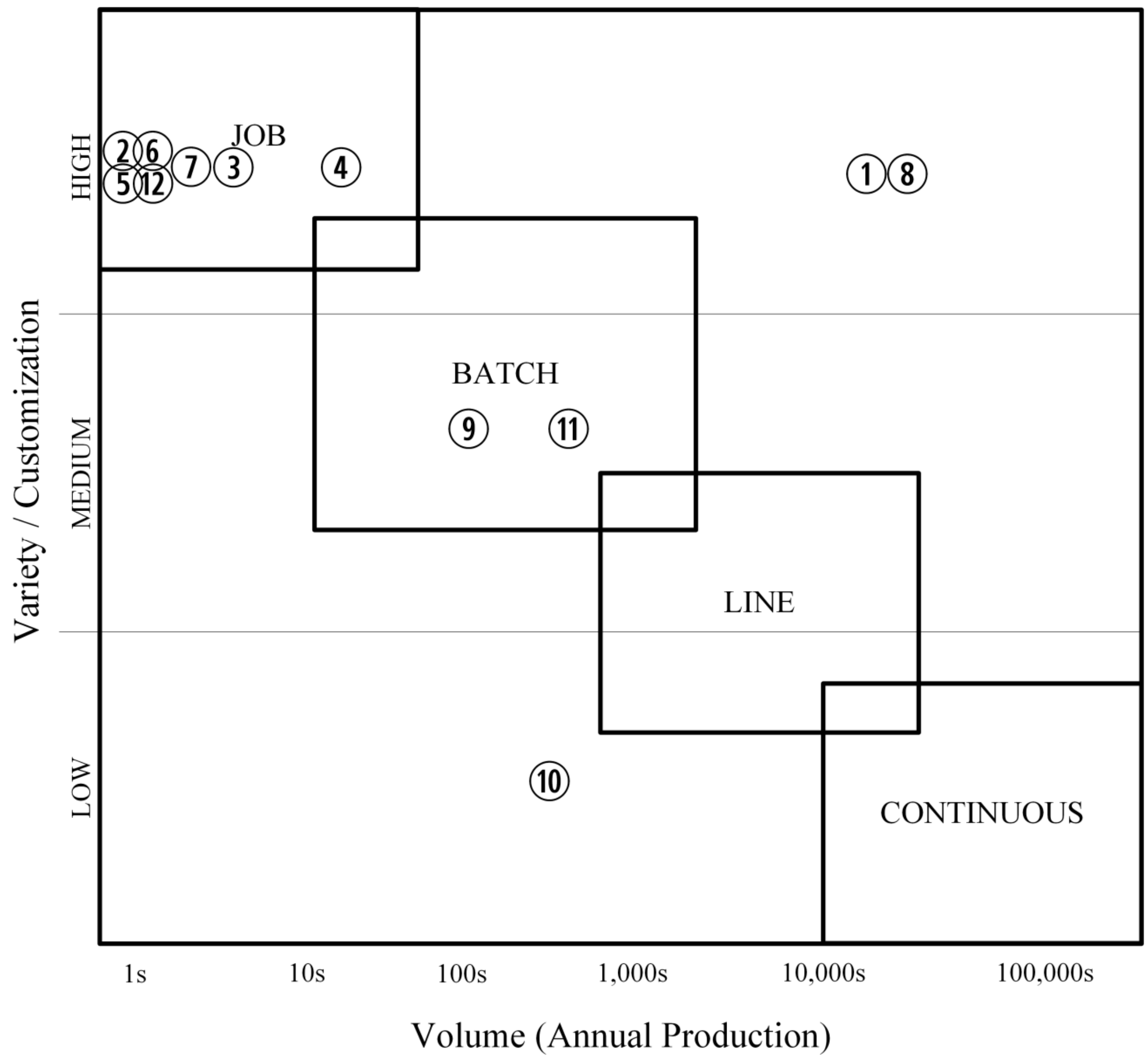


Figure 5.9: Volume-variety assessment for twelve case studies
Source: The Author

Case No.	Additive Mfr	Case Name	Annual Volume	Variety
1	HearingCo	Hearing Aid	10,000’s	High (Customized)
2	LittleCo	Model Ship	1	High (New Product)
3	LittleCo	Archaeological Models	4	High (New Product)
4	LittleCo	Architectural Models	20	High (New Product)
5	LittleCo	Exhaust Tool	1	High (New Product)
6	LittleCo	LittleCo Fixtures	1	High (New Product)
7	LittleCo	Sensor Tool	3	High (New Product)
8	BigCo	Surgical Guides	10,000’s	High (Customized)
9	BigCo	Custom Lamps	100’s	Medium (Customization)
10	BigCo	Standard Lamps	100’s – 1000	Low (Standardized)
11	BigCo	Modular Fixture System	100’s – 1000	Medium (Customization)
12	BigCo	Furniture	1	High (New Product)

Table 5.4: Volume and variety for twelve case studies
Source: The Author

5.7.2 Identified alignment to Hayes and Wheelwright's model

Figure 5.9 demonstrates that in commercial practice, Industrial Additive Manufacturing Systems are employed to meet a range of volume and variety requirements, and for nine of the twelve cases a good alignment to the traditional 'diagonal' exists.

Job-based processes

Seven of the case studies demonstrated a strong alignment to the low-volume, high-customization, job-based manufacturing system defined by Hayes and Wheelwright (1984) and presented in Table 2.5. In terms of equipment, general-purpose resources are used to produce products in short runs with frequent setups. Production is slow, discontinuous, with multi-week lead-times required to fulfil demand as a result of much effort demonstrated in design, pre-processing, and post-processing (as previously evidenced in Sections 4.4 - 4.6) in the production of these new products. These cases demonstrate a close linkage between customer and manufacturer in the development of designs, and in the production of the required products. Akin to Hayes and Wheelwright, labour in the design, pre-processing, and post-processing activities is typically skilled (see Sections 4.4 - 4.6), though is not required for attended operation of the Additive Manufacturing machine.

Batch-based processes

Two cases demonstrated characteristics typical of batch-like manufacture, whereby production of parts utilized general purpose equipment in the production of multiple similar (although often not identical) parts. These products have a lower degree of customization than those produced in job-based processes, requiring less effort in terms of human labour in their preparation and manufacturing. Some scale economies can be observed, particularly in the relatively labour intensive post-processing activities, and as a result of these parts being produced in their hundreds, BigCo had developed software solutions to reduce labour requirements in the design and pre-processing stages of production, and post-processing techniques were refined based on experience in production. Furthermore, BigCo demonstrated that batch production could also be aligned to material management in order to improve overall production quality:

> "that is one primary reason for going to batch production – that we have control, so we are basically creating internal batches for which we know the origin of each batch and the virgin powder coming in, so we know the material."
>
> *Operations Director, BigCo*

5.7.3 Identified disjunction from Hayes and Wheelwright's model

Whilst Figure 5.9 demonstrated most cases enjoying a good alignment of demand to job and batch process types for low volume products of high and medium variety/customization, three cases do not conform to such expectations and are explored in this section.

Line-based processes for high customization

Cases 1 and 8 are both evident as deviating from the normal alignment with the product-process matrix. Both are examples of medical applications, for which the nature of customization is very high, with each item made specifically to fit the individual patient requirement. However, both examples also represent the largest production volumes faced by the manufacturing system, with tens of thousands of each product produced annually.

In their production, Cases 1 and 8 demonstrated many of the attributes Hayes and Wheelwright (1984) associated with line-based production. The production facilities were physically large, using specialized technologies with a rigid flow of activities through the system. The repeatability of production allowed both companies to optimize their processes in terms of performance and cost, with machines tuned to promote optimal performance and repeatability. Where bottlenecks existed in the flow of parts these were known to the organizations. By comparison to the other cases, labour content in the production of these processes was reduced as a result of investment in software configurators for design, and defined approaches to pre-processing and machine setup. Whilst labour is not eliminated from the manufacturing system (as was proposed by Tuck et al. 2008), it is reduced, and the skillset required is focused.

In terms of the Additive Manufacturing machines, the geometric customizations required in the production of the individual products have no notable influence on production equipment, a capability that has been termed 'geometry for free' (Hague et al. 2003a). Combined with the use of software tools in design and pre-processing, the effects of geometric customization requirements on the manufacturing system are lessened. Both HearingCo and BigCo set up dedicated line-based production facilities in response to these high volume products:

> "This is a change compared to a couple of years ago, and what we see is that mostly if you get an application that produces volumes then you will setup dedicated machines and production lines and that of course changes the whole game, moving into a more industrial, conventional approach. You organize it, but are also getting quality from the machines – repeatability, things like that, so getting a better grip on technology."
>
> *Technical Director, BigCo 2013*

Batch-based process for low customization

In Case 10 the production of standardized lamps is shown to deviate from the natural diagonal of matrix. These parts have no customization options, and having a lower volume than was deemed worthwhile investing in line-based system configurations, production of these parts was demonstrated in BigCo to be performed in batch processes, sometimes in the same batch as the customized lamps of Case 9.

The absence of a need for customization, but with a production volume requirement less than justifiable for a line positions this case off-diagonal. Traditionally, this would be suboptimal with the process having excess flexibility and therefore an associated cost (Hayes and Wheelwright 1979). For this case, the lack of customization makes no difference to the production machines with the manufacture and post-processing of the lampshade taking the same time as a comparable custom item. The main distinction identified is in design (which is eliminated due to the repetitiveness of production), and pre-processing (which is simplified as a result of repetition in production).

5.8 Discussion

The purpose of this chapter is to explore **Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?** This chapter has therefore tackled the identified research gap that has developed as Industrial Additive Manufacturing has moved from one-off production of prototypes and custom parts through to higher volume manufacturing. To answer the research question this chapter has provided a detailed exploration the nature of demand experienced, before focusing on the way in which different demand requirements are satisfied in contemporary commercial practice through Industrial Additive Manufacturing Systems. This chapter therefore evidences the manufacturing system in operation, and by exploring alignment and disjunction to the well-established work of Hayes and Wheelwright (1979), demonstrates characteristics that differentiate it from ‘conventional’ manufacturing systems which is an important contribution of this part of the research.

The first part of this chapter has focused on understanding the nature of demand, and the empirical data presented in this study has shown that Additive Manufacturing companies are subject to many challenges familiar for ‘conventional’ manufacturing. Evidence of these has been achieved through interviews with multiple managerial sources in Section 5.3, providing a clear demonstration of the requirements being placed on the manufacturers. Such an understanding is important since it exemplifies the requirements for which the Industrial Additive Manufacturing System needs to respond. It is shown that a wide range of variety requirements is experienced, often producing products that are often either highly customized or bespoke for individual applications. By extension, the need to achieve responsiveness in the satisfaction of such order has also been shown, and these attributes are consistent with perspectives held in the literature of the suitability of the technologies for customized applications (Section 2.9). However, two further characteristics that are seldom observed in the Additive Manufacturing literature are identified through this research: the application of the technologies for higher volume production, and the nature of uncertainty that exists for demand overall. Received wisdom in operations management has frequently identified variety as introducing many challenges for manufacturing (Table 2.4), making this a particularly interesting area of research that makes an important contribution in the understanding of how Industrial Additive Manufacturing Systems are able to address challenges that are difficult in conventional approaches.

Having identified the nature of demand placed upon the manufacturing system, Section 5.4 has shown how it is satisfied in practice through Industrial Additive Manufacturing Systems, with three case studies being reported in detail. Consistent with the literature it is shown that Industrial Additive Manufacturing Systems are able to produce a wide range of different products, with much capability in terms of geometric customization. However, this section also evidences a multitude of activities that are undertaken both pre- and post-fabrication, and it is particularly notable that a range of different activities are undertaken for different products, particularly in terms of design and preparatory activities. This makes an important contribution to the research as it documents in detail the activities and resources of the manufacturing system, rather than focusing solely on the individual machines.

This detailed understanding of the nature of demand and the way in which it is satisfied makes an important precursor to the exploration of how Industrial Additive Manufacturing Systems can be considered relative to conventional approaches. As identified in Section 2.9, two papers (Helkiö and Tenhiälä 2013; Tuck et al. 2008) have offered conceptual propositions that Additive Manufacturing technologies could effectively overcome constraints inherent in conventional manufacturing. The contribution of Section 5.7 has been to provide an evaluation of these propositions through case study research, which has been visualized in Figure 5.9. The research has been demonstrated that that in commercial practice Industrial Additive Manufacturing Systems are employed in production both on-and-off the 'optimal' diagonal. Seven cases are shown to align well to the traditional job-based process, with low volume production requiring much labour effort in the design and configuration of the work. Similarly, two cases with more volume, more repeatability, and less effort needed in design and configuration demonstrate alignment to a traditional batch-based process. In total these nine cases demonstrate the Industrial Additive Manufacturing System employed in a similar manner to 'conventional' manufacturing systems.

However, that three cases that do not conform to the accepted ‘diagonal’ is a very significant finding made in this chapter, and understanding why this is the case represents an important contribution of the work that has been shown in Section 5.7. This section has demonstrated that geometric customization of parts (when combined with appropriate design elicitation techniques) has very limited impact on the manufacturing system, thereby allowing customized parts to be produced in the same manner as their standardized equivalents. This is best evidenced in the comparison between Case 9 (Customized Lamp) and Case 10 (Standardized Lamp), both of which are produced in batch processes. Previously, Hague et al. (2003b) has identified that customized geometry is achievable within the machines “for free”; this study shows that the impact of geometric customization on the rest of the system can also be achieved at minimal cost providing the work involved in design elicitation and preparation can be appropriately managed (e.g. through configurators). The implications of this capability also extend into the application of Industrial Additive Manufacturing Systems in high volume and high customization applications. Cases 1 (ITE Hearing Aid) and 8 (Surgical Guides) both show that where expected volumes are sufficient, investment in design elicitation and pre-processing mechanisms can readily support the use of Industrial Additive Manufacturing Systems to achieve customized parts are high volume without the penalties observed in conventional approaches to the production of these customized parts. The managerial quotes, together with commercial success of these products highlight the importance of these findings, and also align to the suggestions of previous authors. Common to these cases is a reduction in the impact of customization on the manufacturing system using software tools promoting the reduced specificity posited by Helkiö and Tenhiälä (2013), together with a focusing of labour reducing its overall contribution to manufacturing as suggested by Tuck et al. (2008).

The research presented in this chapter therefore makes an important contribution to knowledge concerning the nature of demand and the way it is satisfied by Industrial Additive Manufacturing Systems. It provides a detailed understanding of the nature of demand for contemporary practice, highlighting not only the requirements for responsiveness and customization, but also the range of different production volumes and uncertainties within which the system operates. In addition, it evaluates the manufacturing system with respect to the product-process matrix, through which the ability to effectively deviate from conventional norms has been shown.

5.9 Chapter summary

This chapter has tackled the second research question by exploring the nature of demand experienced for three Industrial Additive Manufacturing companies, and shown how it is fulfilled through three in-depth case studies. The applicability of the concept of an Industrial Additive

Manufacturing System has been demonstrated through the qualitative case studies, together with the supporting analysis and empirical assessment of alignment to established manufacturing theory.

Chapter 6 The Flexibility of Industrial Additive Manufacturing Systems

Chapter Aims

1. Distinguish between internal and external perspectives of flexibility for Industrial Additive Manufacturing Systems.
2. Identify the relevant flexibility types and measures for Industrial Additive Manufacturing Systems.
3. Examine the sources and inhibitors of flexibility for Industrial Additive Manufacturing Systems.

6.1 Chapter overview

The purpose of this chapter is to examine the nature of flexibility that is achieved in Industrial Additive Manufacturing Systems, which as shown in Figure 6.1 follows the work of previous chapters that have defined and demonstrated the application of the system concept. These chapters have noted the requirement for flexibility, and in the current chapter the following research question is tackled: **Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?**

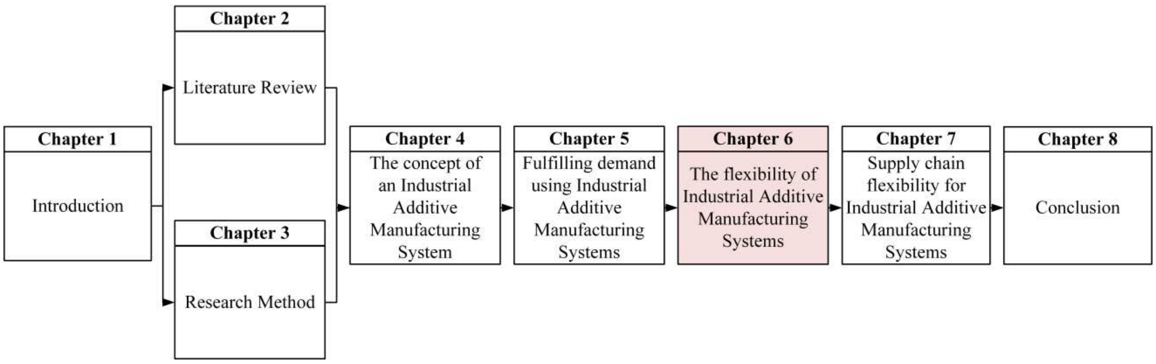


Figure 6.1: Thesis structure
Source: The Author

Section 2.10 evidenced that the complex and multifarious concept of flexibility has received limited research attention in the context of Additive Manufacturing. It was identified that the nature of flexibility for Additive Manufacturing is often subject to a somewhat liberal interpretation in many publications, with little specificity concerning the meaning of 'flexibility' in terms of manufacturing, despite its long establishment as a competitive objective for manufacturing organizations (e.g. Leong et al. 1990). In particular, uncertainty exists in understanding the types of flexibility that are required, and the extent to which these are enabled as a result of both Industrial Additive Manufacturing machines and the other resources of the system. The research topic tackled in this question therefore brings knowledge of flexibility from the general operations management literature to the context of Industrial Additive Manufacturing, in satisfaction of Research Question 3.

6.2 Method overview

Section 2.5 explained the complex nature of flexibility, for which there are a multitude of interpretations. Recognizing such confusion, Oke (2005) identified a need to separate flexibility assessments in terms of:

1. How flexibility is perceived external to the manufacturing system.
2. The tools and techniques that are able to deliver flexibility.
3. How flexibility is characterized at the internal manufacturing system level.

This guidance is followed in structuring this chapter as shown in Figure 6.2, supported by an overall summary evaluation of internal and external perspectives.

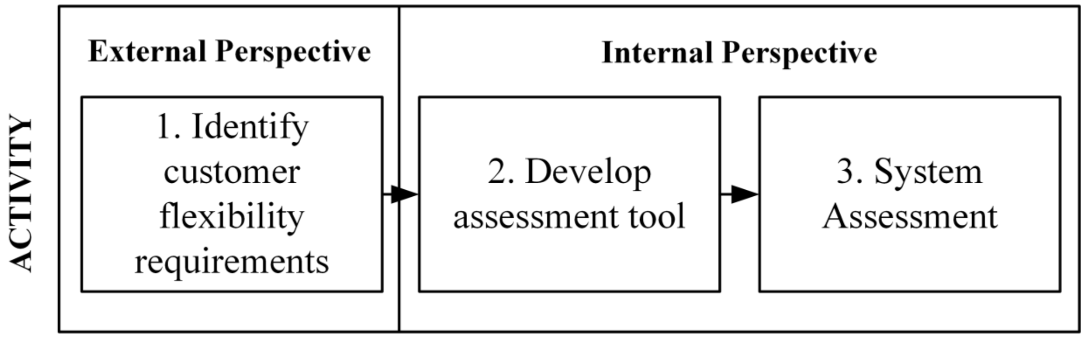


Figure 6.2: Activities undertaken in this chapter
Source: The Author

In Section 6.3, consideration is given to the external nature of flexibility through an investigation of customer requirements. Through interviews conducted with four of the case study customers an understanding is developed of the different flexibility types that are important to them. This section therefore presents a demand-side appraisal of flexibilities requested of the manufacturing system.

It is already established that the achievement of flexibility in manufacturing systems arises from the contributions of the individual component resources (Slack 1989), and in Section 6.4 a typology and assessment tool is developed using published literature with an operations management focus. In Section 6.5 this tool is used with the twelve case studies to evaluate internal flexibilities arising from the resources of the Industrial Additive Manufacturing System, with a supporting narrative explaining sources and inhibitors of flexibility.

6.3 The external perspective of flexibility in Industrial Additive Manufacturing Systems

Notwithstanding the established literature on the nature of customer involvement in the fulfilment process dictating the nature of customization achieved in a product (Duray 2002; Lampel and Mintzberg 1996; Piller et al. 2005; Reichwald and Piller 2003), in general customer awareness of manufacturing processes can be very limited. Customers may evaluate the outputs of the manufacturing process (e.g. the product quality), but there is less awareness of the activities that actually take place in the achievement of the product. These customers may be deemed *product focused*, and are concerned with the product that they receive, rather than the mechanisms by which it is produced. Conversely, some customers may be considered to adopt a more *process focused* perspective with regards to their product. These customers place emphasis on the way their product is produced, and assign value to the activities that support its achievement. This is perhaps best evidenced by customers who source products with a focus on ethical or sustainable processes (e.g. understanding the difference between battery and caged hens in the process of egg production), or for those who assign value to the manufacturing process itself (e.g. craft production of jewellery).

As demonstrated in Chapter 5, the commercial nature of the Industrial Additive Manufacturing companies explored within this research requires that they manufacture products in satisfaction of actual customer demand. This was evidenced in the manufacturer interviews, where discussions of their capabilities were frequently interspersed with reference to customers served in terms of meeting various competitive objectives (e.g. cost or delivery requirements), and the processes by which this was achieved. All three Industrial Additive Manufacturing companies involved in this research volunteered to show their production facilities, and were keen to demonstrate the mechanisms by which they satisfied demand.

By contrast, the interviewed customers were mainly focused on the product, rather than the process by which it was achieved. Whilst three of the four customers had visited the Industrial Additive Manufacturer to discuss and view the Industrial Additive Manufacturing process, their principal motivation was to be able to exploit the technology to realize their chosen product, and as a result they generally displayed a limited awareness of the internal processes by which a product is fabricated in an Industrial Additive Manufacturing facility. When questioned, all customer respondents had a basic understanding of the layer-wise production process, but were unfamiliar with the other activities arising in the Industrial Additive Manufacturing System which results in the manufacture of their products. For example:

> "We had this digital data, and we thought "What are our options?" We knew about the 3D printing – the Z-Corp machines, but it's brittle… we were aware of Rapid Prototyping, but we didn't know anything more than that until we contacted LittleCo. And it was at that point we got into discussions about the advantages of materials, what the advantages are of polyamide versus other technologies..."
>
> *Project Manager, Model Ship (Case 2)*

This lack of expertise regarding the capabilities of Additive Manufacturing technologies was shown to be problematic for both BigCo and LittleCo, particularly with regards to expectations in design.

> "Researcher: Are your feelings that as you move into the less experienced designers (like me), our expectations are going to be just as high (if not higher) than the people who actually appreciate the processes? Do you think that could be a problem?
>
> Respondent: It's not a problem - it's a hard fact.
>
> Researcher: It's a challenge?
>
> Respondent: It is a challenge"
>
> *Technical Director, BigCo*

Despite customers lacking awareness of the operational challenges facing manufacturers, they may still require them to achieve 'flexibility' in satisfaction of demand. In the context of flexibility the perspective of the 'outsider looking in' established here has been formally characterised as "external flexibility" (Naim et al. 2006; Oke 2005), through which a perception of flexibility is achieved by the customer. The importance of flexibility from the customer's perspective was emphasized most succinctly by one customer:

> "flexibility and service are the two things that I look for [in selecting a supplier]."
>
> *Engineer, Sensor Tool (Case 7)*

As shown in Table 6.1 there are four established external flexibility types: volume, mix, product, and delivery (Naim et al. 2006); previously these have been identified as the fundamental "first order" flexibility types (Suarez et al. 1996), and these are used in the next section to consider customer perspectives on flexibility.

External Type	Definition
Product	The range of, and ability to accommodate the production of new products
Mix	The range and ability to change the products currently being produced
Volume	The range of, and ability to accommodate change in production output
Delivery	The range of and ability to change delivery dates

Table 6.1: The four external flexibility types
Source: Naim et al. (2006)

For four of the twelve case studies it was possible to interview the customers to understand their requirements for flexibility, and to relate these to the external flexibility types shown in Table 6.1. When considering the external perspective, it is important to recognize that the customer is not necessarily the end consumer; for each of the case examples presented in this chapter the respondent customer is a professional working on behalf of the final consumer, normally in a design or configuration capacity. The findings of these investigations are summarized in Table 6.2, and discussed in greater depth through Sections 6.3.1 – 6.3.5.

6.3.1 Product Flexibility

Product flexibility may refer to the customization of an existing design, or the development of an entirely new product. New products require new designs, whereas for customization a standard product design already exists, and within bounding constraints this may be modified to meet the customized requirement. Existing literature has frequently considered the capability of Additive Manufacturing in terms of its ability to achieve a range of possible geometries (e.g. Gu et al. 2009; Schaaf 2000) or for new parts (Rosen 2004).

Table 6.2 highlights the focus of customers concerning the manufacturing firm's ability to offer product flexibility either through the development of new products, or in the customization of existing offerings. These may be identified according to the three FFF manufacturing measures:

1. Form: the geometry, size, mass, colour, and other visual characteristics which define the physical characteristics of the product.
2. Fit: the way in which the product either assembles or interacts with other products.
3. Function: the ability of the product to perform the actions for which it is intended.

			External Flexibility Requirement				
Case No.	Case Name	Customer	Product		Mix	Volume	Delivery
			New	Custom			
1	Hearing Aid	Audiologist	-	Form Function	Range	Range	Expedite
2	Model Ship	Archaeologist	Form Fit Function	-	-	-	Expedite Delay
4	Architectural Models	Architect	Form	-	-	-	Expedite
7	Sensor Tool	Engineer	Form Fit Function	-	-	-	Expedite

Table 6.2: Customer requirements for flexibility types
Source: The Author

Customized Products

For Case 1, the ability to perform customizations for two of the three FFF measures represents an important requirement for the customer:

1. Form: Change the geometry of the shell to fit the individual patient ear and to include accessibility options such as removal latches and colour matching to approximate customer skin-tone.
2. Function: Change the functional capability of the device to meet the patient's individual hearing-loss profile in terms of conductive and sensorineural hearing loss. This is defined by the patient's audiogram, which serves as the basis for the configuration of the DSP within the device.

The specification of these requirements is made at the point of order and a configuration form may be found in Figure 5.3.

New products

These require the initiation of a wholly new design for fabrication, and as identified in Chapter 4, for manufacturers to undertake the associated planning for their production. As evidenced through literature in Section 2.10, the ability to offer flexibility in the fulfilment of a new product should be simplified as a result of the ability to fabricate directly from the 3D model. However, this can be an oversimplification, with two distinct capabilities required by customers:

1. Flexibility to prototype: The ability to explore and test the feasibility of new product designs before commitment to manufacture. This may consist of virtual, physical, and/or functional

prototyping activities. This phase of product fulfilment will typically necessitate dialogue between manufacturer and customer to discuss the results of prototyping, and from this to agree the parameters for production of parts. In the prototyping phases it was identified that there may be several iterations of design, planning, and physical realization. As shown in Table 6.3 the nature of these prototypes is case-specific, with customers having different priorities in terms of form, fit, and function.

2. Flexibility to manufacture: The ability to produce a new product demanded by the customer using Additive Manufacturing processes, through the direct manufacturing capabilities espoused in literature. The new product may be standardized in nature, or may form the basis for future customized production.

Case No	**Case**	**Prototyping Requirement**	**Verification Requirement**		
			Form	**Fit**	**Function**
2	Model Ship	Sample Holes	Hole Circularity	Screw suitability	
		Sample Timbers	Surface Resolution Geometric Accuracy of features CAD Scaling configuration	Part Hollowing Part thickness	Functional suitability
4	Architectural Models	100 x 100mm test cube	CAD Scaling configuration		Material suitability
7	Sensor Tool	Sample part	Geometric Accuracy of features	Potential for assembly	Functional suitability

Table 6.3: Attributes verified through physical prototyping
Source: The Author

6.3.2 Mix Flexibility

Mix flexibility is the ability of the manufacturer to change between different products within a product range (Bateman 1999). From the external customer perspective, it is therefore inherent in the definition that to afford mix flexibility, the customer must be aware of the other products within the defined range that is being offered by the manufacturer (i.e. the product range is *known* to the customer). The absence of examples of mix flexibility in these case examples may be rationalised by an absence of a defined product range by LittleCo; customers were aware that the company made a variety of products, but there is no ‘catalogue range’ to choose from.

A customer requirement for manufacturers to change between different product mixes was only evidenced for Case 1, for which the company has a standard range of hearing aids. In selecting a suitable product for the patient the audiologist chooses from this range of products; irrespective of the manufacturing process the expectation exists that the manufacturer will be able to demonstrate flexibility to shift between product ranges to fulfil the individual order.

6.3.3 Volume flexibility

One of the advantages of Additive Manufacturing is its ability to fabricate at very low volumes, and particularly the potential to make single unit manufacture a feasible proposition (Hopkinson et al. 2006b). The ability to feasibly produce low volumes from short production runs has been identified as advantageous by authors including Chhabra and Singh (2012) and Ford et al. (2014). From an external perspective, volume flexibility refers to the perceived ability of the manufacturer to effectively and economically respond to varying production volumes in satisfaction of the customer requirement, and should therefore be considered in terms of the ability to increase or decrease production to meet the external demand requirement.

For Case 1 an ongoing relationship exists between the audiologist and manufacturer, with orders normally placed each workday. Annual demand at the manufacturer from the audiologist network is tens of thousands of units, and whilst on a monthly basis demand is stable (without seasonality or other temporal influences), on a daily basis the interviewed audiologist identified variation of average order intake is commonplace:

- Although ITE hearing aids are typically demanded on an individual basis, the potential exists that patients will require multiple identical hearing aids (typically to be retained as spares), and so audiologists may order several identical units.
- Potential for damage or loss to devices mean the need to make repeat orders for replacement devices.
- Demand is driven by the nature of the patients, and on any given day demand for ITE devices is identified to fluctuate considerably: the audiologists consulted identified the range of daily demand from their individual shop to be between 0 – 15 devices, with little ability to accurately forecast requirements.

From the perspective of the audiologist, the ability of the manufacturer to offer flexibility in the volume produced was recognized to be relevant in accommodating these variations of demand.

Cases 2, 4, and 7 demonstrated a requirement for low volume production, but not for flexibility in terms of volume. The relative temporariness of these relationships with the manufacturer simplifies volume flexibility from the customer perspective, as in terms of range they simply have a single order which is to be fulfilled, within a negotiated response time. As flexibility refers to the propensity to change, from the external customer perspective these case examples with fixed volume requirements have no requirement for volume flexibility.

6.3.4 Delivery flexibility

Delivery flexibility is the ability to accelerate the overall fulfilment of a customer order beyond the original expectation, or to put it back (Gupta and Goyal 1989). In terms of existing literature, this can be linked to the flexibility of Industrial Additive Manufacturing for 'on-demand' production, rapidly producing a part as the customer need arises (Reinke 2007).

Each of the cases demonstrated a requirement for Industrial Additive Manufacturers to be able to expedite their production, typically as a result of unexpected issues faced by the customer. In Case 1 the need to replace lost hearing aids was identified by the audiologist as being a likely eventuality for unexpected and urgent demand. Stressing the implications for patient quality of life arising from the product, the audiologist highlighted the ability to expedite particular orders as an essential requirement of the manufacturer.

Delivery flexibility may also be desired by the customer in order to better align with the performance of their own operations, whereby fulfilment is delayed until the product can be utilized. For Case 2, particular emphasis was placed by the customer on the requirement for flexibility in delivery, with the overall order of model timbers and other components broken into ten smaller orders for delivery over eighteen months, rather than as a single consignment that LittleCo advised could have been satisfied within two weeks of order receipt. In illustration of this, Figure 6.3 provides the production schedule, together with an illustration of the contents of one of the individual builds.

This desire for flexibility in delivery was motivated by the customer on two principal grounds:

1. Assessment. As this was an experimental application of the technologies for which both the manufacturer and customer were largely unfamiliar it was deemed desirable to test and evaluate the initial manufacturer parts before committing to the full production volume.

2. Alignment. Relative to the manufacturer's fabrication speed, the development of individual design models (by reverse engineering and CAD modelling) was a very slow process taking two years to complete. Production of ten smaller batches of parts enabled improvement in flow between design, manufacture, and assembly and eliminated component inventory stocking. The customer identified that space within their

warehouse was not the issue, and that the concern was more likely damage or degradation arising through storage.

Batch No.	Mfr Date	No. Parts
01	2009-06-23	027
02	2009-08-13	124
03	2009-11-02	103
04	2010-02-09	084
05	2010-02-23	051
06	2010-04-14	080
07	2010-03-19	063
08	2010-06-07	089
09	2010-08-15	067
10	2010-11-13	036

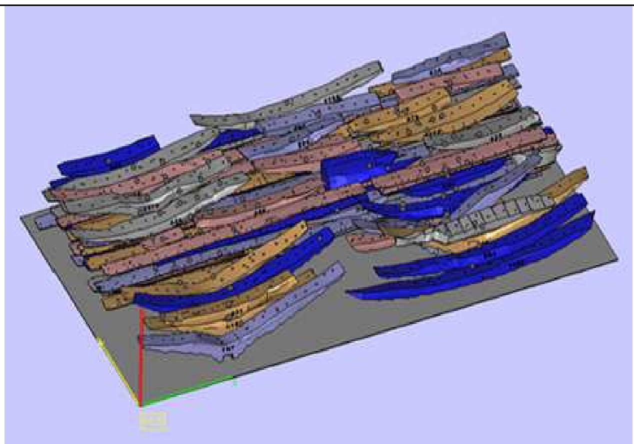


Figure 6.3: Case 2 production records (left) and batch 04 (right)
Source: LittleCo

6.3.5 Summary of external flexibilities

This section has demonstrated the perspectives of four different customers in terms of flexibility, highlighting their requirements and motivations for its achievement. All customers demonstrated a requirement for product flexibility, whether in the provision of new or customized products. As identified in Section 2.10 the capability to produce a wide range of parts with a single machine is often identified as a flexibility characteristic of Additive Manufacturing, and this study evidences this capability to be desirable for the focal customers.

Other flexibility requirements have less evidence from these cases. Delivery flexibility is identified as a desirable characteristic typically for expediting, but also demonstrated as a means of delaying fulfilment in synchronization of the customer operations. One-off project-based demand is shown to have little requirement for mix or volume flexibility; the customer does not require the manufacturer to change between products or output levels, as they only require satisfaction of a single order at a given volume.

6.4 A typology and assessment mechanism for internal flexibilities in Industrial Additive Manufacturing Systems

Internal flexibility types describe the behaviour of the manufacturing system as experienced by the operations that are exploiting it. This distinction therefore separates the lower-order flexibility types experienced by those involved with the manufacturing processes internal to the organization, from the four more aggregated perspectives observed by customers (Naim et al. 2006; Oke 2005). Based on this delimitation of flexibility types, it is evident from Section 2.10 that the capabilities listed in the Additive Manufacturing literature have focused primarily on the external flexibility types for which the system is perceived capable, but without detailed exploration of the internal characteristics that afford these. The purpose of this section is to develop a means of assessing internal flexibilities for Industrial Additive Manufacturing Systems.

6.4.1 Typology development

As recognized in Section 2.5 hundreds of flexibility types have been proposed, and have been distilled in various reviews in the provision of typologies. Section 2.10 identified that no explicit typology exists for flexibility in the context of Industrial Additive Manufacturing, and therefore for this study it was necessary to identify an appropriate approach.

To achieve a manageable critique of Industrial Additive Manufacturing, the typology in Table 6.4 was developed based on extant literature that has identified the most fundamental flexibility types proposed in the literature (Suarez et al. 1996). Its development was motivated by three factors:

1. The identified flexibility types are well defined and understood in academic literature.
2. Empirical data collection with manufacturers and some customers highlighted their awareness of flexibility for other manufacturing processes, and so it was desirable to use similar terminology in this assessment.
3. Some alignment between existing Additive Manufacturing literature and these types is evident (as discussed within the appraisal text).

Several minor modifications to the original definitions are made in this work for clarity and applicability to Industrial Additive Manufacturing Systems, using unambiguous vocabulary to differentiate the various nuances between types. Most notably, to avoid confusion between Industrial Additive Manufacturing machines and other devices considered in this study, the term ‘equipment’ flexibility is used rather than ‘machine’. Within the typology each of the flexibility types is dimensional, for which established dimensions of range (the range of states a system may enter), and response (the cost in time or effort in changing between states) proposed by Slack (1987) are employed.

Flexibility Type	Definition	Definition Source
Equipment	The ability of the equipment to change between different operations.	Narasimhan and Das (1999)
Process	The ability to produce parts in the same manufacturing system in different ways.	Naim et al. (2006)
Operation	The ability to change the sequence in which production occurs.	Browne et al. (1984)
Capacity	The ability to increase or decrease production capacity.	Naim et al. (2006)
Routing	The ability to change the route taken by parts through the production process.	Browne et al. (1984)
Program	The ability for equipment to operate unattended for extended time periods.	Sethi and Sethi (1990)
Material Handling	The ability for materials to move effectively though the plant.	Sethi and Sethi (1990)

Table 6.4: A typology of Industrial Additive Manufacturing Systems flexibility
Source: The Author

6.4.3 Measures of flexibility

The objective of this chapter is to demonstrate the capabilities of an Industrial Additive Manufacturing System that support or inhibit flexibility, rather than to attempt to quantify these; this study explores the qualitative *how* rather than the quantitative *how much*. As already identified in the literature review, quantification of flexibility measures is notoriously difficult. As Beskese et al. (2004) observes it is both context and user specific, and this is true of Industrial Additive Manufacturing where contextual factors often yielded interview respondents to prefix their answers with “It depends...”. Primrose and Verter (1996) go as far as to suggest that measurement of flexibility is unnecessary, since it does not help provide any additional useful information to managers in their decision making.

In the ideal situation, for a system to be flexible it must be capable of moving between states with little penalty in terms of cost, time, or the degradation of output (Upton 1994). However, the characterisation of ‘little’ penalty is relative to the individual manufacturing environment – observations in this study highlighted what may be inconsequential in one situation may be intolerable in another. For example, LittleCo highlighted that an acceptable material changeover for a LS machine to be one working day; at BigCo a similar machine should be changed within half this time. This aligns with the observations of Holweg (2005) that motivations for flexibility can be industry or company specific. Flexibility is therefore a relative measure which must be considered in its assessment, and variations between perspectives on what constitutes an acceptably ‘little’ penalty was evident in all of the Industrial Additive Manufacturing factories observed, and with research informants at different levels of the organizations. The nature of the penalty must also be considered relative to the benefit of achieving flexibility. Flexibility is seldom the goal of an organisation: typically it is only a means to other ends (Slack 1987). A firm that easily achieves flexibility but to no benefit might reasonably be considered to be at a disadvantage to one that achieves great benefits, even if this incurs some cost. Firms may wish to achieve flexible capabilities in order to react to product variety, product customization, variability of demand, shorter life-cycles, or shorter delivery times (Brabazon and MacCarthy 2005). Therefore to understand the penalty, it is important to understand the context in which flexibility is desired and its intended purpose.

Acknowledging the potential futility of quantification of flexibility measures, this study employs a classification based on the penalty arising from change. To address this issue, the development of a flexibility framework for Industrial Additive Manufacturing is orientated around the response dimension of flexibility. Through this approach, each flexibility type is categorized in terms one of three different response penalty rankings:

1. Class 1 flexibility: offering a particular flexibility type that enjoys a high degree of range flexibility yet does not incur a penalty of response.
2. Class 2 flexibility: offering a high, or relatively high, range flexibility but with a small associated penalty in making this response.
3. Class 3 flexibility: offering a high, or relatively high degree of range flexibility but with a commensurate and tolerable response penalty that is acceptable based on the advantage gained through this capability.

Class 3 flexibility is the lowest class recognizable as meriting a ‘flexible’ definition; any lower capabilities are not deemed to adequately meet the characterisation of ‘little’ penalty offered by Upton, and are hence considered ‘inflexible’ in the context of the current study.

This tool does not attempt to quantify flexibility, but to provide a coded indicator that, in combination with a supporting narrative, helps to explain the nature of flexibility observed in practice. There is precedent for such range-based flexibility assessments in published qualitative research. For example, Naim et al. (2010) utilized “High-Medium-Low” assessments based on transport flexibility, an approach also used by Sawhney (2006) to categorize process flexibility and Oke (2005) to explore manufacturing flexibility in general. In each case the authors use illustrative examples to support their assessment, typically describing the observation that lead to their flexibility assessment.

Unlike physical resources of a factory (e.g. tools, materials, people), flexibility is a capability and not a physical artefact that can be readily observed. It is recognized that research undertaken through Critical Realism is able to accommodate qualities “that are not directly observable, (and hence refracting to quantification); [this] does not rule them out of consideration for analysis” (Ackroyd and Fleetwood 2000). This assessment tool therefore takes a pragmatic approach to understanding the achievement of flexibility in organizations through the evaluation of relative benefits.

6.4.4 Flexibility assessment procedure

Based on the data collected through observation and interview, evaluations of flexibility were made by the researcher for each of the twelve case studies. These data collection instruments produce predominantly qualitative data, and so a qualitative evaluation is most appropriate. For each of the four system components, the nature of flexibility was evaluated in terms of the seven identified flexibility types, leading to 28 flexibility assessments for each case. To direct the evaluation, the following was asked when making each assessment:

“In the pursuit of a high degree of range flexibility for the focal type, what is the nature of the penalty observed, and why?”

To answer this question it was necessary to

1. Identify what constitutes a “high range” in the terms of the focal type and case context.
2. Identify demonstrated evidence from observation and interviews to evaluate the achievement of this flexibility for each case.
3. Identify potential opportunities not directly evidenced, but that are reasonable based on the evidence. These must be clearly noted as potential in all evaluations.

The assessment is therefore informed by data from the cases, but the assessment is made by the author. This approach is intended to ensure consistency in cross-case comparisons, and is consistent with earlier works that examine flexibility in terms of the organizations implementing it (e.g. Corrêa 1994; Naim et al. 2010; Sawhney 2006). It also recognizes the importance of the researcher in qualitative inquiry (Denzin and Lincoln 2008), and is compatible with the abductive approach taken in this work. It is, however, acknowledged that this approach has several limitations and in Table 6.5 details of how these have been addressed in this study are explained.

Issue	Consideration	Approach taken in this study
Inconsistency in case assessment	How to ensure the same evaluation is made for each case?	A statement to direct evaluation for each type has been provided. A clearly defined typology explains the nature of each flexibility type.
Cross-case comparison	How to ensure consistency between cases and companies?	The researcher makes final evaluation for all cases based on defined assessment technique.
Data availability	How to access adequate data to make assessments?	Multiple data sources (interviews, observation, and company data) are used to support triangulation. Longitudinal participation from two companies (LittleCo and BigCo) allow for flexibility demonstrations to arise over time. Where uncertainties existed in evaluation, follow-up clarification was conducted by the researcher.
Bias	How to minimize bias in evaluation?	Limiting evaluation to the researcher removes bias from the researched, though does not eliminate issues of researcher bias. Other studies e.g. (e.g. Sawhney 2006) have used multiple investigators to lessen this risk, however this is not possible in this independent doctoral study
Confidence in results	How to be confident of the accuracy of the assessment?	Supporting notes were maintained in the assessment of flexibility, and these have been used in the development of supporting narratives. An interim conference paper was provided to BigCo and LittleCo
Flexibility as a potential capability	How to identify potential opportunities for flexibility?	Research informants were questioned regarding demonstrated past experiences of flexibility. Longitudinal participation from two companies (LittleCo and BigCo) allowed evaluation of flexibilities as experienced over time.
Subjectivity in assessment	How to minimize subjectivity in assessment?	Flexibility, and assessments of it are inherently subjective and this is acknowledged in this work. To minimize this undesirable characteristic the assessment rationale are clearly defined, and evaluations are supported by a narrative explanation.
Quantification of results	How to quantify results?	No attempt is made to quantify the flexibility types, instead a classification is proposed supported by a narrative explanation.

Table 6.5: Considerations in the conduct of flexibility assessment

Source: The Author

6.5 Sources of flexibility in Industrial Additive Manufacturing Systems

6.5.1 Flexibility in Design

The design component of the manufacturing system draws principally on computer/information processing resources and labour in the achievement of a CAD model for manufacture. Assessments of flexibility are therefore in terms of the ability to process and move information, rather than physical production materials and so the typology is interpreted in this context. In Section 4.8 it was demonstrated that an Industrial Additive Manufacturing System draws upon a number of different resources (e.g. labour, machines, information systems), and these have been included in all evaluations.

The following section describes the nature of achievement of flexibility, and is summarized in Table 6.6 in terms of the previously developed flexibility classes. Note that from Table 4.2 there are no design activities identified for Case 10 as a result of its standardized design, and so this Case is omitted from this assessment.

	Assessed flexibility class for each Case Study											
	HCo	**LittleCo**						**BigCo**				
Type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Equipment	1	1	1	1	1	1	1	1	1		1	1
Process	1	2	2	3	2	3	3	2	2		2	3
Operation	-	3	-	3	-	-	3	-	-		-	-
Capacity	2	-	-	-	-	-	-	-	1		-	-
Routing	2	3	3	3	3	3	3	3	1		1	1
Program	-	-	-	-	-	-	-	-	1		-	-
Material Handling	3	1	1	1	1	1	1	1	1		1	1

Table 6.6: Assessment of internal flexibility types in design
Source: The Author

Equipment flexibility refers to the ability for the focal equipment to achieve a range of different operations with ease. A high range is observed where many more operations are available than actually employed for the focal case. Within the eleven cases flexibility was evaluated as having a high range, but with no observed penalty and therefore classified accordingly.

- In Cases 1, 2, 3, 5, 8, and 11 3D scanning equipment is used to elicit a design based on a physical artefact, and concerns the ability to switch between different predefined quality/resolution modes, and the ease with which this can be achieved. This is equipment dependent, but is typically achieved through software configuration and is noted to be easily achieved.

- In Case 9 the use of a configurator limits the range of possible options to a selection of typefaces, material finishes, and a free-text field. Moving between these specified options is achieved with ease. Similarly, Cases 8 and 11 utilize a configurator to assist in the design of those parts.
- In Cases 1-8, and 11-12 3D CAD terminals/computers were used to design and evaluate parts. Flexibility in this context is the ability to move between various software functions, which is also achieved without evident penalties. The main inhibitor to the movement between functions is the experience of the human operator.

Process flexibility concerns the number of different parts that can be produced by the focal resources in different ways. A high range in this context arises from the ability to produce many part variants of the focal case. To afford design freedom, it is important that designers are not constrained by the tools.

- In Cases 1, 2, 3, 5, 8 and 11, 3D scanning equipment was shown to facilitate the scanning of almost any design, providing it could be scanned. This supports a high flexibility assessment.
- In Cases 4, 6, 7, and 12, 3D CAD software is used to create an original design, which in principle should allow high flexibility through design freedom. In practice it was identified that designers needed a high degree of skill to create different designs, and moving between different parts required extra work, incurring a notable penalty.
- In Cases 2, 3, 5, and 8, manual assessment and fixing of designs using 3D CAD was necessary, which whilst needing less time and effort than original design, still incurred work specific to the part and therefore a slight penalty is identified.
- In Cases 9 and 11 sophisticated configuration software assists the designer in producing different parts, reducing the demand for skilled labour and easing the process of manufacturing different parts so that only a minor penalty is observed. For Case 1, the observed activities of the technicians highlighted no penalty arising from different parts.

The twelve cases demonstrated that the freedoms afforded by 3D CAD and scanning equipment offer high flexibility, however in implementation it is the labour resource that constrains both the range of designs and the penalty of their achievement. For scanned parts, skilled labour is required to ‘fix’ some parts of the model incorrectly reproduced in the realized design. Similarly, in the creation of new designs through CAD, it is the ability of the designer that constrains the number of parts that can be achieved, not the CAD terminal software.

Flexibility in operation affects the sequence in which activities are undertaken. A high range is considered to exist where there are multiple different sequences that can be achieved for most activities. The assessment of activities in Table 4.2 implies an ordering of activities, particularly where a necessary precedence occurs (e.g. preparing items for scanning must occur before the item can be scanned).

The cases were particularly informative in the assessment of this flexibility type.

- Where production was repetitive and had no requirement for design exploration through physical prototyping (e.g. cases 1, 5, 6, and 8 - 12), manufacturers fixed the sequence in which operations were undertaken to support efficiency and quality in production. In these examples, operations flexibility was neither achieved nor desired. For example, in Case 1 the ability to sequence work enabled the organization to achieve standard times for all activities, the data for which may be found in Table 5.3.
- By contrast, where iterations and exploration was required as part of the design process, the sequencing of activities was shown to be flexible, but led to large penalties in the efficiency with which the design was created. Cases 2 - 4, and 7 all had iterations between the manufacturer in physical prototyping, which led to re-sequencing and repeating of design activities.

Capacity flexibility concerns the ability to expand or contract the system to meet changing demand levels. Capacity is defined by Alp and Tan (2008) “as the total productive capability of all utilized productive resources including workforce and machinery”. A high range capacity is considered where a significant change (increase or decrease) in overall capability is achieved.

For the long-term two of the three manufacturers identified this could be planned for, and changes to the systems made, however ability to change capacity demonstrated by BigCo in the long term are identified as exhibiting characteristics of *changeability* rather than *flexibility*. The techniques employed have permanency; either in the physical ownership of new assets (buildings, machines etc), or the upskilling of workforce. The ability to revert to a lower capacity is impaired by these investments, and in line with Oke (2005) these examples are not used as evidence of flexibility.

- LittleCo identified that in the duration of this research total production volume had fallen, yet they had not been able to make significant changes to reduce the capacity of the system and some design equipment was increasingly idle.
- BigCo identified that sufficient volume for a given product would promote the development of specialist departments, within which staff would be trained on focused tasks to promote efficiency. Likewise, software tools could be used to remove some of the labour activities and thereby increase the capacity of the system. This was demonstrated by Case 8, where labour resources were dedicated to the focal product type.

Over the duration of this research, total demand for BigCo grew considerably, and in 2013 the company commenced work to expand its factory to cope with this requirement. This infrastructural investment of premises, and new structural resources such as equipment and labour provides a clear example of how capacity is expanded in the production system in a manner similar to that observed in conventional manufacturing practise. There was, however, no evidence for capacity flexibility to in response to contracting volumes.

In the short-term, cross-case assessments highlight the role of labour in the design process as being of significance in the ability to achieve capacity flexibility. Overall, the cases demonstrated little evidence to support short-term flexibility for design activities. As evidenced in Table 4.4, labour is involved in many of the activities for which both BigCo and LittleCo demonstrated that the skilled nature of the activities undertaken constrained abilities to increase short-term capacity through temporary staff.

However, two notable exceptions may be observed:

- In order to match supply with demand at different components of the system, for Case 1 HearingCo multi-skilled its staff, and deployed them through the system as required. Although this leads to some instances of suboptimal skill assignment (e.g. skilled staff performing relatively unskilled roles), the overall benefit was deemed worthwhile by the company.
- The use of a configurator in Case 9 eliminates the need for manufacturer's labour in the design of a product. Customers configure their own products via a self-service website, which can accommodate large demand variations without penalty.

Routing flexibility considers the ability to route work through the system, and is often considered in the context of a resource failure. A high range is considered to include multiple different routes for most activities through the system. Within this study, observed issues requiring flexibility included CAD terminal failure and absenteeism in labour. The ability to achieve routing flexibility was affected by the availability of alternate resources, and case product specificity for a particular resource to be used.

- In Case 1, the existence of multiple instances of resources supported routing for most operations. The availability of spare equipment, and multi-skilled labour promote different routes through the design process. Skilled staff performing semi-skilled work are acknowledged to be underutilized, whilst semi-skilled staff performing skilled work was either infeasible, or achieving inferior output; both of these scenarios represents a small penalty.

- In Cases 2 – 7, the ability to achieve routing flexibility was identified as being constrained by the limited number of possible routes through the design component. The company employed a single experienced designer, but demonstrated an ability to route work to less skilled staff when necessary. However, this approach demonstrated a loss of uniformity; the alternate staff typically worked slower than their skilled counterpart, representing a large but tolerable penalty.
- In Cases 8-12 the large scale of BigCo relative to the other firms demonstrated multiple instances of the resources used in design, and it could readily reroute some of the less complex work without penalty.

Program Flexibility concerns the ability of the resources to work unattended for an extended period of time. A high range flexibility is expected to achieve most, if not all, of the operations required of it unattended and so the presence of labour is an inhibitor to this flexibility type.

- For all cases except 9 there is a high proportion of labour effort involved in design, and so there is no flexibility evidenced for this type.
- For Case 9, the software configurator is shown to run continuously without human intervention, demonstrating a penalty-free flexibility.

Material handling flexibility relates to the ability to effectively move materials through the system. A high degree of flexibility is considered be achieved where the cost and time to achieve the transfer is low relative to the total manufacturing time.

- For Case 1, design information is initially transferred as a physical mould sent from audiologist to manufacturer, before digitized data is transferred through the network. Notably, this physical transfer takes time and has transportation costs, leading to a notable but tolerated penalty.
- For Cases 2 - 12 this refers to the electronic data that defines the product. All cases demonstrated a high degree of flexibility by their ability to send files across networks at very little cost, and no penalty is observed in sending one design vis a vis another.

6.5.2 Flexibility in Pre-processing

As with design, the pre-processing component of the manufacturing system draws principally on computer/information processing resources and labour to finalize designs for production, produce production plans, and to determine optimal parameters for manufacturing. Assessments of flexibility are therefore in terms of the ability to process and move information, rather than physical production materials and so the typology is applied in this context.

	Case Reference Number											
Type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Equipment	1	1	1	1	1	1	1	1	1	1	1	1
Process	1	2	2	2	2	2	2	1	1	-	2	2
Operation	-	1	1	1	1	1	1	-	-	-	-	-
Capacity	2	-	-	-	-	-	-	-	2	2	2	2
Routing	2	-	-	-	-	-	-	-	2	2	2	2
Program	-	-	-	-	-	-	-	-	-	-	-	-
Material Handling	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.7: Assessment of internal flexibility types in pre-processing
Source: The Author

Equipment flexibility in the context of pre-processing concerns the ability for the machine resources to perform different activities. A high degree of flexibility is achieved where the focal resources can achieve a wide range of different activities with ease.

- For all cases the same types of equipment are used in pre-processing, and is identified as typically being conventional desktop computers, used to perform a variety of activities in the preparation stages. In all three companies skilled or semi-skilled labour is utilized to operate these, and there is no evidence of penalty in moving from one activity to another.

Process flexibility for pre-processing concerns the capability to process multiple parts, and a high degree of flexibility is achieved where multiple parts can be produced with ease. As with equipment flexibility this is afforded by computers and appropriately skilled labour. Whilst there is little or no penalty identified for software to produce one part relative to another, labour requirements were shown to affect the flexibility achieved

- For Cases 1, 8, and 9 although each part is customized, the similar nature of each part requires no additional evaluation by labour resources, and so no penalty is observed.
- For Cases 2 – 7, and 11 – 12 moving between different parts results in a slight penalty. For each part, the pre-processing requirements differ slightly, requiring the technician to evaluate the consequences of any changes.

Operation flexibility concerns the ability to sequence activities in a different manner, with a high range flexibility achieved where most activities can be sequenced.

- For Cases 2 – 7 this was a capability particularly demonstrated by LittleCo. The small nature of this organization meant a shared labour resource carried out many of the activities involved in pre-processing, and sometimes this would lead to batching of tasks (e.g. multiple STL validations, then multiple manufacturability evaluations). No overall penalty was identified as a result of such practices.
- For Case 1, as in Section 6.5.1 activities are fixed in sequence.

- For Cases 8 – 12 the potential to achieve operations flexibility is identified as feasible, though not evidenced in the course of this research.

Capacity flexibility is the ability to increase or decrease the number of parts that can be prepared for manufacture. As explored in Section 6.5.1, the focus is on short-term flexibility rather than long-term changeability. For pre-processing the main identified inhibitor of flexibility was identified to be labour

- For Cases 1, and 8-12 HearingCo and BigCo were able to reallocate staff for the production of many cases with a small penalty.
- For Cases 2-7 as LittleCo had only one staff member to perform these activities reallocation is not possible, and so flexibility is not evidenced.

Routing flexibility is the ability to move work between different resources, and links strongly to the availability of capacity.

- For Cases 1, and 8-12 HearingCo and BigCo were able to used flexibility in their workforce to achieve routing flexibility.
- For Cases 2-7 as LittleCo had only one staff member to perform these activities reallocation is not possible, and so flexibility is not evidenced.

Program flexibility concerns the ability for the pre-processing resources to operate for an extended period of time unattended; however as labour is required for all cases this was not evidenced.

Material handling flexibility relates to the ability to effectively move materials through the system; for pre-processing this refers to the electronic data that defines the product.

- All cases demonstrated a high degree of flexibility by their ability to send files across networks at very little cost, and so overall penalties between different parts is negligible.

6.5.3 Flexibility in Manufacturing

The manufacturing component of the Industrial Additive Manufacturing System transforms digital designs and raw materials into physical parts. In Section 2.10, it is typically identified that the capabilities of Industrial Additive Manufacturing machines has supported overall considerations of "flexibility". This section provides a consideration of the attributes that achieve the flexibility types, and is summarized in Table 6.8.

It is noted that four different technologies are evidenced in this work, and similarities and differences between these in their achievement of flexibility are highlighted in this section. Case 1 uses Perfactory machines, Cases 5-6 employ Selective Laser Sintering, and Cases 2-4, 7-12 use Laser Sintering. Case 10 uses either laser Sintering or Stereolithography, depending on the product requirement.

	Case Reference Number											
Type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Equipment	2	3	3	3	3	3	3	2	3	3	3	3
Process	1	1	1	1	1	1	1	1	1	1	1	1
Operation	1	1	-	1	1	1	1	1	1	1	1	-
Capacity	-	-	-	-	-	-	-	-	-	-	-	-
Routing	1	-	-	3	3	3	3	-	1	1	1	1
Program	-	1	1	1	1	1	1	1	1	1	1	1
Material Handling	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.8: Assessment of internal flexibility types in manufacture
Source: The Author

Equipment Flexibility concerns the ability of equipment (e.g. machines) to change between performing different operations. High range flexibility is therefore considered in terms of the ability of the focal resource to achieve a multitude of different operations. For machines, Sethi and Sethi (1990) identify that this change between operations should be achieved without prohibitive effort in switching from one operation to another; for example as a result of changeover or setup operations. For manufacturing as a whole, Gupta et al (1992, p. 310) noted that "the more flexible a machine the shorter the changeover times, but the more expensive a unit of capacity", implying the existence of a cost-flexibility trade-off.

As evidenced in Appendix C, each manufacturing technology has a different approach to manufacturing (e.g. sintering versus photocuring) and each performs a number of different operations. For example, LS machines have automated material feeding, frame heaters, temperature management systems, as well as sintering capabilities. The machines move between these different operations with ease, and without the need for human intervention. From this perspective, a high degree of equipment flexibility is achieved without penalty for all cases exploiting these technologies.

However, whilst industrial Additive Manufacturing machines are often described as having ‘no setup’, the evidence in this study (summarized in Table 6.9) finds that between each build setup operations are normally required.

Common to all cases was the need to prepare the machine by loading materials. This was identified by BigCo as a particularly laborious task, and a legacy issue arising from the low-volume production expectations of Rapid Prototyping equipment. It was identified that materials for the LS and SL machines are supplied in 10kg vessels, which are manually loaded into machines by human operators. As the firm typically purchases 2,000kg of powder per month for its LS processes alone, unpacking and loading was identified as requiring considerable labour effort. Similarly, as noted by Hopkinson and Dickens (2001), material recovery for recycling is a manual process which LittleCo identified as detracting from a swift changeover. Interviews with BigCo identified that flexibility could be improved if materials were supplied in a larger volume container, allowing a direct hopper-feed to the machines. This was envisaged to be a more effective approach to material supply, and by reducing the penalty of machine loading the potential for improved flexibility exists.

The penalty of changeovers depends on the machine type, and the experience of the organization. In terms of LS, for LittleCo it was expected the process would take a single operator approximately a day to complete a full changeover; at BigCo the expectation is for half this. As a result of the penalty that arises in material changeover, all manufacturers expressed a preference for minimizing the occurrence of this eventuality. Both LittleCo and BigCo acknowledged the ability to change between material types incurred a large penalty, but that it was justified in the capability it provided:

> “Respondent: …ideally speaking we should have enough work on a particular material so that we can keep it running on a machine
>
> Researcher: I guess, being [company name] that because you have a good number of machines, you are able to do less changeovers?
>
> Respondent: Yes, yes, yes – but even with our capacity when we have the new materials, before you get enough market demands for it that you can run a machine full time on it, it is taking time, and on top of that, what we have done that is attracting the attention of the market, you have dip at peak time that you have to employ more machines than one... and it is a difficult balance and we are more and more swapping materials on machines.”
>
> *Operations Director, BigCo [2011]*

> "Respondent: [Relative to 2011] We are changing a bit more often our materials on our LS equipment"
>
> Researcher: You are finding this a feasible opportunity?
>
> Respondent: Well, let's say that economically spoken it not so interesting at the moment, but there is a growing number of materials available and we have to be able to offer the market an interesting portfolio of materials if it is becoming necessary to swap over"
>
> *Operations Director, BigCo [2013]*

Case No	Case Name	Technology	Material Loading	Material Mixing	M/C Configuration
1	Hearing Aid	EnvisionTEC	Manual	Automatic	Fixed
2	Model Ship	LS	Manual	Automatic	Manual
3	Archaeological Models	LS	Manual	Automatic	Manual
4	Architectural Models	LS	Manual	Automatic	Manual
5	Exhaust Tool	SLS	Manual	Automatic	Manual
6	LittleCo Fixtures	SLS	Manual	Automatic	Manual
7	Sensor Tool	LS	Manual	Automatic	Manual
8	Surgical Guides	LS	Manual	Automatic	Fixed
9	Custom Lamps	LS	Manual	Automatic	Manual
10	Standard Lamps	LS/SL	Manual	Automatic	Manual
11	Modular Fixture System	LS	Manual	Automatic	Manual
12	Furniture	LS	Manual	Automatic	Manual

Table 6.9: Principal machine setup operations identified
Source: The Author

Machine setup was identified as being exasperated where material types were changed, and all manufacturers identified benefits in dedicating individual machines as material specific.

- For Cases 1 and 8, each part required produced used the same material configuration and setup parameters, and the manufacturers were able to dedicate machines to producing only these parts. In doing so, they reduced the need to clean between builds, reduced reconfiguration requirements, and improved repeatability by 'tuning' of machines to specific parts.
- All other cases required individual setups as a result of different parts being produced

In all cases the need to changeover machines was identified as being undesirable, and the strategies and quotations demonstrate that manufacturers avoid these where possible. However, in practice changeovers could be performed, and a wide range of potential configurations (machine parameters and material types) is possible. A large penalty is observed, but the evidence of the focal companies suggest it is often worthwhile.

Process Flexibility is afforded by the ability of machines to vary the way parts are made in order to fabricate a range of different parts. It is by exploiting process flexibility that the individual Additive Manufacturing machine may produce a multitude of different parts, for a range of applications and industries.

From the case studies two principal capabilities were identified as supporting process flexibility.

1. Ability to produce a wide range of part designs within a single machine was demonstrated as allowing the manufacturers to produce a wide range of different parts.

- Case 1 demonstrated the production of customized hearing aids that fit the individual ear perfectly, which contributes to the enablement of the Product Flexibility (Customized) described in Section 6.3. The penalty for the machine in producing one hearing aid, relative to another is determined simply from the physical size of the product to be produced. A larger ear requires a larger shell, which in turn needs more material (and hence longer manufacturing time). This minor penalty, however, relates to the nature of the product, not the process enabling it and no penalty is assigned.
- Cases 2-7 demonstrate a range of different parts being produced using the same LS or SLS machines at LittleCo, and Cases 8-12 demonstrate a range of different parts for LS or SL machines at BigCo. There is no notable penalty in producing one part over another; as with Case 1 product size influences build time and costs, and is product related therefore assigned no penalty.

The principal exception to this flexibility capability was identified for both BigCo and LittleCo, where parts of 'awkward' geometries affected the overall utilization of the build chamber. Similarly, for LS processes, LittleCo highlighted the issue of large sintering perimeters from complex parts as affecting material recyclability. Production of such parts was therefore more costly, and flexibility inhibited, and the proposition of process flexibility leading to "Geometry for Free" (Hague et al. 2003a) was identified to be slightly inhibited.

2. Ability to produce wide range of production parameters (part characteristics). Manufacturers may choose from a variety of parametric settings including part orientation, layering strategies, and processing speeds (Munguia et al. 2008; Williams and Deckard 1998). A further opportunity for flexibility afforded by Additive Manufacturing machines is the ability to configure the orientation of parts within the build chamber. Both LittleCo and BigCo demonstrated the use of different build orientations within their machines for two reasons:

i. To offer an increased range of product sizes

The dimensions of the build chamber within an Additive Manufacturing machine represent the physical constraint for the size of parts which can be manufactured in one piece. For thermal processes (e.g. LS) whilst temperature variations constrain the full utilization of the chamber, by rotating parts it is therefore possible to 'fit' larger pieces within an individual machine, or to make better use of space within an individual build.

ii. To influence the quality of parts

A second implication of build orientation concerns the physical properties of the parts produced. It is known that orientation affects both the dimensional accuracy (Pham et al. 1999) and mechanical capabilities (Gibson and Shi 1997) of the parts being produced, and so it is commonplace for manufacturers to consider these issues when choosing the orientation of parts within a build.

The incremental layer-wise approach to Additive Manufacturing can lead to degradation in surface quality as a result of stair-stepping (Sager and Rosen 2008), and so manufacturers can choose to orientate parts to minimize the implications for the quality of the part. In the Model Ship case, the stair-stepping in ship timbers was highlighted as inadvertently making the timbers look more wooden; the customer acknowledged that whilst this may have seemed more aesthetically pleasing, it detracted from the overall accuracy of the part to resemble the original timber as intended.

The exploitation of this capability to promote flexibility is evidenced in Table 6.10.

Case No.	Case Name	Part Orientation Exploited	Motivation	
			Sizing	Quality
1	Hearing Aid	☒	-	-
2	Model Ship	☑		☑
3	Archaeological Models	☑	☑	
4	Architectural Models	☑	☑	
5	Exhaust Tool	☑		☑
6	LittleCo Fixtures	☑		☑
7	Sensor Tool	☑		☑
8	Surgical Guides	☑		☑
9	Custom Lamps	☑		☑
10	Standard Lamps	☑		☑
11	Modular Fixtures	☑	☑	☑
12	Furniture	☑	☑	☑

Table 6.10: Exploitation of parameters for case examples
Source: The Author

Operation flexibility concerns the sequence in which parts are made, for which Browne et al. (1984a) emphasize the opportunity to interchange the ordering of operations for a given product type. In operation flexibility, sequencing of activities are ex-ante (de Toni and Tonchia 1998), allowing the plant control system to assign activities in response to the state of the plant. Having this potential to vary the order in which activities are undertaken can be useful in utilizing resources; by moving work under-utilized processes may be better exploited, and those under excess loading have their work reduced.

The cases evidenced a principal factor affecting operations flexibility to concern the ability for simultaneous manufacture of multiple parts. The production of an individual part relative to the remainder of the batch can be decided in build planning, and such capacity has been identified by Thijs et al. (2010) as affording a high level of flexibility for Additive Manufacturing, and is popular for processes such as LS to improve machine utilization and lessen unit costs (Ruffo et al. 2007).

- Cases 1, 2, 4 – 11 all exploited the capability to achieve simultaneous manufacture, for which there is no penalty identified.
- Cases 3 and 12 did not exploit simultaneous manufacture since their physical size filled the build chamber to capacity.

Capacity Flexibility concerns the ability to vary capacity in the short term. Both LittleCo and BigCo identified that purchasing new machines was identified as being a long-term investment in a fixed asset; this leads to changeability rather than flexibility.

- To achieve greater capacity from the existing equipment, LittleCo identified the potential to increase production speed by increasing layer thickness in LS, which both reduces layer count and build time, but this is to the detriment of part quality (with increased stair-stepping). Whilst feasible, it was not evidenced in any of the cases explored.

Routing flexibility is the ability to change the route that a part takes through the production environment. Browne (1984a) originally asserted that routing flexibility was employed in response to equipment breakdowns, however this flexibility type may also be exploited to accommodate ‘rush jobs’ by using alternate equipment. High routing flexibility in manufacturing is achieved by switching between different machines with ease.

- Cases 1, and 9-12 demonstrated a high degree of flexibility, with no observed penalty. For these cases identical equipment (in specification and configuration) is available, making routing flexibility straightforward and requiring only the transfer of the data file to an alternate process with no observed penalty.
- Cases 2 and 3 are manufactured by LittleCo using a large EOS P700 machine to accommodate the size of parts produced. The manufacturer does not have an alternative

machine with an adequate build chamber to accommodate these parts, and so routing flexibility is not possible.

- Case 8 uses machines that are ‘tuned’ to meet the specific high-quality requirements of the application. These parts cannot be easily moved to generic machines, however BigCo has several identical machines that can be employed supporting a high degree of flexibility.
- Cases 4 - 7 are produced by LittleCo using LS or SLS machines. All parts which fit the smaller machine can be made in the larger machine, but the size constraint means the reverse is not true. Furthermore, the machines are configured differently, requiring a changeover operation of materials which lessens the identified flexibility.

Program Flexibility concerns the ability of the machines to run unattended for extended periods of time. There is debate over what constitutes an ‘extended period of time’ for machines; examples from Jaikumar (1986) indicate that higher degrees of flexibility arises from machines running unattended for the duration of shifts (or overnight). The emphasis in program flexibility is to achieve fewer, quicker setups, from which it is necessary to have an enhanced knowledge of the manufacturing system in order to systematise these tasks (Sethi and Sethi 1990).

In principle once the Industrial Additive Manufacturing machine has been started by a human operator, no further involvement is required until the build is complete, and since the duration of the build is largely predictable Additive Manufacturing offers the potential for a very high degree of program flexibility.

- For Case 1 program flexibility is constrained by the relatively short cycle time of the machines, requiring human attention on an hourly basis to empty the components and reload raw materials. Whilst program flexibility is therefore limited to one hour, from the perspective of the company, this hourly production of a small batch of components promotes flow within the overall processes.
- For Cases 2 – 12 the LS/SLS and SL machines results in builds that run unattended for multiple shifts (with the majority of production typically concentrated overnight in a lights-out environment).

However, the main detractor from the achievement of program flexibility for LS/SLS and SL is the potential for build failure. Both companies identified that that the potential exists for machines to crash mid-build, and BigCo quantified that 5-10% of all builds terminate in failure. As the machines are unattended, both companies reported the problems of “failure discovery”, where operators expect to find a completed build, only to discover a partial build and crashed machine. This was described as having significant implications for manufacturing cost, and also for disruption in production planning as they attempt to reschedule the work within the overall production plan. In an attempt to lessen the problems of unattended build failure, BigCo has invested in process monitoring measures to alert human operators of machine failure through an electronic messaging system.

Material Handling Flexibility in the context of an Industrial Additive Manufacturing machine *during manufacture* is a fully automated process. For example, for the LS process between 40kg and 80kg of powder material is fed into the machine automatically from storage tanks of new and recycled powder using an electric motor. Individual layers of powder are applied by a recoater, pre-heating and sintering are performed, and the build platform lowered in preparation for a further layer of material added. Similar levels of automation (albeit using different techniques) are found in all other commercial systems highlighted in Appendix C.

6.5.4 Flexibility in Post-processing

The post-processing phase involves the final activities in manufacturing that finish the part/product ready for downstream operations or the final customer. As evidenced in Chapter 4, it involves machines of a range of automations, computing resources, and labour. For each case post-processing activities are different, yet individual manufacturers must accommodate their requirements by achieving flexibility in their operations.

	Case Reference Number											
Type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Equipment	-	-	-	-	-	-	-	-	-	-	-	-
Process	1	1	1	1	1	1	1	1	1	1	1	1
Operation	-	3	3	3	3	3	3	-	-	-	-	-
Capacity	2	-	-	-	-	-	-	-	3	3	3	3
Routing	1	-	-	-	-	-	-	-	1	1	1	1
Program	-	-	-	-	-	-	-	-	-	-	-	-
Material Handling	3	3	3	3	3	3	3	3	3	3	3	3

Table 6.11: Assessment of internal flexibility types in post-processing
Source: The Author

Equipment flexibility concerns the number of different operations that are achievable by the post-processing resource.

- Common to all cases, for most of the post-processing resources used in the cleaning of parts equipment flexibility was very low, and typically they could achieve only a single function. The majority of such activities were largely dependent on labour resources for their operation, which were typically semi-skilled and assigned to a small number of operations. Similarly, several cases (1, 5, 7, and 9 - 11) demonstrated assembly operations arising as part of the post-processing activity which drew upon skilled or semi-skilled labour together with manual tools.

Process flexibility concerns the number of different parts that can be processed by the post-processing resources. A high flexibility is observed where a large number of parts can be processed without penalty arising.

- In each of the case examples, the parts produced are different, requiring that the manufacturing system is able to effectively post-process this range of parts. The simplicity of the activities undertaken by the post-processing resources (e.g. airblasting) promotes their application to a wide range of parts, with little consequence arising in terms of a penalty. Effectively the low equipment flexibility achieved by these resources is counteracted by their heightened abilities for process flexibility.

Operation flexibility concerns the sequence of activities undertaken in the post-processing, and as with design this capability was observed to relate to the repeatability of production.

- For Case 1 and 8 the production of similar customized parts leads to the sequencing of post-processing activities for efficiency and quality.
- By contrast, where production is relatively unique, operators need to make assessments about the best way to process a part (Soe and Eyers 2014); this may lead to exploitation of activity sequencing, but incur a penalty in terms of efficiency.

Capacity flexibility concerns the ability to vary post-processing resource capability to meet demand.

- For Case 1, as with other components HearingCo effectively reallocated multi-skilled staff between activities with slight penalty.
- For Cases 2- 7, as with other components LittleCo only has one resource for post-processing, and so could not reallocate work.
- For Case 8 the specialist nature of the post-processing inhibited the use of alternate resources for post-processing activities.
- For Cases 9 – 12 BigCo identified some opportunity to utilize agency workers to increase overall capacity for low-skilled requirements.

Routing flexibility concerns the number of routes that a part may take through the post-processing element of the system. A high degree of routing flexibility is achieved where many routes can be taken without penalty.

- For Cases 1, 9 – 12 both HearingCo and BigCo demonstrated multiple examples of each post-processing resource, with little penalty observed in switching between each of them for all cases.
- For Cases 2 - 7, as with other components LittleCo only has one resource for post-processing, and so could not re-route work.
- For Case 8 where post-processing involved specialist parts, as with other elements of production BigCo refrained from promoting routing flexibility to maximise quality.

Program flexibility concerns the ability for the post-processing resource to operate for an extended period of time unattended; however the emphasis on labour in these activities mean that this was not evidenced in any of the cases.

Material handling concerns the effectiveness of moving materials through the post-processing part of the system. None of the companies possessed any automated facility for material movement, with both parts and materials being carried by operators. Although this approach enables work to be moved to any station without prior planning, the efficiency in which it is achieved is limited, and as a result a high penalty is experienced in all cases.

6.5.5 Summary of internal flexibility assessment

This section has examined the nature of flexibility within Industrial Additive Manufacturing Systems, focusing on the contribution made by different resources to the achievement of individual flexibility types. Through an examination of each of the four components of the system, it is demonstrated that the nature of flexibility differs by type and by enabling resource at different stages of the manufacturing process. A summary of these findings is presented in Table 6.12.

It is recognized that much care is needed when summarizing and generalizing from these results. The qualitative nature of the inquiry, the subjective nature of the flexibility concept, and the contextual aspects that lead to research participants commenting “it depends” discourage such an approach. Yet for case research, the ability to extend explanation beyond the individual focal case is an inherent requirement (Ketokivi and Choi 2014), and there are several common threads of evidence concerning the different flexibility types that may be identified in the three manufacturers and twelve cases.

		HCo	LittleCo						BigCo				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Design	Equipment	1	1	1	1	1	1	1	1	1		1	1
	Process	1	2	2	3	2	3	3	2	2		2	3
	Operation	-	3	-	3	-	-	3	-	-		-	-
	Capacity	2	-	-	-	-	-	-	-	1		-	-
	Routing	2	3	3	3	3	3	3	3	1		1	1
	Program	-	-	-	-	-	-	-	-	1		-	-
	Material Handling	3	1	1	1	1	1	1	1	1		1	1
Pre-processing	Equipment	1	1	1	1	1	1	1	1	1	1	1	1
	Process	1	2	2	2	2	2	2	1	1	-	2	2
	Operation	-	1	1	1	1	1	1	-	-	-	-	-
	Capacity	2	-	-	-	-	-	-	-	2	2	2	2
	Routing	2	-	-	-	-	-	-	-	2	2	2	2
	Program	-	-	-	-	-	-	-	-	-	-	-	-
	Material Handling	1	1	1	1	1	1	1	1	1	1	1	1
Manufacturing	Equipment	2	3	3	3	3	3	3	2	3	3	3	3
	Process	1	1	1	1	1	1	1	1	1	1	1	1
	Operation	1	1	-	1	1	1	1	1	1	1	1	-
	Capacity	-	-	-	-	-	-	-	-	-	-	-	-
	Routing	1	-	-	3	3	3	3	-	1	1	1	1
	Program	-	1	1	1	1	1	1	1	1	1	1	1
	Material Handling	1	1	1	1	1	1	1	1	1	1	1	1
Post-processing	Equipment	-	-	-	-	-	-	-	-	-	-	-	-
	Process	1	1	1	1	1	1	1	1	1	1	1	1
	Operation	-	3	3	3	3	3	3	-	-	-	-	-
	Capacity	2	-	-	-	-	-	-	-	3	3	3	3
	Routing	1	-	-	-	-	-	-	-	1	1	1	1
	Program	-	-	-	-	-	-	-	-	-	-	-	-
	Material Handling	3	3	3	3	3	3	3	3	3	3	3	3

Table 6.12: Summary of internal flexibility assessments
Source: The Author

Equipment Flexibility

The cases highlight a disjunction between the flexibility that is achievable by equipment in the processing of information, and that which is achievable by equipment for the processing of materials. In the design stages, CAD and scanning equipment are shown to enable an almost infinite range of opportunities, and similarly the pre-processing software is capable of preparing these for manufacture. However, the constraints of setup and changeover are to the detriment of equipment flexibility in manufacture, leading to manufacturers demonstrating a preference to dedicate machines to individual products to lessen changeovers (Cases 1 and 8). In post-processing, the simplicity of the manual tools employed in the cleaning and finishing constrained their ability to achieve a range of operations.

Process flexibility

The cases highlight commonality for penalty-free flexibility in the manufacturing and post-processing components of the system, with no identified penalty in the production of one part vis-à-vis another. By contrast, in design the need for labour to understand and develop new designs incurs a penalty, which is similarly experienced in pre-processing activities. Process flexibility is therefore more apparent for physical manufacturing, rather than design or preparatory activities.

Operation flexibility

Operation flexibility supports the reordering of activities, for which the case evidence demonstrates a number of contextual factors. For design it is evident only for the LittleCo manufacturer in terms of labour allocation, who demonstrated it in the context of physical prototyping, and in the batching of work in pre-processing. These activities were not evidenced for the other manufacturers, and so no evidence of flexibility could be observed. By contrast, in manufacturing, the ability to re-order the production of parts within the build chamber of the focal machine was shown by all manufacturers, highlighting the capability of the Industrial Additive Manufacturing machines.

Capacity flexibility

Compared to the other flexibility types, the demonstration of capacity flexibility in the manufacturing system was limited. The ability to increase or decrease capacity in the short term was shown to be constrained by the need to invest in equipment, and in the training of skilled labour to perform activities. There is evidence that the scale of operations affects the potential to achieve capacity flexibility. In design, the volume of parts to be produced merited investment in a software configurator; this was able to achieve a wide range of designs without penalty. Similarly, in pre-processing and post-processing, the ability to reallocate staff in the larger BigCo and HearingCo companies enabled capacity flexibility that was not possible at the small LittleCo. In manufacturing, capacity flexibility was not demonstrated by the companies involved; the need to invest/divest equipment was identified as a long-term factor of changeability.

Routing flexibility

The ability to change the routes by which work moves through the system is shown to be largely manufacturer-specific, though some deviation can be identified in individual cases. As with capacity flexibility, larger manufacturers were observed to have multiple instances of different resources to draw upon, supporting increased flexibility. In the focal cases this is evidenced for

HearingCo and BigCo, who were able to draw upon the scale to achieve routing flexibility in design, pre-processing, and post-processing.

Program flexibility

The inherent requirement of program flexibility is the operation of a process without labour, however as evidenced in Chapter 4 many of the activities undertaken in an Industrial Additive Manufacturing System rely on labour for their achievement. The most prevalent observation of program flexibility is in manufacturing, where the larger machines operate for extended periods of time unattended (although it is acknowledged that some degree of human monitoring is performed by both BigCo and LittleCo). A notable contribution to program flexibility for design is achieved by BigCo, where a software configurator runs unattended to assist customers in the specification of their designs.

Material handling flexibility

Within this study material was delimited in terms of information materials and physical materials. In design and pre-processing, the digital data is shown to be easily moved through the computer network, with no notable penalty observed between parts. Similarly, in the physical manufacture of parts there is no observed process-related penalty observed in the production of one part relative to another. By comparison, in post-processing the need for labour resources to physically move different parts through the system incurs a notable penalty.

6.6 Discussion

The purpose of this chapter is to explore **Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?** In the preceding chapter demand requirements from customers together with the response from manufacturers was explored, and in this chapter this consideration is focused explicitly on the flexibility capability. Flexibility is often regarded as a desirable objective for operations to achieve, and the benefits of achieving flexibility in the manufacturing system are long established (Slack 1987). For Additive Manufacturing, the literature review (Section 2.10) identified a lack of specificity in terms of what is meant by the term ‘flexibility’, and an emphasis on individual machines rather than the manufacturing system. Flexibility is a complex and mutli-faceted concept, and different types of flexibility have different benefits for customers and implications on operations. In tackling this research question, the research in this chapter addresses this identified research gap by exploring flexibility requirements from customers, together with the types of flexibility afforded my manufacturing systems. The important contribution of this chapter is therefore the achievement of increased specificity of the flexibility concept in the context of Industrial Additive Manufacturing Systems, together with an empirical evaluation of flexibility achieved through a detailed appraisal of twelve case studies.

For the focal case studies it was shown that the external perspective demonstrated a consistent requirement from all customers that the manufacturing system should offer product flexibility. For these customers, product flexibility concerns either the creation of a wholly new product, or the customization of an existing one. To provide a more detailed understanding of the nature of this product flexibility this chapter has employed the three FFF measures, through which a range of different motivations have been identified. This appraisal is important, providing more detail than is afforded by the overarching product flexibility type. By comparison, the other flexibility types were identified to be of lesser importance to customers, however some demonstrated requirement for delivery flexibility was identified to either satisfy accelerated requirements, or to delay delivery to suit the customer.

To understand how flexibility was achieved and/or inhibited in the manufacturing system, a typology and assessment procedure were developed in Section 6.4. In doing so, this part of the research contributes to the achievement of obtaining more specificity in understanding and assessing the nature of flexibility in Industrial Additive Manufacturing Systems, moving from the general capabilities identified in literature (Section 2.10), to recognized flexibility types.

In Section 6.5 the nature of flexibility was considered from an internal perspective, using data gained from all twelve case studies and three collaborative companies. Within this section the enablers and inhibitors of components of the Industrial Additive Manufacturing System were explored in detail, with the summary findings presented in 6.5.5. The literature review in Section 2.10 identified that Additive Manufacturing machines contributes to a number of different capabilities in manufacturing as a result of its flexibility, and this study has shown some alignment to this in highlighting a number of flexibility types enabled by the machines. However, the findings show that the achievement of flexibility within the system is enabled by a multifarious range of different resources, not just the individual machine. Moreover, fulfilment of demand requires more than just the manufacturing component of the system, and it has been shown that different types of flexibility are enabled and constrained for different components of the manufacturing system.

By examining the flexibility of the Industrial Additive Manufacturing System from both external and internal perspectives this chapter has therefore clearly identified the requirements for flexibility, and the means by which it is achieved and constrained.

6.7 Chapter summary

In satisfaction of the third research question, this chapter has explored the nature of flexibility for Industrial Additive Manufacturing Systems, providing a detailed appraisal of the internal and external perspectives. A typology and qualitative assessment mechanism has been developed, enabling a detailed investigation of the way in which different flexibility types are enabled and constrained in Industrial Additive Manufacturing Systems.

Chapter 7 Supply Chain Flexibility for Industrial Additive Manufacturing Systems

Chapter Aims

1. Develop a framework of supply chain flexibility for Industrial Additive Manufacturing.
2. Identify the nature of Industrial Additive Manufacturing supply chains.
3. Explore how flexibility is characterized within Industrial Additive Manufacturing supply chains.

7.1 Chapter overview

The purpose of this chapter is to explore the nature of flexibility in Industrial Additive Manufacturing supply chains. The preceding chapter (identified in Figure 7.1) has provided a detailed appraisal of flexibility from the perspective of the manufacturing system, but did not consider the wider supply chain in which the system operates. Whilst the achievement of completive operations through flexibility in manufacturing operations is important, the need for effective flexibility in the wider supply chain is becoming increasingly apparent (Christopher and Holweg 2011). As shown in Figure 2.11, previous work by Sawhney (2006) has delimited supply chain flexibility in terms of the manufacturing firm and its inputs and outputs. In the same manner, this thesis has therefore examined flexibility from the perspective of the manufacturing system distinctly in Chapter 6, before considering the supply chain in the current chapter. Despite the importance of the supply chain concept, in the context of Industrial Additive Manufacturing there has been relatively little research conducted. This chapter extends the limited research that has largely focused on either the internal chain, or the dyadic relationship between the manufacturer and customer. In doing so, it answers **Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?**

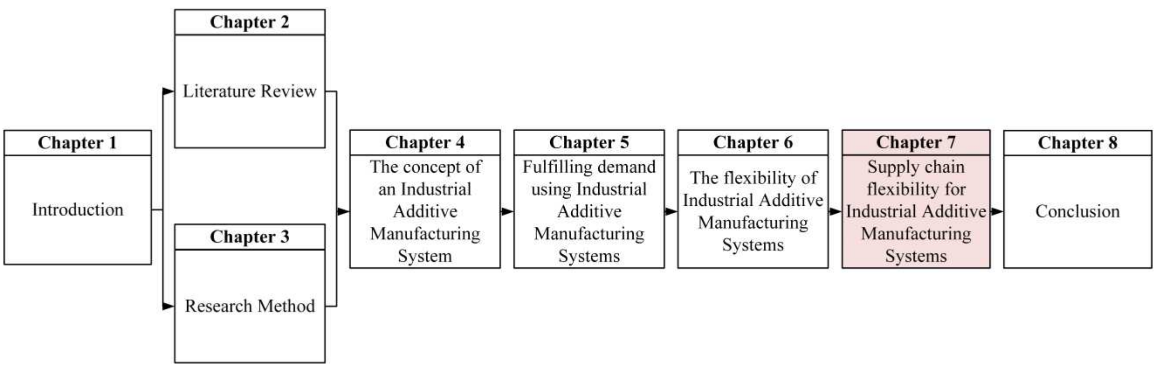


Figure 7.1: Thesis structure
Source: The Author

7.2 Method overview

Supply chain flexibility is emerging as an important topic generally (Moon et al. 2012), however Section 2.11 evidenced a dearth of scholarly research in terms of Additive Manufacturing. This absence of contextualization demonstrates an important research gap, and motivates the development and demonstration of a framework and assessment technique grounded in the existing supply chain flexibility principles. Figure 7.2 overviews the three principal activities undertaken in the achievement of this objective:

1. Building on the existing literature considering supply chain flexibility, a general framework applicable to Industrial Additive Manufacturing is developed, identifying the different types of flexibility and means for their assessment. An abductive approach is taken, with iterations performed between literature concerning supply chain flexibility and observations from industrial practice, which enabled the researcher to identify pertinent aspects of supply chain flexibility relevant to Industrial Additive Manufacturing.

2. Using the twelve case studies explored in this study, the fundamental principles of Industrial Additive Manufacturing supply chains in terms of scope and structure are established. This serves to explain how Industrial Additive Manufacturing supply chains are configured in practice, providing a basis from which to explore their flexibility.

3. The nature of supply chain flexibility in Industrial Additive Manufacturing is explored, with flexibilities both upstream of manufacturing in terms of machine and material suppliers, and downstream to the customer identified and discussed. Examples of practices that promote and inhibit flexibility are identified, contributing to a better understanding of supply chain flexibility for Industrial Additive Manufacturing.

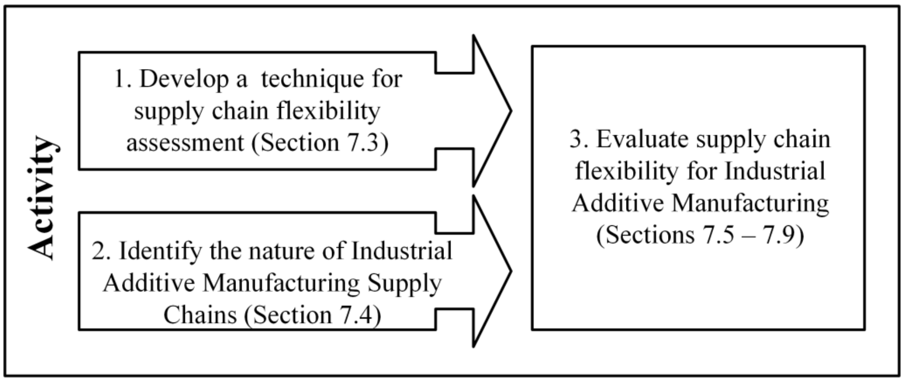


Figure 7.2: Activities undertaken in this chapter
Source: The Author

In the conduct of these activities, this chapter draws on several data sources as shown in Figure 7.3. The scope of this assessment concerns all process-specific contributors to the supply chain, and therefore considers companies both upstream and downstream of manufacturing. It is however acknowledged that access and resource limitations prevented a detailed appraisal of the internal operations of 'conventional' suppliers. These are typically large, complex organizations for which it was not possible to gain access for the purposes of this study.

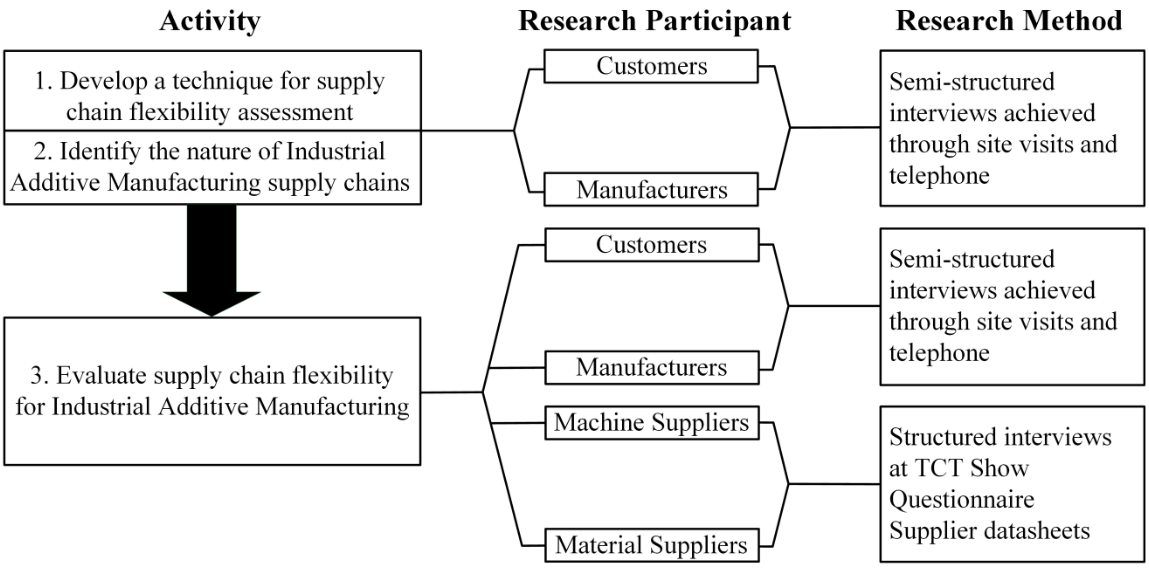


Figure 7.3: Research participants and methods used in evaluating supply chain flexibility
Source: The Author

7.3 Developing a technique for supply chain flexibility assessment

The purpose of this Section is to provide a means by which to evaluate flexibility in the supply chain, which is then utilized in the remainder of this chapter.

7.3.1 Identifying approaches to evaluation

In Section 2.6 the concept of supply chain flexibility was explored, and a number of different approaches to its evaluation were identified. One notable distinction in these existing studies is their focus either on whole-chain analysis of flexibility (e.g. Kumar et al. 2006; Vickery et al. 1999), in which supply chain flexibility is identified as an overall capability, or contributor-focused arising from individual entities (e.g. Duclos et al. 2003; Garavelli 2003; Lummus et al. 2003).

In this study, a contributor-focused approach to the evaluation of supply chain flexibility in the context of Industrial Additive Manufacturing was chosen for three reasons:

1. It allows evaluations to take place at identified points in the supply chain.
2. It identifies sources and inhibitors at different points of the supply chain, rather than in an aggregate evaluation.
3. It promotes transparency in the sources of data, and the methods by which they are attained. The complexities of supply chains mean it unlikely that a complete evaluation may be achieved. The research therefore needs a mechanism to explain which data are included, how they are obtained, and those which are omitted from the evaluation.

7.3.2 Identifying methods of assessment

Purvis et al. (2014) identified that existing research for supply chain flexibility has typically focused on conceptual frameworks, rather than empirical investigation. As discussed in Section 2.6 (and Table 2.9), empirical studies from the literature were shown to have employed a range of methods in the achievement of breadth or depth in their investigations. As the current study is undertaken in an area where there has been little prior research, the motivation is to achieve an understanding of *how* flexibility within the supply chain is characterized, and two exemplar works can be used to identify approaches to the achievement of depth through qualitative case studies.

1. In research for supply chain flexibility in aerospace, rail, and automotive industries Stevenson and Spring (2009), examined inter-firm flexibility to qualitatively explain enablers and inhibitors of flexibility, principally using interviews to gain understanding, and quotations to provide the supporting evidence with which to substantiate these.
2. In research for construction supply chains, Gosling et al. (2010) used case research to provide a qualitative evaluation of supply chain flexibility. Through interviews, observation, and brainstorming activities a detailed account of the way in which flexibilities arose in the focal supply chains was developed.

Such existing studies that focus on the nature of flexibility within a particular industry are identified to refrain from quantification, instead using description and quotation to communicate their findings, with Gosling et al. (2010) using high/medium/low range descriptors to assist in the communication of their assessment. The strength of both papers is their ability to convey detailed explorations of ‘how’ supply chain flexibility arises, which support the selection of similar methods for the current study in the context of Industrial Additive Manufacturing. Hence the precedent set by these authors for qualitative, case-based research is continued in this research, where the intention is to identify the nature of flexibility within the supply chain, rather than its quantified measurement. Furthermore, in Table 2.9 it is evident that breadth of understanding is supported by gaining data from the application of survey techniques, with a number of authors (e.g. Moon et al. 2012; Sánchez and Pérez 2005; Vickery et al. 1999) drawing upon the technique. Whilst many of the surveys evidenced attempts for quantification, this need not be the case since the method is also valid for qualitative research (Fink 2002). As a result, to provide a broader understanding of flexibility upstream of the Industrial Additive Manufacturer, an industry questionnaire is utilized (as previously described in Section 3.7)

7.3.3 Defining an assessment framework for Supply Chain Flexibility for Industrial Additive Manufacturing

As existing research has not considered flexibility in the context of Industrial Additive Manufacturing supply chains, it was necessary to identify relevant types of flexibility to evaluate. This was achieved by reviewing contemporary approaches for supply chain flexibility (as developed in Table 2.8), together with exploration of the focal supply chains found in the 12 case studies (discussed further in Section 7.4). From this evaluation, a modified version of the Duclos et al. (2003) approach to supply chain flexibility was selected for this evaluation. This is justified for three reasons:

1. The component types found in the Duclos et al. (2003) framework are consistent with the topics that have been explored in the conduct of this study.
2. As demonstrated in Table 2.8 there are many different types of flexibility that may be considered for supply chains, though some are more prevalent than others. The Duclos et al. (2003) framework encompasses many of the most popular types.
3. There is a good alignment with the understanding of an Industrial Additive Manufacturing supply chain developed in this research (Figure 7.5).

Despite this identified alignment, developments since Duclos et al (2003) have arisen, and some of those were deemed pertinent for inclusion in this study as shown in Figure 7.4.

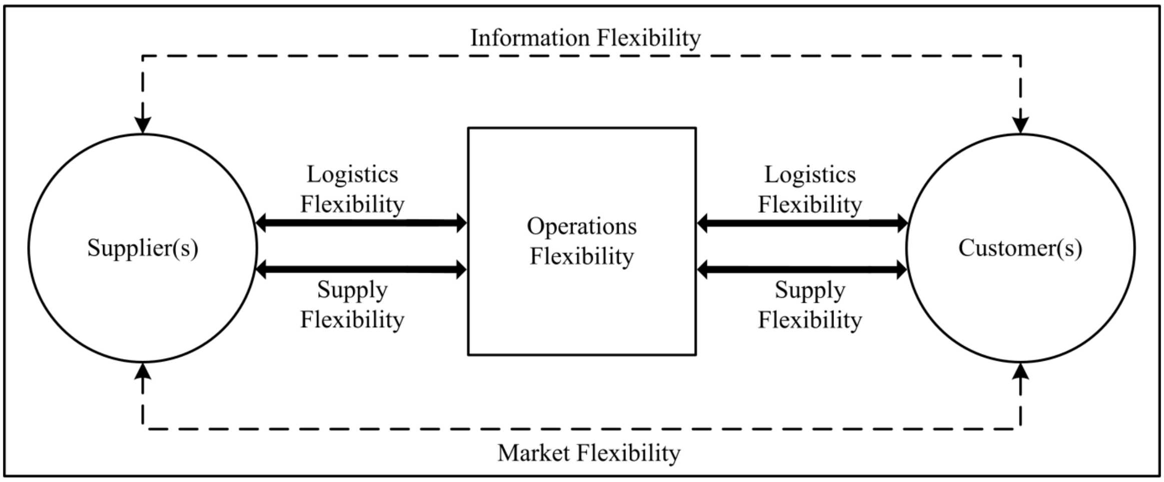


Figure 7.4: A framework for the evaluation supply chain flexibility for Additive Manufacturing
Source: The Author

1. Interrelationship of operations within the organization

The original framework of Duclos et al. (2003) distinguishes between operations flexibility as referring to "assets and operations", and organizational flexibility in terms of the "labour force", and justifies this by asserting that reconfiguration of the operations is constrained by limits placed upon it by the organization in which they operate. Whilst it is essential to recognize the interrelationship between different flexibility types, by removing the distinction between operations and organization flexibility, the modified framework attempts to lessen the distinction that operations only concerns 'operational' matters, which Slack (2010, p. 62) has previously identified to be an oversimplification of the operations concept. In terms of Industrial Additive Manufacturing Systems, the preceding chapter has already demonstrated the contributions made by labour and machines differ between product and focal company. Likewise, established perspectives on manufacturing systems typically include organizational components (Parnaby 1991). As operations flexibility can arise through the assets of the organization (e.g. its people, infrastructures, and machines), making an explicit separation between these components may not always be optimal in the evaluation of the supply chain.

2. Flexibility as a bi-directional concept

The Duclos model implies that flexibility is unidirectional, arising at one node of the supply chain and passing to the next (represented by directed arcs in the model). Such emphasis suggests that one element of the supply chain achieves flexibility in isolation, and without the co-operation of other supply chain members. This may be an over-simplification, and existing research has already identified flexibility to be bidirectional (Sawhney 2006; Sethi and Sethi 1990). In this study, the co-operation between machine suppliers and their customers demonstrates this bidirectional capability. For some machine manufacturers, the ability to expedite an individual customer order was shown to arise from renegotiating the delivery dates for other customers. In this approach, flexibility in supply is not a capability of the machine supplier's manufacturing capability, but its ability to effectively exploit flexibility in the supply chain. Collaboration to achieve flexibility is therefore an important and relevant topic, and given the evidence of its practical application for Additive Manufacturing supply chains, it is useful for the framework to accommodate this potential. To achieve this, the arcs within Figure 7.4 have been shown as bidirectional components of the framework.

3. Limitations of inter-nodal assessment

Duclos et al. (2003) identified that flexibility was required between nodes of the supply chain, and without such flexibility, overall change within the supply chain would be inhibited. One of the attractive aspects of the model is that by explicitly identifying each node in the supply chain, this approach makes individual contributions to flexibility explicit. However, whilst inter-node flexibility implies that between each node of the supply chain flexibility exists, for concepts such as Information Systems flexibility this may be an oversimplification. Within the case research of this study, integrated information systems were particularly evident in medical applications (e.g. Case 8), through which data are shared between customer, manufacturer, and assembler entities within the supply chain. As organizations move towards open systems, opportunities for decentralized data storage and processing through developments such as cloud computing offers the opportunity to consider flexibility in a holistic manner, rather than the more piecemeal inter-nodal proposition. This is shown by dashed arcs extending the supply chain.

7.3.4 Components of Supply Chain Flexibility for Industrial Additive Manufacturing

Based on the modified Duclos et al. (2003) framework, five components of supply chain flexibility may be evaluated in terms of Industrial Additive Manufacturing:

1. Operations Flexibility is achieved at individual nodes of the supply chain, and concerns the capability to change the operations function to meet the external customer requirements for product, mix, volume, and delivery flexibilities.

2. Supply Flexibility incorporates all of the transforming and transformational resources which are used in the manufacturing process but originate outside the organizational unit. It represents the flexibility arising between supplier and customer in terms of physical resources such as materials and labour. Gosling et al. (2010) identified that flexibility in supply may be fundamentally divided into two categories:

1. Vendor flexibility: the ability of given vendors that support the operations to achieve flexibility in supply. This definition links closely with that of Operations Flexibility, but can also include non-operational capabilities.

2. Sourcing flexibility: the ability to reconfigure the supply chain by selecting/deselecting suppliers as appropriate. For sourcing flexibility, Lao et al. (2010) identify four principal measures:
   i) The number of alternate supply sources
   ii) The time incurred in switching between suppliers
   iii) The cost incurred in switching between suppliers
   iv) The impact on performance

   This evaluation is identified to have resonance with the original fundamental definitions of flexibility (Slack 1983, 1987; Upton 1994) in terms of range (number of sources), response (penalties of time and cost), and uniformity (performance impact).

Such an approach to flexibility means that it is not necessary for all individual suppliers to be flexible; as Lao et al. (2010) identified through reconfiguration of the network and partnering, appropriate flexibility can be achieved in the supply chain. By extension, Gosling et al. (2010) demonstrate that there is a need to achieve the right balance between vendor and sourcing flexibility; too much may lead to increased costs as a result of overcompensation for risk and uncertainty, but too little may leave the chain susceptible to risks and uncertainties. Upstream supply flexibility therefore considers vendor and sourcing flexibilities for raw materials and Additive Manufacturing machines. Downstream, supply flexibility concerns the flexibility between the Industrial Additive Manufacturing company and its customer.

3. Logistics Flexibility involves all processes involved in the movement of physical materials, whether in raw, in-progress, or in finished states. It is identified by as Zhang et al. (2005) as the capability to respond quickly and efficiently to changing customer needs for inbound and outbound delivery.

Two principal sources of flexibility in logistics are:

1. Transportation and the physical ability to move materials between providers.

   Naim et al. (2006) demonstrate that transport can be considered from the provider's perspective (internal), or the commissioning user/customers perspective (external). Internal flexibilities therefore focus on the achievement of flexibility in terms of a number of different types (vehicle, routing etc.), whilst external perspectives focus on the objective of these (e.g. the ability to change delivery dates).

2. Postponement as a strategy to delay the forward movement of goods in the supply chain (van Hoek et al. 1998). The contribution of postponement to supply chain flexibility is identified by Barad and Sapir (2003) as arising from the "flexibility of sequential decision making" in which decisions over product differentiation are delayed.

4. Information Flexibility concerns the ability of the information systems of all organizations within the supply chain to adapt to changing information requirements. Information can be considered in terms of supplier information, manufacturer information, distributor information, and retailer information (Zhou and Benton Jr 2007). Lummus et al. (2005) emphasises information sharing and co-ordination between members of the supply chain for flexibility. Opportunities to promote information flexibility can arise from effective utilization of a range of sources, including inter-organizational systems, open systems, and emergent technologies such as cloud computing. For Additive Manufacturing several authors have identified the sharing of information between supply chain entities using electronic communications technologies as being particularly relevant (Eyers and Potter 2015; Luo et al. 2004), with much emphasis placed on the design and configuration of products. In his review, Lan (2009) explores a variety of systems capable of exchanging design data between designer and manufacturer. Similarly, Berlak and Webber (2004a, b) explored how e-procurement systems could be used to co-ordinate relationships with Additive Manufacturing service providers. However, whilst these explorations have considered the potential for information sharing (and particularly the enthusiasm for electronic information exchange), little research emphasis has been afforded to this as an enabler of flexibility.

5. Market flexibility was identified by Duclos et al. (2003) as being critical for the supply chain as a result of its ability to provide new products that exploit new technologies in response to changing market requirements. For Additive Manufactured products there is demonstrated support for the use of the technologies to meet market requirements (e.g. Reeves et al. 2011; Tuck et al. 2008; Tuck et al. 2007b). However, by the definition proposed by Duclos et al. (2003), studies should also explore how other members of the supply chain contribute to the achievement of market flexibility in response to changing market requirements. In this study, emphasis is also placed on market flexibility achieved by upstream machine and material suppliers.

7.4 Identifying the nature of Industrial Additive Manufacturing supply chains

In order to evaluate the nature of the supply chain, Cooper et al. (1997) have identified that it is necessary to define the number and nature of firms that are involved in the chain (the 'scope'). Much of the existing Additive Manufacturing research has typically focused on the "internal chain" as described by Harland (1996). For example, to explore what constitutes a Rapid Manufacturing supply chain, Hasan and Rennie (2008) took a process-based approach in their classification of the activities undertaken, identifying an increased number of actions that are evident where the technologies are used to produce functional, end-use parts compared to the production of prototype models. In a more detailed exploration, Tuck et al. (2007a) examined whether the technologies of Rapid Manufacturing lend themselves to lean, agile, or leagile supply chains, focusing on how these are achieved within the single manufacturing firm. Similar perspectives for 3D printing are offered by Nyman and Sarlin (2012). Whilst valuable contributions, it is however acknowledged that focusing on individual companies omits consideration of the important supply chain linkages (Stevenson and Spring 2007).

More recent research has evaluated the supply chain from a dyadic perspective. In terms of spare parts supply chains, Holmström et al. (2010) and Khajavi et al. (2014) examined potential configurations for aerospace supply chains, demonstrating theoretical opportunities for Additive Manufacturers to offer localized and centralized production to satisfy customer demand. Similarly, related work on internet-based approaches (e.g. Cheng and Bateman 2008; Ranganathan 2007) have predominantly taken the scope of the supply chain to extend to the relationship between the Additive Manufacturer and its customer. Such demand-side strategy focuses on value creation by firms in the provision of products to the marketplace, but does not consider the value captured or added which is inherently dependent on factors upstream of the manufacturer (Priem and Swink 2012).

In this current study, through interviews and participant observation with the three Industrial Additive Manufacturing companies, managerial perceptions of the scope of the supply chain were identified to extend both downstream and upstream of Industrial Additive Manufacturing. The notion of the supply chain as external to the organization was identified for these, and no mention was made of the company's own operations as being part of an 'internal chain'. Upstream considerations focused on the supply of the physical resources of Industrial Additive Manufacturing machines and materials. BigCo identified that machine purchases were the same for other technologies, though material holding tended to be more expensive.

> "Machines… I don't see any difference with conventional [supply chains]. We have two types of machines – and we standardize those two types of machine."
>
> *Operations Director, BigCo*

> "The material supply is also very conventional – we buy material…. We have certain requirements (so they must have certain grades)…. If you look at BigCo as a company we have a lot of value in our materials: for a lot of conventional manufacturing companies they would not classify this as a need."
>
> *Operations Director, BigCo*

Downstream considerations focus on the next supply chain echelon as the customer. It was acknowledged that this customer was sometimes an intermediary, for example an audiologist in the ITE Hearing Aid supply chain. Additionally, where 'conventional' resources supported production these were sometimes mentioned (e.g. light bulbs to make Additive Manufactured lamps functional).

This practical understanding of the Industrial Additive Manufacturing supply chain encompasses current dyadic understandings in academic research, but also highlights the important omission of upstream suppliers in contemporary work. From the case research, Figure 7.5 is identified as representing the membership of a generic Industrial Additive Manufacturing supply chain. Process-focused members are shown with solid lines, whilst product-specific members are shown with dashed lines. In Table 7.1 the principal roles of each member of the chain are presented, and for each case, Table 7.2 provides details for each identified member of the supply chain.

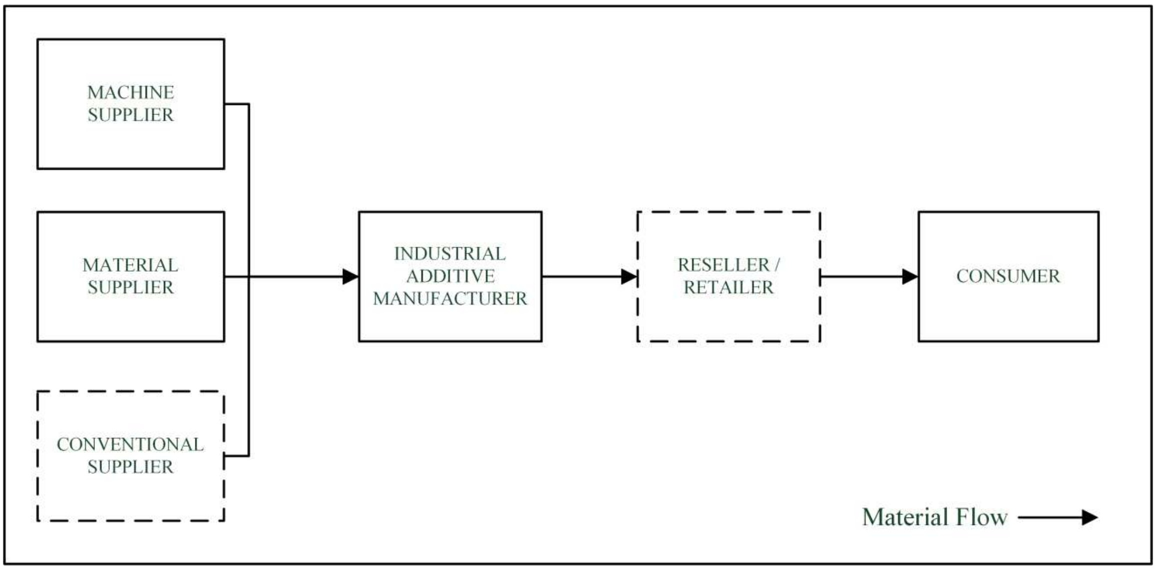


Figure 7.5: The scope of an Industrial Additive Manufacturing Supply Chain
Source: The Author

Role	Primary Function	Nature of relationship
Machine Supplier	Supplier of Additive Manufacturing machines. May also provide spares and servicing	Some manufacturers are represented by intermediaries depending on geographic market
Material Supplier	Supplier of Additive Manufacturing materials (e.g. powder/resin)	Either OEM or 3rd party supplier of materials
Conventional Supplier	Supplier of components and materials that will be combined with the Additive Manufactured parts to complete the customer order	Either works on one-off projects, or have long-term relationships with Additive Manufacturers
Industrial Additive Manufacturer	Additive Manufacture of parts or products	Manufactures own products and/or as an outsourced service bureau for other companies
Reseller / Retailer	Provider of retail and/or configuration capabilities	Supply chain stock location, or may serve a more active role (e.g. elicitation of design or post-production configuration)
Consumer	Final recipient of the Additive Manufactured part/product	Can be wholly involved in realization, or simply purchaser of final product

Table 7.1: Identified roles in the Industrial Additive Manufacturing supply chain

Source: The Author

Case No	Case Name	Additive Manufacturing Supplier		Conventional Supplier	Structure	Intermediary	Consumer
		Machine	Material				
1	Hearing Aid	EnvisionTEC	EnvisionTEC	Modular Components	MTO	Retailer	Patient
2	Model Ship	EOS	EOS	Fittings	MTO	Archaeologist	Museum
3	Archaeological Models	EOS	EOS	☒	MTO	Archaeologist	Museum
4	Architectural Models	EOS	EOS	☒	MTO	☒	Student
5	Exhaust Tool	3DSystems	3DSystems	Metal supplier	MTO	☒	Manufacturer
6	LitttleCo Fixtures	3DSystems	3DSystems	☒	MTO	☒	Manufacturer
7	Sensor Tool	EOS	EOS	☒	MTO	☒	Engineer
8	Surgical Guides	EOS	EOS	Modular Components	MTO	Clinician	Patient
9	Custom Lamps	EOS or 3DSystems	EOS or 3DSystems	Modular Components	MTO	☒	Customer
10	Standard Lamps	EOS or 3DSystems	EOS or 3DSystems	Modular Components	ATO/STS	Retailer	Customer
11	Modular Fixtures	EOS	EOS	☒	MTO	☒	Engineer
12	Furniture	EOS	EOS	☒	MTO	Designer	Exhibition

Table 7.2: Identified supply chain scope for cases

Source: The Author

7.5 Operations Flexibility

Operations flexibility concerns the flexibility that is achieved by the internal operations of the firm. Prior work by Sawhney (2006) has separated the internal manufacturing system from the external supply chain, and in the current study operations flexibility arising from Industrial Additive Manufacturing System is discussed separately in Chapter 6 of this thesis.

7.6 Supply Flexibility

In this section the ability to achieve flexibility in terms of Industrial Additive Manufacturing machines, materials and products is explored[3].

7.6.1 Industrial Additive Manufacturing Machines

Sourcing flexibility

Both BigCo and LittleCo identified that the purchase of new machines represented a strategic, long-term investment for which there was much interaction with the potential supplier prior to purchase. In interviews, BigCo identified that commitment to purchase a new machine was undertaken 5-6 months in advance of anticipated requirement, and given the relative costs of the machines such decisions were carefully considered in terms of the current or expected demand for a given technology. In the case of LittleCo it was demonstrated that this time was greatly extended, and during the course of this study the researcher observed negotiation and planning for a major new machine to take in excess of two years.

The technical review in Appendix C demonstrates that a range of different Industrial Additive Machines are commercially available. Each has different capabilities in terms of the materials they can process, and the results that can be achieved. Although some resellers do exist in the marketplace, as each technology is provided by a single supplier, no evidence was identified for effective sourcing flexibility. The case research found that Industrial Additive Manufacturers are reliant on the ability of the vendors to provide flexibility in the supply of the machines.

The situation for replacement parts is slightly different. Of manufacturers responding to the survey, all identified that they would supply parts to the customer, and five identified that independent stockists were also approved to supply parts. As these companies were not involved in this aspect of the research, it is not possible to evaluate benefits or penalties in terms of cost or time for using them.

[3] Consolidation of machine manufacturers means that the market is dominated by a few large companies. To assure anonymity in this study easily identifiable characteristics have been omitted, and their responses to questionnaires & interviews have not been linked to cases.

Vendor flexibility

Information regarding the supply of machines was elicited from the supplier survey as shown in Table 7.3. From this data an assessment of the vendor flexibility can be made as follows:

Product flexibility in the supply of new machines was identified for six of the seven machine suppliers in the form of customization, with a variety of customization options for material input (e.g. additional material feeders or mixing capabilities), build chamber configuration, or minor options in terms of the processing capabilities. Notably, for each supplier, the number of product variants is typically low, with only one supplier offering a double-digit range of products.

Mix flexibility may be evidenced since all suppliers offered a small range of different machines. Furthermore, where the data was available all suppliers indicated product lifecycles of five or more years, suggesting that despite the significant industry growth, individual machine designs remain viable for multiple years. When in-service, LittleCo noted that machines were typically upgraded to approach the specification of the latest models.

Volume flexibility concerns the ability to change the number of machines, for which it is notable that the total install base of individual machine types is relatively low, and this is consistent with the survey findings of Wohlers (2012). Industrial Additive Manufacturing machines are expensive, and typically revenues are based on selling a small number of high-value machines.

Delivery flexibility concerns the ability to revise delivery times. In the supply of new Industrial Additive Manufacturing machines, lead-times varied between 1 and 16 weeks, with firms principally manufacturing machines in response to customer orders or from stock. However, five of the seven manufacturers identified the ability to expedite customer orders, either by exploiting logistics flexibility in the utilization of air shipments, working overtime, or rearranging their order book to satisfy requirements for urgent customer orders.

	Machine Characteristics				Supply Characteristics			
Mfr	Products Offered	Install base per machine	Custom options?	Product Lifecycle (years)	Lead-time (wks)	Technique(s) to expedite orders	Supply technique & geographic sourcing	Typical install base per customer
A	4	20 - 40	Yes	8-10	12-16	-	MTO 90% Germany MTS 10% Germany	1 – 2
B	5	-	Yes	10	12-16	Overtime	MTO in USA	1 - 3
C	4	100 - 150	Yes	5-8	1-8	Rearrange orders or overtime	MTS in USA	1 - 2
D	3	-	No	>10	12	-	Unspecified in Sweden	1 - 5
E	26	Varies	Yes	5	2	Air Shipment	MTS in USA/UK	Varies
F	7	200 - 500	Yes	8	6	Prebuild	ATO in Germany & US	3
G	7	20 - 400	Yes	10+	16	Rearrange orders	MTS in Germany	1-20 (UK – 3)

Table 7.3: Survey findings on the supply of Industrial Additive Manufacturing machines
Source: The Author

7.6.2 Industrial Additive Manufacturing Materials

Sourcing flexibility

The ability to achieve sourcing flexibility in terms of materials concerns the ability for a manufacturer to obtain materials for their machines from different suppliers. For BigCo and LittleCo, the supply of materials was frequently acknowledged as a constraint affecting their businesses, prompting focus on this element of the supply chain in this study.

In early interviews both BigCo and LittleCo identified that the suppliers of their machines placed emphasis on the utilization of 'genuine' materials in their machines, otherwise on-going maintenance and support may be discontinued. As one respondent at LittleCo emphasized:

> "they'll kill us if we don't use their material."
>
> *Production Manager, LittleCo*

Whilst there is no evidence of this statement being enacted in a literal sense, the importance of utilizing approved materials was clear in the discussions. LittleCo identified that the costs of a failed build (in terms of lost time and materials) were significant, and that failure was more likely with 3rd party materials. By extension, LittleCo expressed concerns that utilization of 3rd party materials would lead to invalidation of machine service contracts. This was identified as being particularly risky for the organization, as machine failure as a result of poorly performing materials would lead to significant financial costs in repair.

In the earlier interviews, BigCo shared some concerns with LittleCo regarding the need to only use materials sourced from the approved sources. It was highlighted that these materials were of much better quality, and that there was little justification to consider alternative suppliers, but still the reliance on the approved materials was problematic:

> "There are only two suppliers – it's not like in the plastic industry where you can buy it by the crate or in every local store, we order it in Germany... so your material has to come from Germany, and as you have only two suppliers – so you have some risk in that sense: if it gets held up from Germany the motorway systems collapses – so [for this reason] you hold materials."
>
> *Operations Director, BigCo*

BigCo therefore expressed concern about their reliance on materials suppliers to fulfil orders as a result of disruptions in the supply chain, particularly arising as a result of transport problems. In principle, dual-sourcing should alleviate risk arising from the failure of an individual supplier, however BigCo acknowledged that even by having a second potential supplier, there still remained a single point of failure within the supply chains:

> "It's even worse in the sense that if you track down where the suppliers buy their materials from, it's all from one company… if something goes wrong at [company name] the whole industry comes to a standstill, at least the sintering market."
>
> *Operations Director, BigCo*

> "[in terms of stockouts] Never had a real issue, but a couple of times come close. What that shows is the fragility of the market itself, where currently there is a high demand in the market for powders, and the lead times absolutely went from two to three to four weeks, and knowing that we are ordering one to two times per month – normally we are supplied within two weeks
>
> Researcher: That pushes-
>
> Respondent: That pushes your nerves! [both laugh].
>
> Researcher: And that's why you have a little stock on site?
>
> Respondent: Yes, a couple of months ago we really had to force that a few hundred kilos were shipped by express courier to keep our machines running or we would have run out of powder."
>
> *Operations Director, BigCo*

For LittleCo, single sourcing of materials combined with failure to hold sufficient stock as a result of unexpected demand was succinctly demonstrated in the following quotation:

> "Researcher: Did you ever run out of material?
>
> Respondent: Uhh…we did.
>
> Researcher: Why did that happen?
>
> Respondent: Panic. We had this two week schedule, and because we think we will have enough material to make two full builds, but we have a failure.
>
> Researcher: So you have to rebuild?
>
> Respondent: We have to rebuild… This is one case. Second case is that there are some holidays from [supplier name], like at Christmas time. Third case is that you have a machine failure, because machine has to make 50/50%, but machine only takes from the new powder because of the machine failure… so the machine basically take more new powder – those are uncontrollable factors
>
> Researcher: So all your prime material is used and only your recycled material is left. You can't get any more stock because [supplier name] is on holiday…
>
> Respondent: Yes, that's right."
>
> *Production Manager, LittleCo*

Both BigCo and LittleCo identified that inflexibility in material supply required stocks of raw materials (powders and resins) to be held in anticipation of demand. This is contrary to prevailing guidance that Additive Manufacturing enables 'just in time' supply (Tuck et al. 2007a). Compared to conventional manufacturing, materials are acknowledged to be considerably more expensive; BigCo identified that some materials were 10 times more expensive than comparable conventional counterparts, and so careful management of inventory is necessary to balance production and financial constraints. This was exemplified by an interview with an Additive Manufacturing reseller that also offered manufacturing capabilities:

> "it's alright for you lot in universities – you've got very deep pockets and you can afford to keep plenty of this stuff [materials]. We've gotta be much more careful 'cos we gotta pay for this stuff to be in the store".
>
> *Reseller representative (interviewee 1)*

The concerns of BigCo and LittleCo regarding its material supply base are supported by observations from the industry as a whole. During the timeframe of the current study, evidenced supply failure was demonstrated by several Japanese Additive Manufacturing companies, whose pipeline of materials ran dry as a result of the 2011 earthquake and tsunami in Tōhoku, Japan. This prompted affected manufacturers to initially ration material supplies, and subsequently to postpone deliveries to customers. As shown in Table 7.4, the material supplier survey identified that three of the seven manufacturers permitted alternate supply-sources for materials, though it is noted that the number of approved suppliers is limited.

Mfr	Alternate sources approved?	Number of approved alternative sources
A	Yes	3-4
B	No	n/a
C	Yes	8
D	-	-
E	No	n/a
F	No	n/a
G	Yes	Unspecified

Table 7.4: Survey findings on supplier approval for alternative material sources
Source: The Author

In structured interviews undertaken at a major industry conference, the views of fifteen representatives of machine manufacturers were solicited. As shown in Table 7.5, for the twelve different Industrial Additive Manufacturers represented, ten manufacturers were identified to only support the usage of manufacturer-sourced materials, which was most commonly justified by concerns for warranty adherence and machine reliability. The respondent for interview number 10 explained that such practices were the "industry standard", noting this to differ substantially to the 3D printing machines for home and office use.

Of the two permitting the utilization of 3rd party materials, they acknowledged that they could not effectively prevent the user availing of cheaper alternatives. In support of these findings the direct survey of Additive Manufacturing machine manufacturers identified that five of the eight participant companies required their customers to utilize only materials provided by the manufacturer; this was further evidenced by BigCo:

> "[technology name] is probably the most difficult one in the sense that the [technology name] machines by [supplier name] have all been shielded off from any other supplier than [supplier name], and at the moment quality speaking [supplier name] machines are still the best that you find. In the Open Source market there are a growing number of machines; on those machines the supply of raw materials is much easier."
>
> *Operations Director, BigCo*

At present the requirement to source materials from the supplier of Additive Manufacturing machines places constraints on the sourcing flexibility that can be achieved. However, as BigCo noted, for different process technologies changes in the marketplace are acknowledged:

> "[In terms of LS there are] two principal suppliers, but that landscape is starting to change. What we see is here are new players in the market, and they start to offer quite ok materials – it is starting to change."
>
> *Operations Director, BigCo [2013]*

	Interview No	Manufacturing Technology	Reseller	Manufacturer	Machines	Materials	Approved Materials Only?	**Justification for approved materials only**				
								Warranty/ Service	**Quality**	**Reliability**	**Machine performance**	**Unspecified policies**
	1	I	☑		☑	☑	☑	☑		☑		
	2	II		☑	☑	☑	☑	☑				
	3	III		☑	☑	☑	☑	☑		☑		
	4	V		☑	☑	☑	☑	☑		☑		
	5	IV & II	☑		☑	☑	☒					
	6	I		☑	☑	☑	☑	☑		☑		
	7	VI		☑	☑	☑	☒					
	8	VII	☑		☑	☑	☑					☑
	9	VIII	☑		☑	☑	☑					☑
	10	IV		☑	☑	☑	☑	☑		☑		
	11	VI		☑	☑	☑	☑					☑
	12	IX		☑	☑	☑	☑					
	13	X		☑	☑	☑	☑		☑	☑	☑	
	14	XI		☑	☑	☑	☑		☑	☑		
	15	XII		☑	☑	☑	☑			☑	☑	
Manufacturer Distinct Totals		**12**	**4**				**☑ = 10** **☒ = 02**	**5**	**2**	**7**	**2**	**3**

Table 7.5: Structured interview summaries
Source: The Author

For the cases studies explored in this study, Table 7.6 identifies the number of material sources identified as suitable by the focal Industrial Additive Manufacturers. Notably, whilst alternate suppliers are available for some processes, the manufacturers identified the need to keep products distinct; when recycling materials it was noted as being important that these were not mixed else the mechanical integrity of the materials would be compromised.

BigCo identified that although the supply of raw materials from approved suppliers was all of a certified quality, small differences between batches lead to notable challenges in the achievement of consistent quality in production. To achieve consistency in the raw materials, BigCo routinely purchased whole production batches from its suppliers (on a consignment stock basis), thereby reducing the variation experienced in their operations. LittleCo acknowledged the issue with inter-batch consistency, but admitted that they did not have adequate 'buying power' to enter into bulk purchase arrangements with suppliers.

Case Study	Technology	No. Sources	Time Penalty	Cost Penalty	Uniformity
1	Perfactory	1	-	-	-
2 3 4 5 6 7 8 9 10 11 12	LS	2	Low	Low	Good, but cannot mix suppliers
9 10	SL	2	Low	Low	Good, but cannot mix suppliers

Table 7.6: Supply flexibility for Industrial Additive Manufacturing materials
Source: The Author

Vendor flexibility

As shown in Table 7.7, the survey highlighted that for those responding to this question (n=4), a catalogue of material products is offered for each process technology. For those companies not replying to the questionnaire, secondary analysis of their websites confirmed this to be consistent practice within the industry.

For the manufacturers supplying materials, it was identified from secondary literature and company websites that frequent releases of new and updated materials are made to their range. As a customer of these companies, LittleCo acknowledged that this enabled a range of new possibilities for Additive Manufacturers. For example, the availability of a rubber-like material for LS was favourably received by LittleCo, allowing them to produce apparel products. It was noted that these materials are process-specific, and thus the introduction rate is not consistent across all material suppliers.

Survey respondents indicated the production lead-time was typically between 1-2 weeks, and for three of the four material manufacturers this was produced on a Make-To-Stock or Ship-To-Stock basis. All respondent suppliers held stocking locations in Germany, and these were complimented by other European locations and USA. Notably, the responsiveness of manufacturers may be identified as being very different, with variation was observed in the ex-works lead-time for materials, ranging between a single day to 1-2 weeks. It is additionally recognized that two suppliers commented on the estimated variability of customer orders, which they identified as being 10% and 50% respectively.

Mfr	Number of materials	Mode of fulfilment	Lead-time	
			Production	**Supply**
C	11	MTS	2 wks	1-2 wks
E	67	STS	2 wks	1 day
F	7	MTO	2 days – 1 wk	5 days
G	7	MTS	-	-

Table 7.7: Survey findings on material supply by manufacturers
Source: The Author

7.6.3 Additive Manufactured Products

Sourcing flexibility

As shown in Table 7.8, the ability to use alternative manufacturing sources was identified for a number of the case studies. In these examples customers may avail of other manufacturing bureaus to produce their products, though for larger parts the need for a large-capacity machine for fabrication is recognized as constraining supply.

In Table 7.8 three characteristics identified as affecting sourcing flexibility are presented

1. Vendor specificity in products. These products are only manufactured by the focal company, and may be protected by intellectual property rights. Sourcing flexibility for these products is not possible.
2. Consultancy requirements. These products require considerable involvement in prototyping and development activities that draw on the specialist capabilities of the focal manufacturer. Moving to an alternate source is possible, but not all bureaus offer consultancy services and so flexibility is constrained.
3. Processing constraints, particularly in terms of the size of parts that could be built.

Case No.	Additive Mfr	Case Name	Sourcing flexibility	Observations
1	HearingCo	Hearing Aid	●●●	Established relationship with four other providers
2	LittleCo	Model Ship	●●○	Consultancy requirement
3	LittleCo	Archaeological Models	●●○	Size of parts limits production to larger processes
4	LittleCo	Architectural Models	●●○	Consultancy requirement
5	LittleCo	Exhaust Tool	●●○	Consultancy requirement
6	LittleCo	LittleCo Fixtures	●●●	Consultancy requirement
7	LittleCo	Sensor Tool	●●○	Consultancy requirement
8	BigCo	Surgical Guides	○○○	Vendor specific product
9	BigCo	Custom Lamps	○○○	Vendor specific product
10	BigCo	Standard Lamps	○○○	Vendor specific product
11	BigCo	Modular Fixture System	○○○	Vendor specific product
12	BigCo	Furniture	●●○	Size of parts limits production to larger processes
Key	○○○ None ●○○ Low ●●○ Medium ●●● High			

Table 7.8: Sourcing flexibility case analysis
Source: The Author

Vendor flexibility

The flexibility of the three Industrial Additive Manufacturing companies has been previously explored in Chapter 6, and the reader is directed to this text for a detailed evaluation of flexibility achieved within the manufacturing system.

7.7 Logistics flexibility

Logistics flexibility may be considered in terms of both transport flexibility and postponement opportunities, and in this section these are evaluated for machines, materials, and products. All questions in the supplier survey were optional.

7.7.1 Industrial Additive Manufacturing Machines & Materials

Transport flexibility

The supply of both machines and materials to Industrial Additive Manufacturing companies is usually managed by 3rd party logistics providers, who manage the transit of goods from the supplier warehouse to the customer.

Postponement

The definition of logistics flexibility also incorporates the postponement of operations, for which 'place postponement' entails the repositioning of inventories in distributed operations. Thus by extension of this concept, a second attribute of logistics flexibility is the achievement of flexibility in the location of production, in order to reduce transportation requirements.

As shown in Table 7.3, machine manufacturers typically produce machines in one or two locations, from which orders worldwide are fulfilled. Five of the seven suppliers ship from a single country, whilst the others have two manufacturing plants from which demand may be satisfied. Three companies provided details on strategies for production and storage of their three most popular materials, with evidence for the distribution of inventories to satisfy demand as shown in Table 7.9.

Material Supplier	Material Popularity	Production	Storage
C	1	UK	Germany
	2	Germany	Germany
	3	USA	USA
E	1	Switzerland	Germany
	2	Switzerland	Germany
	3	Switzerland	Germany
F	1	Germany	Germany
	2	Germany	UK
	3	USA	USA

Table 7.9: Survey findings on material production and location
Source: The Author

7.7.2 Industrial Additive Manufactured Products

Transport flexibility

Similar to assessments of transport flexibility in the supply of machines and raw materials, the utilization of 3rd party logistics providers was employed by each of three Industrial Additive Manufacturers. The operations of these firms have not been examined in this study, however it was identified from the Industrial Additive Manufacturers that the utilization of these providers was based on their experience and core competence in delivery. An additional transport option provided by both BigCo and LittleCo is for customers to arrange their own collections, which was frequently employed for customers local to the production facility. Within this, transport flexibility in terms of mode, capacity, and temporal types as identified by Naim et al. (2006) may be exploited based on the selection of a range of different third party logistics providers.

Postponement

By producing the product nearer to the demand it may be identified that attributes of transport flexibility (e.g. delivery date) can be affected by shortening the distance that finished goods are required to travel. Bateman and Cheng (2002) identified this as 'devolved manufacturing', and such localization has been identified in several studies as offering benefits for spare parts supply chains (Holmström et al. 2010; Khajavi et al. 2014). There was little evidence of this capability in this study, except some specialist medical products which demonstrated the capability for BigCo to manufacture products in either Europe or US depending on the demand requirement. This was observed to promote shortened lead-times and improve responsiveness in the supply of medical products, and to a lesser extent reduce transportation costs. However, where demand was adequate BigCo viewed such localization to be feasible:

> "Also it is becoming easier in the locations where it is needed to produce parts – this is not something that will be ready for tomorrow, although the reason why it will not be ready for tomorrow is because you need the volumes. But if demand is there, today it is possible – if I look here, it took us something like [confidential] months to set up production in the US – it is not that complicated once you know how to do it. If the demand is there then you can do very local manufacturing".
>
> *Operations Director, BigCo*

Notably, localized production approaches place additional emphasis on information flow within the supply chain, but have been previously demonstrated by the author (Eyers 2010) to optimize the transportation of finished products and enhance overall responsiveness to demand.

7.8 Information flexibility

The ability for information to be shared and synchronized across the entire supply chain has been identified as an advantageous element of supply chain flexibility (Lummus et al. 2005), however in practice for the focal supply chains in this study there is little evidence of a well-coordinated approach between all supply chain members. Instead, information typically decouples at the point of manufacture as examined in this section.

7.8.1 Industrial Additive Manufacturing Machines & Materials

Both BigCo and LittleCo identified that the activity of purchasing new machines typically involved extended discussions with potential vendors, with detailed information typically shared with the manufacturer in-person, complimented by follow-up email and telephone conversations. As identified in Section 7.4, BigCo noted that the purchase of Industrial Additive Manufacturing machines was similar to conventional approaches. LittleCo noted that discussion on material supply may also feature in these negotiations, with orders typically placed by telephone or email. Within this study no examples of integrated ordering systems for materials were demonstrated, though collaboration was observed. Li and Lin (2006) acknowledged that manufacturers facing uncertainties in demand for their customers are likely to share more information with their suppliers, and this is evidenced to occur for both BigCo and LittleCo. For BigCo close working relationships with machine and material suppliers are particularly apparent for materials management, with BigCo routinely providing forecast material demand requirements to its suppliers. For LittleCo, information exchange is much less formal and exists through semi-formal discussions between production staff and representatives of suppliers. For both manufacturers, the provision of this information to suppliers was typically ad-hoc, and may have been initiated by either side of the relationship. Very little emphasis was placed on the utilization of advanced information systems in the exchange of this information.

7.8.2 Industrial Additive Manufactured Products

Within the cases, principal information exchange between customers and the Additive Manufacturer varied in nature and co-ordination as summarized in Table 7.10.

- Integrated electronic information interchange, achieved through a defined and controlled system with automation for communication and order management (e.g. EDI, web-based configurator)
- Non-integrated information interchange, achieved in an ad-hoc manner with no control or management (e.g. in person, telephone, email exchange)
- Collaborative approaches typically involved extensive interaction between the customer and the Industrial Additive Manufacturer in the developmental stages of production (including support with designs and prototyping). Information exchange was typically detailed, and manufacturers had a good understanding of the customer requirements.
- Separated approaches demonstrated the withholding of information from the Industrial Additive Manufacturer until the point of ordering (termed the “Over to you” syndrome by Childerhouse et al. (2003)). For the manufacturer, the receipt of the order is unexpected although the customer may have previously traded with the company before.

Integrated electronic approaches promote information sharing and management within the supply chain, with automation possible for activities such as part configuration and therefore promote information flexibility. Similarly, collaborative approaches provide depth of information to the manufacturer, particularly in anticipation and expectation of the customer order, allowing them to prepare their operations accordingly.

Additive Mfr	Case Name	Integrated	Non-Integrated	Collaborative	Separated
HearingCo	Hearing Aid		☑		☑
LittleCo	Model Ship		☑	☑	
LittleCo	Archaeological Models		☑	☑	
LittleCo	Architectural Models		☑	☑	
LittleCo	Exhaust Tool		☑	☑	
LittleCo	LittleCo Fixtures		☑	☑	
LittleCo	Sensor Tool		☑	☑	
BigCo	Surgical Guides	☑		☑	
BigCo	Custom Lamps	☑			☑
BigCo	Standard Lamps	☑			☑
BigCo	Modular Fixtures	☑			☑
BigCo	Furniture		☑	☑	

Table 7.10: Assessment of attributes of information flexibility
Source: The Author

7.9 Market flexibility

The ability for a supply chain to have market flexibility requires co-ordination across the supply chain in the achievement of new offerings to meet the customer requirement, particularly in terms of customization and support. Within this study, it is interpreted in terms of multiple members of the supply chain working together in the provision of a customer-focused solution. It is identified that whilst relationships between suppliers and Industrial Additive Manufacturing companies may be close (as described in Section 7.7.1), overall there is little evidence of these leading to whole-chain solutions. The only example identified in this study is for the ITE Hearing Aid device, whereby the machine manufacturer (envisionTEC) offers specific equipment for shell manufacture (Perfactory Digital Shell Processor) that is used by the Industrial Additive Manufacturer (HearingCo) to provide custom products to audiologists in satisfaction of the individual customer requirement.

7.9.1 Industrial Additive Manufacturing Machines & Materials

The industry survey identified that in order to respond to marketplace demand, most (n=6) manufacturers provided customization options for their machines. This included process options such as material input, substrate handling, and powder sieving. These configuration options were identified as being made at the time of purchase; some (but not all) options could also be made in future machine upgrades.

In the supply of materials there was little evidence of flexibility in terms of market requirements, particularly in terms of customization. A standard product range is normally offered by the material providers, and there was little identified opportunity for Industrial Additive Manufacturers to tailor these to their own requirements. Instead, the emphasis from both LittleCo and BigCo was consistency and reliability in the materials that they used, and they both identified a reliance on quality materials best suited to the focal machine types:

> "Material is the most important to us because if the machine fail[s] because of material problems, then we have big problems."
>
> *Manager, LittleCo*

> "Researcher: The [research] papers will tell you that powder is powder is power: from our conversations I appreciate that it is not, and that it does vary a lot?
>
> Respondent: Yes – exactly that."
>
> *Operations Director, BigCo*

7.9.2 Industrial Additive Manufactured Products

The ability to respond to the requirements of the market in terms of the provision of new products, or the customization of existing ones was demonstrated for all three of the focal manufacturers.

- For HearingCo, Case 1 demonstrated responsiveness in the customization of products to meet the exact requirements of individual patients.
- In the LittleCo manufacturer, Cases 2-8 demonstrate the company's ability to utilize its Additive Manufacturing capabilities to produce new products for a range of different customers. Through its design and manufacturing consultancy activities, LittleCo demonstrated capabilities to elicit customer demands, and to work with those customers to achieve the required products.
- BigCo demonstrated several examples of responding to market requirements
    - Developing new products and supporting software tools to promote their customization (Cases 8, 9, 11)
    - Providing frequently updated catalogue products to reflect changing market tastes (Case 10)
    - Providing new products as designed by its customers (Case 12)

7.10 Discussion

The purpose of this chapter is to tackle **Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?**

Whilst the importance of supply chain management is well acknowledged (Christopher 1997), there has been limited consideration of the management of Additive Manufacturing supply chains, and in Section 2.11 it was evidenced that there is a particular dearth in terms of supply chain flexibility. To tackle this research gap this chapter has developed a supply chain flexibility framework for Industrial Additive Manufacturing, and using data collected from sources both upstream and downstream of manufacturing, provided an appraisal of the nature of flexibility observed. This consideration extends the limited research that has largely focused on either the internal chain, or the dyadic relationship between the manufacturer and customer, and the achievement of these activities represents the principal contribution of this chapter.

This chapter has shown that flexibility in the supply chain can be considered in terms of different components, and that there are a number of different enablers and constraints that affect its achievement that have been presented in Sections 7.5 – 7.9. One of the most important findings of this chapter concerns the achievement of supply flexibility, where in terms of the Additive Manufacturing machines and materials, this study highlights that there are a number of constraints that impair its achievement. Whilst the overall market for Industrial Additive Manufacturing is growing annually, as a result of mergers and takeovers the supply of most of the commercial machines is concentrated to a few large companies (Wohlers 2012). Specific technology types are provided by individual machine manufacturers, meaning that *sourcing flexibility* for Additive Manufacturing machines is highly constrained. There is, however, evidence of *vendor flexibility* with respondents to the industrial survey in terms of product flexibility (offering variety and customization in machines), mix flexibility (offering a range of different machines), and delivery flexibility (offering expedited machine orders). The implications of these findings are that whilst Industrial Additive Manufacturing companies who wish to purchase a specific machine type are constrained in terms of vendors, the way in which the vendors operates can provide some overall flexibility in supply.

This study identifies that flexibility in the supply of materials such as powder or resin may also be considered as highly constrained. Through interviews respondents at the Industrial Additive Manufacturing companies identified a requirement to purchase materials from the original machine supplier, which inhibits the achievement of vendor flexibility. Notably, four of the seven machine suppliers responding to the industry survey acknowledged this requirement, though this was more strongly observed in the structured interviews at the trade conference by ten (out of twelve) manufacturers. This inconsistency in position between the survey respondents and structured interview respondents is acknowledged, though the evidence gained from Industrial Additive Manufacturing companies supports an overall assessment that requirements for approved materials does have a constraining impact on material sourcing flexibility.

In the supply of produced manufactured by Industrial Additive Manufacturers, this study has demonstrated some examples of sourcing flexibility, whereby customers are able to choose from a range of manufacturers. Whilst this is not possible where the product is vendor-specific (e.g. cases 8-11), for all other cases opportunities to use other suppliers were identified, though it was acknowledged that the need for specialist consultancy skills would constrain some sources.

This finding has particularly important implications for Industrial Additive Manufacturers, and links to the earlier research within this thesis. In Chapter 5 the nature of demand was shown to often be unpredictable (but necessitating responsiveness), and Chapter 6 identified flexibility characteristics of the manufacturing system to respond to demand. However, for the system to operate the requirement for raw materials as inputs are crucial, and the findings of this chapter indicate that flexibility in the provision of these is constrained. As a result, Industrial Additive Manufacturers were shown to hold large quantities of expensive raw materials as a hedge against uncertainty in terms of both supply and demand.

> Researcher: One of the interesting things (I hope) about the PhD is the nature of flexibility in [Industrial] Additive Manufacturing. I've looked at flexibility within the operation, and within the supply chain, and it seems very interesting that if you drew a multi-echelon supply chain – if you look downstream from BigCo, there's a lot of flexibility in the way things are supplied and delivered. But when we look upstream from you – for Additive Manufacturing we have machine supply and material supply, things there are not very flexible at all it would appear? Things are significantly more constrained....
>
> Respondent: Yes, yes, that is indeed the correct conclusion – yeah.
>
> *Operations Director, BigCo*

This disjunction of supply flexibility upstream of Industrial Additive Manufacturing, compared with that downstream is currently satisfied by stockholding of raw expensive materials. However, as noted by the manufacturing companies, the potential of new alternative supplies may promote sourcing flexibilities that may alleviate this requirement in the future.

7.11 Chapter summary

This chapter has examined the nature of flexibility in Industrial Additive Manufacturing supply chains, and has developed a framework for the assessment of their flexibility. The mutli-method empirical investigation has drawn upon informants across the supply chain, and the findings show that whilst Industrial Additive Manufacturing has a number of attributes that promote flexibility in the supply chain, there remain a number of constraints particularly in terms of supply flexibility for machines and materials.

Chapter 8 Conclusion

Chapter Aims

1. Review the conduct and principal findings of the research.
2. Identify the contribution made to academic knowledge and industrial practice.
3. Summarize identified limitations of the research, and highlight opportunities for further investigation.

8.1 Chapter overview

This final chapter serves to provide a review of the entire study as shown in Figure 8.1. The chapter commences by examining the principal findings of the research, and identifying the original contributions that have been made. This is achieved through the seriatim review of the individual chapters, in which the main findings are presented. Through the appraisal of the research findings each of the research questions are answered, which leads to the development of overall conclusions.

Whilst a thorough and detailed investigation has been performed in the conduct of this work, as with all scholarly research it is acknowledged that there are a number of limitations, and these are detailed accordingly. The chapter concludes with an evaluation of the opportunities for future investigation that are afforded as a result of the research conducted within this study.

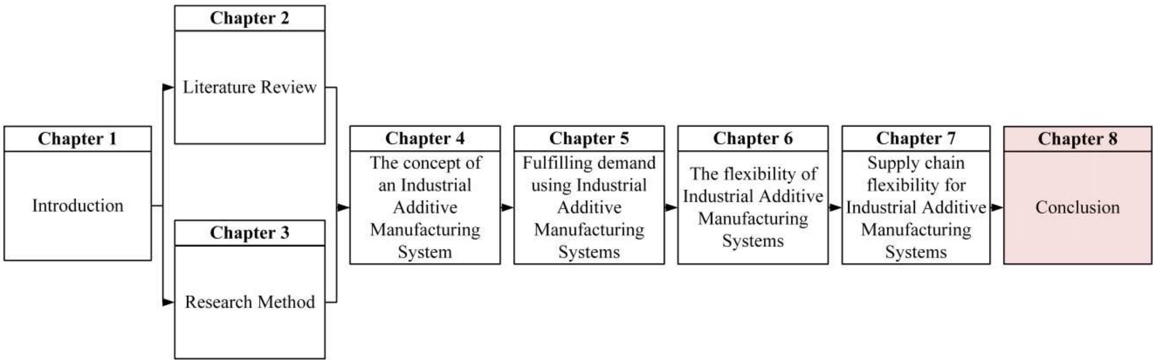


Figure 8.1: Thesis structure
Source: The Author

8.2 Summary of research findings

To summarize the research findings it is useful to revisit the original intentions of the entire study:

The overall aim of this study is to explore the nature of Industrial Additive Manufacturing Systems as implemented by commercial practitioners, with a specific focus on flexibility within the system and wider supply chain.

This motivation was explored in **Chapter 1**, and is underpinned by a discussion of the current state of knowledge concerning the managerial implications of Additive Manufacturing. Despite significant media and academic attention on the growing potential for these technologies, there has been little empirical research regarding the implications for operations and supply chain management. The author identified this in a scoping study conducted prior to the commencement of this research (Eyers et al. 2008), and more recently this has been reiterated by other academics (Bianchi and Åhlström 2014; Fogliatto et al. 2012; Taylor et al. 2013). Furthermore, there is increasing evidence of Additive Manufacturing moving from low-volume prototyping applications through to the direct production of end-use parts, increasingly at higher volumes of production. Understanding the realities of Additive Manufacturing as experienced in modern industry has been identified as essential to its adoption (Wilson 2012), and without an appropriate appreciation of the limitations of the technology's potential, users may become disenfranchised (TSB 2012). This chapter therefore serves to demonstrate the relevance, timeliness, and importance of this research topic.

Chapter 2 provided the theoretical underpinnings for the research, through which the research questions were developed within the overall aim of the study. The lack of detailed Operations Management research for Additive Manufacturing prompted the division of the chapter into two sections: the first to identify the principal theoretical concepts (manufacturing systems, variety/customization, and flexibility of manufacturing systems and the supply chain), and the second within which these were considered in the context of Additive Manufacturing. This approach enabled a logical separation of the literature review types. Part A constituted a traditional literature review, in which the nature and origins of the concepts were explored and an assessment of contemporary research given. Part B exploited the structured review process in order to formalize and identify the extent of research for these concepts conducted in the context of Additive Manufacturing. Through this approach research gaps were identified; this review was updated in the latter stages of the study to confirm the continued existence of these gaps and developments in the research.

This contemporary review of the theoretical concepts provides a unification of the most relevant aspect of these topics in the context of this study, and serves to provide an up-to-date theoretical base for this thesis. Through the structured review process, Part B explored a large volume of published literature on Additive Manufacturing to delimit the state of existing knowledge in the context of this research. During the timeframe of this study the topic has significantly increased in popularity, however the management principles explored remain relatively under-researched demonstrating both the relevance and novelty of this doctoral research.

In **Chapter 3** the design of the research was explored, and through a detailed evaluation the inter-relationship between methodology, method, the individual researcher, and the traditions of disciplines was presented. The selection of an abductive, principally qualitative approach underpinned by the epistemological and ontological beliefs of the Critical Realist researcher was justified, and implications for the study explained. A detailed account of the multiple methods employed in this research is given, including a discussion of the methods of data collection and analysis. Within this chapter the three collaborative Industrial Additive Manufacturing companies were introduced, and the twelve case studies overviewed (supported by Appendix A).

Chapter 4 developed the concept of an Industrial Additive Manufacturing System, drawing upon empirical research and the technical review found in Appendix C. In Chapter 2 it was shown that there has been no consistent understanding of what constitutes an Additive Manufacturing System, which has led to many researchers focusing on opportunities afforded by machines, rather than whole systems. In other contexts such an approach has long been established as suboptimal (Ackoff 1997; Parnaby 1979).

The research presented in this chapter combined Parnaby's established concept of a manufacturing system with data gained through the 12 case studies to explore the activities, resources, and controls identified within the three manufacturing companies. In contrast to many studies, emphasis is placed on elements other than the Industrial Additive Manufacturing machine, in particular the contribution made by the labour components and other contributing manufacturing processes. From this assessment, appropriate boundaries and interconnections are identified, leading to the proposal of a four-component model of an Industrial Additive Manufacturing System. The effective operation of such a manufacturing system requires that despite the external influences placed upon it, long-term stable operation is achieved through appropriate control systems (Parnaby and Towill 2009a), yet as demonstrated in Section 2.8 control has received scant research attention for Additive Manufacturing. Within this chapter, the generic control architectures for manufacturing systems as proposed by Dilts et al. (1991) are demonstrated in the context of Industrial Additive Manufacturing, and their relative merits for this application explored.

Chapter 5 examined the way in which Industrial Additive Manufacturing Systems are employed in the satisfaction of different types of demand. Seminal guidance from Hayes and Wheelwright (1979) has linked manufacturing processes with the volume and variety of products, and these are explored within this chapter. Within Section 2.9 it was shown that existing literature has identified the technologies of Additive Manufacturing as being suitable for the production of many part variants, including those which are customized, but that there is inconsistency in terms of production volumes, and very little evaluation of non-technological components of the system.

This chapter examined the nature of demand experienced by the manufacturing companies, before providing a detailed examination of the application of the Industrial Additive Manufacturing System concept. Through an appraisal of case studies from three manufacturers the opportunities and implications were explored from the perspective of the manufacturing system, rather than just the Additive Manufacturing technologies. Building on this appraisal, and including the other nine case studies of this research, this chapter provided an evaluation of the alignment of Industrial Additive Manufacturing Systems to the Hayes and Wheelwright (1979) product-process matrix, demonstrating several different configuration strategies.

In **Chapter 6** the concept of flexibility was explored from the external (customer) perspective, and the internal (manufacturing operations) perspective. This chapter therefore built on chapters 4 and 5 through which the manufacturing system concept was developed, and then subsequently demonstrated in the satisfaction of demand.

External flexibilities consider the requirements of the customer, and using the established 'first order' flexibilities these are evaluated through interviews to highlight the most pertinent requirements. A detailed evaluation of the nature of internal flexibilities was achieved through the development and execution of a flexibility typology and assessment procedure. Using the data from twelve case studies, each component of the manufacturing system was evaluated in terms of its demonstrated flexibility for each of the seven internal flexibility types. In doing so, enablers and constraints were evaluated with respect to the resources of the manufacturing system, and the concept of flexibility was demonstrated in the context of Industrial Additive Manufacturing Systems from an Operations Management perspective.

Chapter 7 extended the work of the three prior empirical chapters in an evaluation of the Industrial Additive Manufacturing Supply Chain, focusing on its nature and the contributors and inhibitors of flexibility.

This chapter addressed current limitations in literature which tend to concentrate on the potential of Additive Manufacturing to affect either supply chains of the future (e.g. Christopher and Ryals 2014), or focus principally on the internal or dyadic perspectives of the supply chain. By focusing specifically on flexibility within the supply chain, this chapter tackles a topic that has received scant research attention to-date. Within this chapter, the nature of supply chain flexibility for Industrial Additive Manufacturing was explored, building on the earlier analysis found in the literature review. Using the modified framework of Duclos et al. (2003), and drawing upon data from multiple informants, this chapter emphasised the nature of flexibility arising at different parts of the supply chain, and demonstrated enablers and inhibitors of different flexibility types. These were shown to have demonstrable consequences for the management of the internal operations of Industrial Additive Manufacturing firms.

Chapter 8 is the current chapter which provides a summary of the main findings of this research, and directions for further investigation.

8.3 Original contributions made by this research

This research has demonstrated the extent of contemporary knowledge concerning the implications of Industrial Additive Manufacturing Systems for Operations and Supply Chain Management through a multi-method literature review, and has therefore been able to clearly delimit the research gaps that are subsequently satisfied in this thesis. These reviews have evidenced a lack of detailed scholarly research concerning the effects of Additive Manufacturing, and the general dearth of empirical investigation conducted in collaboration with practitioners is particularly apparent.

Within the discussion of each chapter a statement of principal contribution has been made, and these are restated in the following summary.

1. **Identification and investigation of Industrial Additive Manufacturing in the context of a manufacturing system [Chapter 4]**

Within Section 2.2 it was shown that whilst a single understanding of the manufacturing systems concept does not exist, sufficient commonality exists to identify its principal nature and benefits arising from managing a system rather than a plethora of individual resources. Building extensively on the seminal works of Parnaby (1979) and Parnaby and Towill (2009) and using evidence collected from three different manufacturers and twelve in-depth case studies, this study has developed and demonstrated the concept of an Industrial Additive Manufacturing System, and the identification of principal activities, components, and approaches to control for the system. To-date, most Additive Manufacturing research has focused on the contribution of the machines in production, and largely overlooked other contributors. This study therefore makes a novel and important contribution in recognizing the other resources used in production, and by demonstrating these in a systems context, enables research to consider holistic rather than piecemeal management and evaluation.

2. Identification of the nature of demand in Industrial Additive Manufacturing Systems, and approaches to its satisfaction [Chapter 5]

Through a multi-method investigation of the focal manufacturing companies the nature of demand has been identified, implications of uncertainty explored, and a detailed understanding of approaches to demand satisfaction achieved. An empirical evaluation of the Hayes and Wheelwright product-process matrix has demonstrated that Industrial Additive Manufacturing Systems can be employed in many different volume-variety combinations, including those which are traditionally identified as being suboptimal for conventional manufacturing systems.

This is an important contribution as it provides a detailed understanding of the application of Industrial Additive Manufacturing Systems in real-world practice, rather than the conceptual or laboratory-based studies that are commonplace for Additive Manufacturing research. In particular, the identification of these systems with respect to the Hayes and Wheelwright product-process matrix provides an important demonstration of the uniqueness of Industrial Additive Manufacturing Systems relative to ‘conventional’ approaches.

3. Development of an assessment mechanism to evaluate the flexibility of Industrial Additive Manufacturing Systems [Chapter 6]

Whilst Additive Manufacturing is often described as ‘flexible’, this term is typically used with little precision, is frequently pleonastic, and normally refers to machine capabilities only. This study has provided redress for this situation by identifying an appropriate typology and assessment mechanism for Industrial Additive Manufacturing Systems, and through a detailed evaluation of twelve cases demonstrated the nature of flexibility (including its enablers and inhibitors).

Flexibility has long been established as a competitive objective for manufacturing operations (Leong et al. 1990), and this research therefore makes an important contribution by increasing the specificity of the concept, and through empirical investigation identifying the nature of flexibility experienced in Industrial Additive Manufacturing Systems.

4. Development of an assessment mechanism to evaluate the flexibility of Industrial Additive Manufacturing Supply Chains [Chapter 7]

Supply chain flexibility is identified in many studies as an important capability in the effective management of supply chains, yet in terms of Additive Manufacturing this study has shown there has been very little research conducted.

This investigation therefore provides an important contribution to this research gap by developing a suitable assessment mechanism of supply chain flexibility for Industrial Additive Manufacturing. Drawing on established supply chain flexibility literature, five constituent components of supply chain flexibility are clearly defined: operations, supply, logistics, information, and market. Each of these is explored in a detailed multi-method investigation of Industrial Additive Manufacturing supply chains, drawing on informants both upstream and downstream of the Additive Manufacturer. In doing so, important enablers and inhibitors of flexibility are identified, allowing for supply chain flexibility to be discussed in depth.

8.4 Answers to research questions

This study applies Parnaby's manufacturing system in the context of Industrial Additive Manufacturing, from which evaluations are made of the Operations Management concepts of demand, flexibility, and supply chain flexibility. It extends existing Additive Manufacturing research on the achievement of customization and low volume manufacturing, particularly in terms of Tuck et al. (2008).

This thesis builds on established concepts for Operations and Supply Chain Management, and contextualises them in terms of Industrial Additive Manufacturing through empirical research conducted with leading practitioners. In contrast to many other studies, by focusing on Industrial Additive Manufacturing in terms of a manufacturing *system*, rather than individual process *technologies*, the research demonstrates both the challenges and benefits arising from the adoption of the machines and their integration within the production environment. As a result, the findings have implications for both research and practice.

Four research questions have been tackled in this study, each of which has been developed from literature gaps identified in Chapter 2 and tackled sequentially in Chapters 4 - 7. The following four sections provide a succinct summary answer to each of these questions, based on the findings of each relevant chapter. As shown in Figure 8.2, each research question tackles an identified gap, contributing to the satisfaction of the overall aim of this doctoral study.

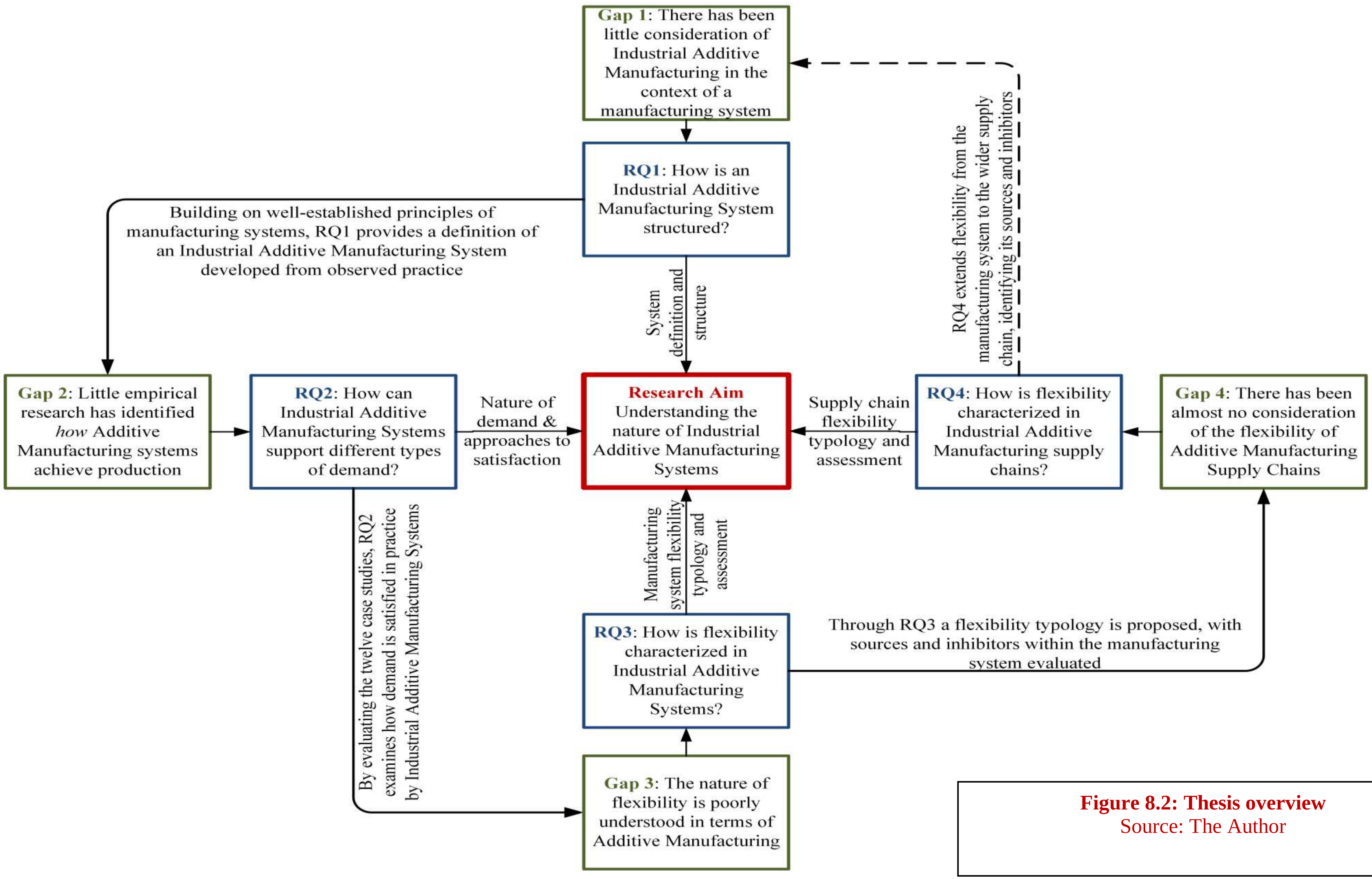


Figure 8.2: Thesis overview
Source: The Author

8.4.1 Research Question 1: What is the structure of an Industrial Additive Manufacturing System?

An Industrial Additive Manufacturing System is comprised of a series of activities, enabled by human, machine, and information resources, operating within the guidance of an over-arching control architecture. Developed from the general concept of a manufacturing system explored in Section 2.2, an Industrial Additive Manufacturing System may be represented visually as shown in Figure 8.3.

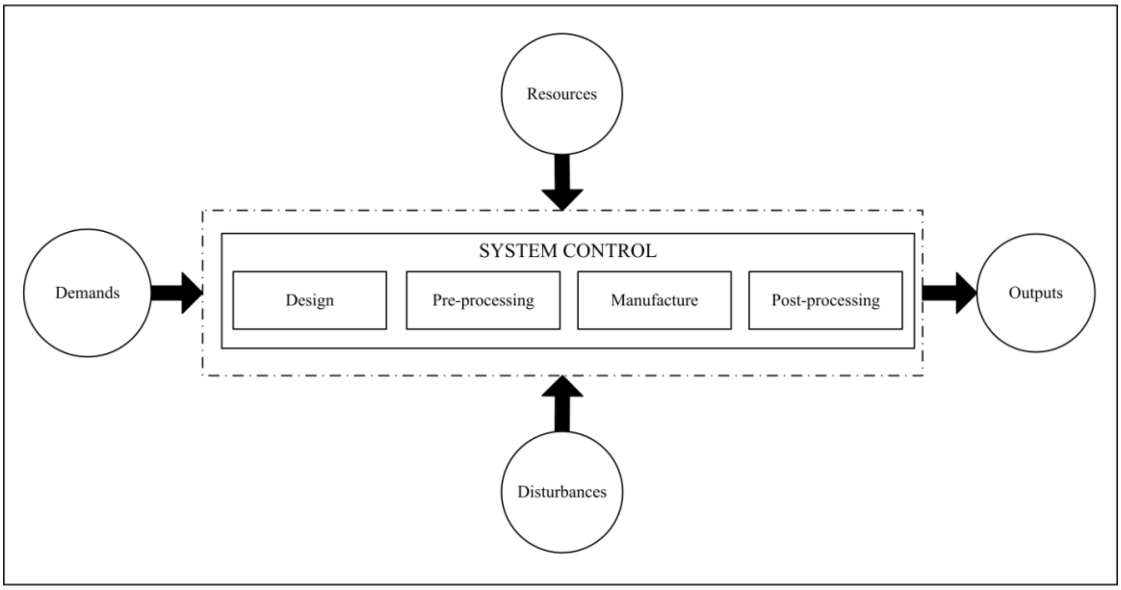


Figure 8.3: The concept of an Industrial Additive Manufacturing System
Source: The Author

Building on Parnaby (1979) and Parnaby and Towill (2009a), the research presented in Chapter 4 identified that there are four principal components that are common to Industrial Additive Manufacturing Systems:

1. Design;
2. Pre-processing;
3. Manufacturing;
4. Post-processing.

Using IDEF0 diagrams principally developed from process observation and interviews, the nature of these components has been identified. It is shown that each of these components is an aggregation of similar activities, behaviours, and controls, and has been demonstrated for all twelve case studies and three manufacturing systems. Whilst the technologies of Industrial Additive Manufacturing are shown to contribute to the fulfilment of production, a range of other machine, labour, and information resources are also identified as being necessary for the system.

In line with conventional manufacturing systems, a number of different control architectures are be identified as being feasible for an Industrial Additive Manufacturing System. Using the synthesis of Dilts et al. (1991), this research has demonstrated the application of control architectures for Industrial Additive Manufacturing Systems, and highlighted the relative merits and constraints for each architecture.

8.4.2 Research Question 2: How can Industrial Additive Manufacturing Systems support different types of demand?

Within this study (Section 2.9) it has been shown that Additive Manufacturing technologies are often promoted to achieve a wide range of geometries, particularly for low-volume and customized demand. The practicalities of how Additive Manufacturing satisfies demand are, however, poorly understood (Wilson 2012), and to better understand the way in which it is satisfied, in Chapter 5 demand has been principally delimited in terms of volume and variety characteristics. To provide context for this evaluation, at the organizational level it has been shown that Industrial Additive Manufacturing firms are subject to a wide range of different demand requirements, often with much uncertainty in its nature.

Through three in-depth case studies a detailed discussion of the activities undertaken for each component of the manufacturing system is presented. In *design* different approaches to the elicitation of demand are demonstrated, highlighting the interaction of the customer and manufacturer. In *pre-processing*, some of the most pertinent considerations and decisions made by the manufacturer are explained. *In post-processing*, emphasis is made on the finishing of parts by labourers and the combination with other components to produce end products. Some authors have suggested Additive Manufacturing leads to a labour reduction and/or deskilling of manufacturing (Nyman and Sarlin 2012), yet this research highlights the need for a careful consideration of many attributes. At present, whilst enthusiasm exists for a ‘just-click-print’ approach to manufacturing (Anonymous 2011a), design elicitation and manufacturing configuration requirements are observed to constrain this potential eventuality. By comparison, *Manufacturing* is shown to be a highly automated process in which parts are typically produced in simultaneous builds; this is in support of earlier economic models for production (Atzeni et al. 2010; Ruffo and Hague 2007). It is demonstrated that for the manufacturing stage, geometric customization has little implication for the production equipment. This supports existing enthusiasm for the technologies to produce customized parts, and to lessen the ‘specificity’ of manufacture (Helkiö and Tenhiälä 2013).

From a detailed appraisal of the twelve case studies, the applicability of conventional manufacturing theory is examined in the context of Industrial Additive Manufacturing Systems. It is shown the Industrial Additive Manufacturing Systems can be effectively employed in production both on-and-off the ‘optimal’ diagonal of the product-process matrix. There are, therefore, multiple configuration strategies that can be employed for Industrial Additive Manufacturing Systems. The case studies identify a reduction in the impact of customization on the manufacturing system using software tools (promoting the reduced specificity posited by Helkiö and Tenhiälä (2013), together with a focusing of labour (reducing its overall contribution to manufacturing as suggested by Tuck et al. (2008) as supporting this capability.

8.4.3 Research Question 3: How is flexibility characterized in Industrial Additive Manufacturing Systems?

Through the structured literature review presented in Chapter 2, the concept of ‘flexibility’ in the context of Additive Manufacturing was demonstrated as being ambiguous, and often poorly substantiated. Drawing on research from a wide range of both theoretical and applied papers it was demonstrated that the concept was most often linked to the ability of Additive Manufacturing machines to produce a range of different products at different production volumes, but as yet there has been little focus on the multifarious concept of flexibility from either an Operations Management or manufacturing systems perspective.

The nature of flexibility for Industrial Additive Manufacturing Systems may be evaluated from both external and internal perspectives, and the application of flexibility types already established for Operations Management is demonstrated as appropriate in this context. Within this study four external types (product, mix, volume, and delivery) are identified, and based on interactions with the manufacturers and customers this study reports on the findings of four cases. Product flexibility is identified as a requirement in all of the focal cases, either in the customization of existing designs or the development of new products. For the latter, the ability to provide prototypes in the support of new product development is shown to be a capability availed of by customers. Mix flexibility was not evidenced in these cases. Volume flexibility was only relevant for a single case, where an ongoing relationship between customer and manufacturer was established. Delivery flexibility was shown to typically involve expediting delivery, however in one case the potential to delay orders was demonstrated as supporting improved alignment between demand and supply of parts to customers.

As identified in Section 2.10 much of the literature has focused on the flexibility *capabilities* of the Additive Manufacturing technologies, rather than the specific flexibility *types* enabled by the system as a whole. The flexibility of any manufacturing system is inherently reliant on multiple contributing components Slack (1987), and by evaluating flexibility in terms of the different types and contributors this study extends these more general works.

To understand the internal nature of flexibility, a typology of seven flexibility types was proposed and explored for each of the four manufacturing system components. For each of the twelve case studies a classification of flexibility was provided based on the penalty observed. It was shown that whilst there are some specific characteristics of cases that influence the findings, for many flexibility types there is both inter- and intra-firm consistency in their achievement, and in Section 6.5.5 these patterns are explored in detail.

8.4.4 Research Question 4: How is flexibility characterized in Industrial Additive Manufacturing supply chains?

In Section 2.11 it was shown that very little consideration has been given to the nature of flexibility within the Additive Manufacturing supply chain. In response to this research gap, sixteen different approaches from other areas of research were evaluated, from which a modification of the Duclos et al. (2003) framework was utilized to assess the Industrial Additive Manufacturing Supply chain in terms of five flexibility types (operations, supply, logistics, market, and information).

One of the most interesting aspects of this research is the nature of supply flexibility within the supply chain. Using data from cases and an industry survey it was shown that a dichotomy of supply flexibility exists, delimited at the point of Industrial Additive Manufacturing. Supply flexibility upstream of the Industrial Additive Manufacturer is currently constrained as a result of sourcing flexibility. Constraints in sourcing materials are shown to make Industrial Additive Manufacturing companies reliant on few (sometimes one) supplier(s) of material. Machines are supplied with a typical three-month lead-time, for which there is no sourcing flexibility. By contrast, supply flexibility downstream of Industrial Additive Manufacturing is typically much greater.

Within this study it is shown that there is high variability of demand from customers, and for general requirements (i.e. not specialized medical applications such as Hearing Aids or Surgical Guides), much sourcing flexibility possible. Although Industrial Additive Manufacturing Systems are capable of improving supply flexibility to downstream customers, current constraints in material and machine supply hinder overall supply chain flexibility. Despite uncertainty in demand, Industrial Additive Manufacturing companies must hold stocks of raw materials to counteract inflexibility in material supply resulting from poor sourcing or vendor flexibilities.

8.5 Limitations of this study

8.5.1 Methodological limitations

The selection of a predominantly qualitative approach to the research conducted in this study is principally justified by its exploratory nature given the lack of research in this area. It is also well suited to the epistemological and ontological perspectives adopted by the author, and within this study it has been demonstrated as suitable in the achievement of in-depth information relevant to Operations and Supply Chain Management. Whilst the appropriateness and application of qualitative research has been discussed at length in Chapter 3, it is acknowledged that qualitative research is harder (but not impossible) to generalize from. Mason (1996, p. 6) notes that qualitative research "should produce explanations which are generalizable in some way, or have a wider resonance", and the author is in agreement, suggesting generalization where appropriate. However, it is important to recognize that this research was not designed with the intention of widespread generalization of results, and it is acknowledged that further research would help to extend the generalizability of the current study's findings.

The adoption of a case-based approach to the research is appropriate for tackling "how" questions (Yin 2009), and within this research it has been shown to enable a detailed understanding of the intricacies of Industrial Additive Manufacturing Systems. Combining different degrees of focus and depth allows the development of cases for discovery, description, and mapping (Stuart et al. 2002), and through the twelve cases presented in this research this has been achieved. Generalization from case data is theoretically possible (Flyvbjerg 2006; Ruddin 2006), and has been demonstrated in this research. However, despite the acknowledged advantages of the case-based approach, the author notes that its conduct does lead to challenges in the management of data, both in terms of its overall volume and the problem of managing different degrees of depth in its analysis. Convincing the sceptical reviewer (particularly those from a quantitative background) of the merits of a qualitative case-based study can be difficult, and for Åhlström (2007) the best approach is to illustrate the analysis process, and provide sound linkage between data and resulting theory. This does, however, require the researcher to distil rich qualitative research into the fundamental essence. Such collecting, processing, and presenting of data is acknowledged to be difficult, and within this research the proposal of Stuart et al. (2002) concerning a process of demonstrating chains of evidence presented in tables has been adopted where feasible.

8.5.2 Execution limitations

The research and preparation of this doctoral thesis must, by definition, be solely the work of a single student author. As a result, finite constraints bound the time and financial resources that are available. Within the physical sciences, student projects are typically conducted in research centres, for which the student may draw upon the collected resources of a large facility. In the social sciences, doctoral research tends to be a more individual pursuit that is unable to leverage some of the benefits arising from research centres. This is true of the current study, and it is acknowledged that the extra efforts needed by the researcher to identify previously unknown research participants and nurture ongoing collaborative relationships takes time away from data collection and analysis.

The nature of the research participants must also be acknowledged as a potential limitation of this study. Overall, this study has drawn from a range of both managerial and operational sources, and their perspectives have been invaluable in the development of this empirical study. The author is extremely grateful for their involvement at all stages of the research, and has recognized this in the opening acknowledgement section of this thesis. However, although much effort was expended in attracting research participants to the study, it was not possible to attract any manufacturers from Asia. As a result, whilst this study has received contribution from many of the 'main players' of Industrial Additive Manufacturing (from UK, Western Europe, and USA), the potential developments in emerging countries such as China has not been explored in this study. Whilst this does not invalidate the findings of this current research, it is important to recognize that the presently emerging markets will need to be considered.

A further limitation concerns the selection of Industrial Additive Manufacturing Technologies evaluated in this work. In choosing Laser Sintering/Selective Laser Sintering and Stereolithography systems, this research has explored the most commercially prevalent technologies (Wohlers 2012), and by complimenting this with the less popular but still relevant envisionTEC Perfactory processes the study attempts to generate findings representative for Industrial Additive Manufacturing Systems as a whole. However, it has been noted within this study that different processes have different implications for operations, and whilst evaluation of an extended range of technologies is not practical within the constraints of this study, the author recognizes that the characteristics of other technologies may have some influence on the activities conducted within the manufacturing system.

In the development of case studies, the utilization of interview methods has been particularly useful in the collection of data, and within the Chapter 3 the theoretical benefits and drawbacks of these approaches is documented. The quality of interviews is inherently linked to the abilities of the interviewer, and the relationship they have with the interviewee. Where possible, multiple interviews were conducted with respondents, allowing for the development of relationships and increased trust. Interviews are, however, an expensive method for data collection – particularly for this type of doctoral research where international travel for their conduct was required. Whilst the data collected in this study is sufficient to draw the conclusions that have been made, with greater resources it would have been beneficial to undertake more interviews with a greater range of participants. This would have allowed more topics to be explored, and also the potential development of research avenues that are acknowledged to exist but have not been travelled in this work.

Finally, the practicalities of publishing research from commercial sources must be recognized. Whilst this study has explored twelve case studies across three manufacturing systems, it is acknowledged that not all information gained could be included in this thesis. Whilst the companies involved shared a large amount of information with the author, commercial sensitivity dictates that some of the material obtained may not be published. The author is extremely grateful to all participants that have engaged in this research, and is mindful of his ethical obligations both to these companies, and also to future researchers who may wish to work with these organizations. For this reason some data is omitted from this thesis, and where necessary the most sensitive withheld data has been destroyed.

8.6 Opportunities for further research

The changing nature of the Industrial Additive Manufacturing landscape means that whilst the current study makes a useful contribution to knowledge, developments in the research (particularly of the process technologies and material availability) offer new avenues for future investigation. From the systems perspective, such changes have important implications:

> "Purposeful systems and their environments are constantly changing. Solutions to problems become obsolete even if the problems to which they are addressed do not." Ackoff (1997, pp. 437-438).

During the conduct of this study there was evidence of applications, technologies, organizations, and supply chains experiencing change, and as a result frequent clarifications were sought from interview respondents to ensure data collected was still valid. Whilst there was little obsolescence of data arising during the conduct of this enquiry, current projections for the future of Additive Manufacturing (Anonymous 2014; CSC 2012; Foresight 2013; Mankiya et al. 2012) and of Operations Management itself (Gunasekaran and Ngai 2012; Holmström and Romme 2012) suggest change will lead to a number of future research opportunities. Five particularly interesting topics for future Operations Management researchers are detailed in the following sections.

8.6.1 Understanding the implications for supply chain risk management

The evidence presented in Chapter 7 examined the nature of flexibility within the supply chain, and in doing so highlighted a number of inflexibilities and implications of these. One most important finding of this research concerned inflexibility in the supply of raw materials for production, where it was shown that Industrial Additive Manufacturers have few sources from which to achieve their materials. This material is often transported through multiple countries to reach the manufacturer, and is susceptible to disruption along the way. As a result, Industrial Additive Manufacturers were shown to hold expensive buffer stocks as a pragmatic hedge against vulnerability in the supply network.

This example serves to highlight one strategy adopted by Industrial Additive Manufacturers towards what is termed 'Supply Chain Risk Management' (SCRM). This concept has gained much traction since 2000, particularly in the wake of serious disruptions to increasingly global supply chains (Dani 2009), and has been recognized an increasingly important element of supply chain management (Ritchie and Brindley 2007). Risks in supply chain concerns disruption to flows (of material, information, products, and money) between organizations (Jüttner 2005), and such disruption has the potential to affect the efficient management of the supply chain (Ghadge et al. 2012). The importance of this topic, together with the increasing knowledge arising from recent research makes an extension into the context of Industrial Additive Manufacturing supply chains. Three feasible directions for research are:

1. Whilst a number of SCRM studies have identified sources of risk for supply chains in general, there has been no appraisal of these in the context of Additive Manufacturing. Jüttner (2005) identify that any SCRM strategy must be broader than an individual organization, and consistent with the current study it is suggested that further research explores the nature of supply chain risk both upstream and downstream of the Industrial Additive Manufacturer.
2. Harland et al. (2003) identify that risk assessment should examine the likelihood (probability) and significance (consequence) of risks. In line with previous activity, further research could aim to better understand the relative importance of individual risks within the supply chain.
3. Identification and evaluation of effective strategies for SCRM in Additive Manufacturing would make an important contribution to knowledge. Strategies for SCRM are often divided into those which are *proactive* (planned in advance of risks materialising) or

reactive (dealing with the consequences of risks that have materialised). Dani (2009) proposed a predictive-proactive methodology that would provide adequate quantitative data (gained through a variety of mechanisms) to help organizations understand risks and form proactive plans. This more structured methodology would build on the results of the more exploratory research posed in the previous two directions, with the potential to provide useful findings for both academia and industry.

8.6.2 Examining the potential implications of low-cost printers

The present study has intentionally focused on Industrial Additive Manufacturing Systems, and this is justified by their process capabilities and state of industrial adoption. However, the market for low-cost printers has shown significant growth (Wohlers 2013), fuelled initially by the expiry of Additive Manufacturing patents (e.g. FDM, and more recently LS). At present these systems lack sophistication and are unable to produce products that compete with either Industrial Additive Manufacturing Systems or most conventional technologies, but it is reasonable to assume the capabilities of these low-cost machines will improve in time. Various authors have suggested this will lead to a revolution in manufacturing (Berman 2012; Bogue 2013), but as yet there is little compelling evidence to support this in the near-term. Further empirical research is needed to explore which applications are most suitable for 'desktop manufacturing', and how this would affect Operations Management.

8.6.3 Identifying the potential of Industrial Additive Manufacturing Systems to support Lean, Agile, or Hybrid (Leagile) Manufacturing

Some initial efforts have been made to establish the suitability of Industrial Additive Manufacturing technologies to support Lean Manufacturing, however this is still at an exploratory stage. Tuck et al. (2007a) identify that Rapid Manufacturing technologies enable lean *and* agile production, and present some initial cases to support their work. Related work in a 3D printing context is presented by Nyman and Sarlin (2012). Similarly, Vinodh et al. (2009a) identify that agility in manufacturing has achieved limited consideration in the research literature, and demonstrate implementation in an SME (Vinodh et al. 2009b). Whilst both examples show some potential opportunities, more detailed work is needed to understand the implications arising for the manufacturing systems in organizations. Within the present study, Chapter 5 shows how some higher-volume products (despite being customized) can be suitable for line-based setup, whilst low volume production may be aligned to job and batch based production. BigCo identified efforts towards achieving lean production within their high volume medical products, but constraints in material supply particularly hampered their ability to minimize stock-holding and engage in JIT production. It would be beneficial for academia and practice to better understand how the principles of Lean and Agile manufacturing could be employed in contemporary Industrial Additive Manufacturing Systems.

8.6.4 Further exploration in the potential of distributed Industrial Additive Manufacturing Systems

Within this study HearingCo identified distributed manufacturing as a potential capability that could be exploited to offer both volume and routing flexibility for the manufacturing operation. BigCo actively demonstrated for its medical division the use of distributed Industrial Additive Manufacturing in the fulfilment of demand for customized medical devices nearer demand. In both cases this yields a physical distribution of Industrial Additive Manufacturing System. The components of design, and pre-processing remain in a centralized facility, whilst manufacture and post-processing occur closer to the final demand.

Initial explorations of distributed Additive Manufacturing have tended to focus on the technical implementation of such systems (e.g. Bateman and Cheng 2004; Luo et al. 2004; Tay et al. 2001), but it is already well known that technology alone is unlikely to improve product development (Sethi et al. 2003). Adoption of e-commerce technologies has many effects on the supply chain, including implications for procurement and supplier selection, visibility and information sharing, pricing and distribution, customization and postponement, and for aspects of decision support making (Swaminathan and Tayur 2003). For Operations Management this yields many interesting and as-yet unanswered questions that would be feasible directions for future research.

8.6.5 Implications of Metal-Processing on Industrial Additive Manufacturing Systems

This research has focused on polymer-based Industrial Additive Manufacturing Systems, which are by far the most prevalent in industry. However, technologies such as EBM and DMLS are increasing in their capability and popularity, particularly for aerospace and medical applications. Whilst there are fundamental differences between the metal and polymer processes, there is much consistency in many of the other activities undertaken in manufacturing. It is therefore hypothesized that the present study is relevant to these technologies also, however further empirical research is needed to establish the extent to which the findings of the present study may be extended to these manufacturing systems.

8.6.6 How does technological immaturity affect the methods used in Operations Management research?

One of the major challenges facing researchers is the selection of appropriate methods for the conduct of their work. As explained in Chapter 3, this requires a careful alignment between the methodological beliefs of the researcher and the acceptance of the methods as valid by the target audiences. For Operations Management, emphasis on positivistic research employing quantitative methods such as surveys and modelling is prevalent in scholarly journals, yet these methods are not typically recognized as the best approaches to exploratory research. For emergent technologies such as Industrial Additive Manufacturing, the limited number of potential research participants and the fragmented nature of implementation are problematic for some positivistic methods. Within the current study it clear that whilst the survey in Chapter 7 has successfully identified the nature of supply of Additive Manufacturing machines and materials relevant to the majority of installed machines, the small population size inherently limits the application of more advanced statistical methods.

If the recognized methods for publishing Operations Management research are unable to explore emergent and immature technologies for manufacturing, then the risk is that it 'reports' practice once established, rather than contributing to its development. Given the identified preoccupation with Operations Management research to be relevant to management practice (Slack et al. 2004), this disjunction between method and audience merits further investigation.

8.7 Chapter summary

This chapter has revisited the individual chapters of this thesis, and has demonstrated how the aim of the research has been achieved through the conduct of the study, leading to the satisfaction of the research questions. Within this chapter the principal contributions to knowledge has been emphasized, within the acknowledged limitations of the study. Whilst this research investigation has achieved its stated objectives, six most pertinent and important directions for the future continuation and development of this research are given.

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Appendix A An overview of the case research presented in this study

In the course of this research three Industrial Additive Manufacturing companies were examined in order to understand the nature of their operations, and the way in which manufacturing was implemented and managed. Each company produced a range of different products, and as discussed in Chapter 3, the Unit of Analysis within these cases is the product. From the wide range of potential cases available for investigation, the following twelve were selected based on:

- Availability of data from the manufacturer and also from other companies within supply chain
- Representativeness of product to typical supply of the company
- Confidentiality constraints
- Willingness and appropriateness of all respondents to participate in the research[4]

Hence, although the research is informed by the participating companies' production of a range of goods, only twelve are selected for inclusion in this study. As an aid to the reader in the following section a brief overview of these cases is presented, and, where confidentiality constraints permit, photographs of the individual products provided to support the discussion.

[4] For example, the author chose to omit one relevant case as he was not satisfied that the participating customer fully understood the implications of their contribution to the study. The author believed that consent must be informed consent, and that for the particular case the research participant was not capable of achieving an adequate understanding of the potential impact of their participation.

Case 1 Hearing Aid Shells

Additive Manufacturer	HearingCo	**Annual Volume**	Tens of thousands
Manufacturing Technology	envisionTEC Perfactory	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	Low
Machine Supplier	EnvisionTEC	**Variation of Demand**	High
Material Supplier	envisionTEC	**Time Window**	Next day
Customer	Audiologists (for supply to patients)	**Approach**	MTO

Case Overview

This case concerns the production of “In The Ear” (ITE) Hearing Aid devices, which are used by individuals with impaired hearing to provide some degree of correction. In the conduct of this case the research interviewed two audiologists (hearing professionals qualified and licenced to supply hearing aids), and also conducted interviews at HearingCo, a Hearing Aid manufacturer. A detailed discussion of the production of Hearing Aids is explored in Chapter 5.

There are several different types of Hearing Aid (Figure A.1), and the ITE device is used for both children and adults with more profound hearing loss. The device fits entirely within the ear canal, selectively amplifying noises from outside the ear. The ITE device consists of an outer shell, within which a number of electronic components are held, including a microphone and a Digital Signal Processor (DSP) which is used to process the external sound and convey it to an amplifier. Each ITE hearing aid is configured to the requirements of the individual patient. This necessitates a customised hearing aid shell to fit the individual ear, and a customised configuration of the internal electronics to match the hearing-loss profile. The configuration process is normally initiated by the patient visiting the audiologist for an assessment of their hearing, either as a new customer or as an existing patient.

HearingCo produced ITE devices using traditional craft techniques until 2000, with devices manually created by a skilled technician. The process has previously been described by Cortex et al. (2004), where having achieved a cast from the ear impression, nine further steps involving recasting, trimming and drilling are necessary to create the final product in a time consuming, fiddly operation.

For Operations Management, the challenge facing manufacturers is the achievement of a highly customized device, but with a very short manufacturing lead-time (often termed the ‘customization-responsiveness squeeze’ McCutcheon et al. (1994). HearingCo identified that the traditional crafting of each shell took three hours, with overall manufacturing lead-times for the entire device being in excess of one week. Quality was identified as being variable, with approximately 35% of all devices being returned by users as a result of poor fit.

In this case, the ability of Additive Manufacturing technologies to produce custom geometries without a penalty over standard geometries is exploited, and technologies suited to small batch production are used to promote flow. These machine capabilities, combined with flexibility in the workforce and focus in terms of the product range being produced result in a line-based manufacturing system capable of producing devices within a few hours, with a reduction of customer returns to 2%.

Figure A.1: Types of conventional hearing aid
Hearing Institute (Undated)

Figure A.2: ITE Hearing Aid
Phoank (Undated)

Case 2 Model Ship

Additive Manufacturer	LittleCo	**Annual Volume**	1 shop comprising approximately 700 individual timbers
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	High – customer visits
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	2 weeks per batch
Customer	Museum	**Approach**	MTO

Case Overview

This case examined the use of Additive Manufacturing technologies in the production of ‘timbers’ for a model ship by BigCo. In the conduct of this research the author engaged in participant observation at LittleCo, and conducted interviews and site tours of the customer premises. In this case the identified customer was an archaeologist and his team, working in a warehouse in South Wales in the preservation and model making of the ship. This case is detailed in Chapter 5.

The techniques of model-making have long been employed in archaeological applications to provide the audience with a tangible physical version of a historic artefact. To be effective research tools, models must achieve a high degree of accuracy - otherwise they are merely ‘pretty pictures’ (Sims 1997). For effective future research, archaeological models must be faithful and accurate reconstructions of the original artefact and so care needs to be afforded in the manufacturing process. The original archaeological find (Figure A.3) has formed a multi-year research project in order to understand the nature of the ship (Nayling and Jones 2014). Possible ideas for the ships design have been drawn (Figure A.4), however a unique element of the project was to focus on the creation of an accurate 3D model. The production of archaeological models has received relatively little research attention from the perspective of enhancing manufacturing processes. Normally produced at very low volumes (single models are commonplace), the manufacturing process has remained a labour-intensive craft process for many years, using traditional materials such as wood and paper in the fabrication of replica items. More recent forays into virtual modelling have provided an alternative to the craft approach, though these have often been shown to be expensive, and do not enjoy universal acceptance in the archaeological community. This case therefore explored how to achieve effective realization of the ship through 3D scanning (Figure A.5), modelling (Figure A.6), manufacture and assembly (Figures A.7, A.8).

Figure A.3 Excavation of ship timbers
Source: Newport Museum Service

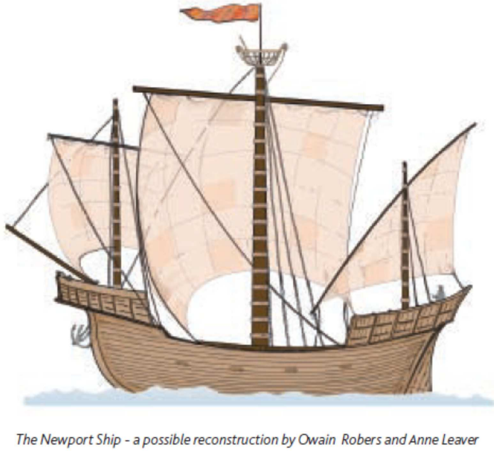

Figure A.4 Artist impression of Newport Ship
Source: Newport Museum Service

Figure A.5 Geometry capture using FAROArm
Source: Newport Museum Service

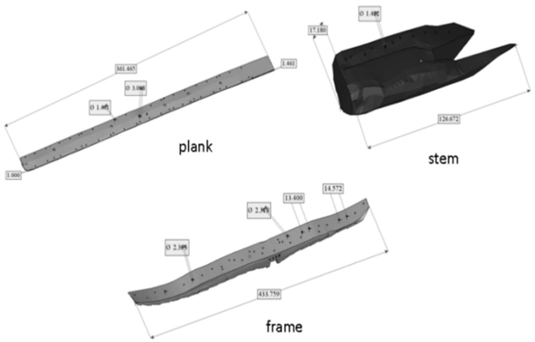

Figure A.6 CAD Model of Newport Ship components
Source: Soe et al. (2011)

Figure A.7 Assembly of model
Source: Nayling and Jones (2014)

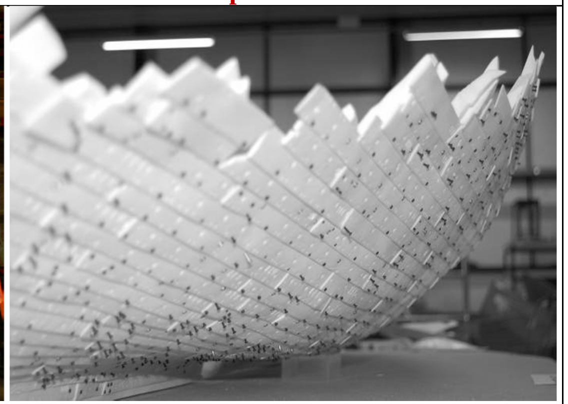

Figure A.8 View of assembly detail
Source: The Author

Case 3 Archaeological Models

Additive Manufacturer	LittleCo	**Annual Volume**	4
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	High – customer visits
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	2 weeks
Customer	Museum	**Approach**	MTO

Case Overview

This case concerned the production of replica medieval stones for display at a museum, with scanning of the original pieces in-situ at an Irish cathedral. Scanning of the original stones was undertaken at the cathedral using a contactless Konica-Minolta VI-900 scanner. This process took twelve hours, leading to the creation of a lattice model with over 300,000 vertices. Each stone was produced life-size, requiring no scaling of the design. To reduce the amount of material used in the production of the stones, each design was hollowed to produce a stone approximately 0.5 meters tall, weighing between 20 and 30kgs. One of the major challenges of this application was to achieve a realistic reproduction of the medieval stones for display in a museum environment, necessitating much consideration of the aesthetic qualities of the artefact. This was particularly challenging given the highly faceted nature of the part surface. As each stone would be professionally painted in post-processing, at the manufacturing stage it was necessary to conduct a series of trial builds to evaluate the best approach with regards to build orientation and the initial post-processing activities of powder removal. Several samples were sent to the model-maker before the final configuration was decided; subsequently it was possible to build two model stones in a single LS build. The EOS P700 machine employed in this task operated at 10mm per hour; the completed stones took 40 hours to build at a combined cost of approximately £3,000. On build completion excess powder was removed to reveal the white stones before shipping to the model-maker to be hand-painted (Figure A.9).

Figure A.9: Archaeological model of a dog
Source: LittleCo

Case 4 Architectural Models

Additive Manufacturer	LittleCo	**Annual Volume**	20
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	High – customer visits
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	1 week
Customer	Architecture Students	**Approach**	MTO

Case Overview

This case concerned the production of 20 individual models created by undergraduate architecture students using 3D CAD software as part of their studies. Whilst the utilization of 3D modelling in commercial practice is becoming increasingly commonplace, student training lags this trend. This case study was developed as a result of participant engagement at LittleCo during the requirements elicitation, manufacturing, and handover activities, and also included interviews with the students' instructor who was overseeing their work. A more detailed exploration of model-making for Additive Manufacturing can be found in the author's related publication (Eyers et al. 2012b).

Models are used in architectural projects for a number of purposes including the development of ideas, the presentation of these ideas to colleagues and clients, the exploration of processes, and the testing of design solutions in a cost-effective and safe manner (De Beer et al. 2004; Gibson et al. 2002). These models can be tangible: physical artefacts which can be held, explored, and manipulated, or alternatively exist in an intangible form where they are Virtual models existing only a computer screen. Since Additive Manufacturing has the potential to create physical artefacts directly from the virtual forms, for architecture it offers the potential to connect these virtual and real worlds (Shih 2006). For architectural applications three types of model are typically created depending on the various stages of the project (Ryder et al. 2002). The first is the 'feasibility model' which is simple, inexpensive, and give a basic idea of form and mass. The second, slightly more complex model is the 'planning model' which provides more detail than its feasibility counterpart. The third, 'final project model' is very detailed and used to demonstrate how developments will look once the project is complete. As shown in Figures A.10 and A.11, the students produced feasibility models within their project brief. Each model was very different in terms of geometry, and ranged from complex lattice-like structures (Figure A.10) through to more conventional, larger surfaces (Figure A.11).

Each design was created by a single student and sent electronically to LittleCo for production. The relative inexperience of the students in the design of products for Additive Manuacture was noted by LittleCo as necessitating considerable pre-processing activities by the bureau, particularly in scaling and fixing designs prior to manufacture. Once all parts were verified, production was planned and the parts produced simultaneously in polyamide 12 using an EOS P700 laser sintering machine. Each part was individually post-processed by a skilled technician, including cleaning and assembly activities.

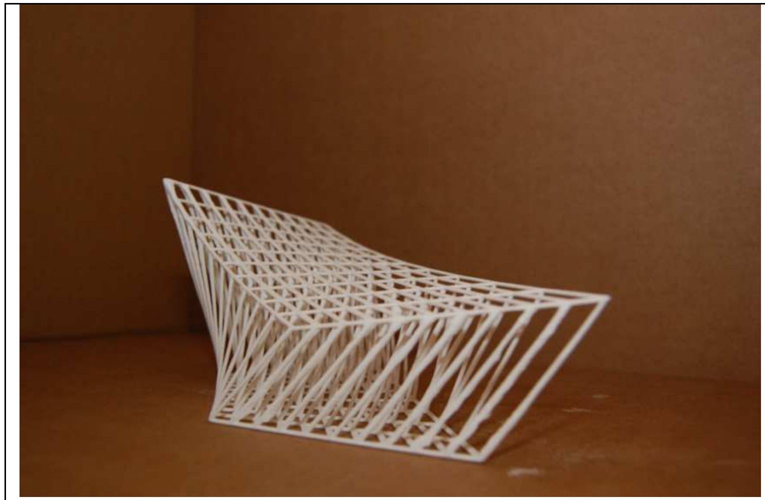

Figure A.10 Architectural model
Source: The Author

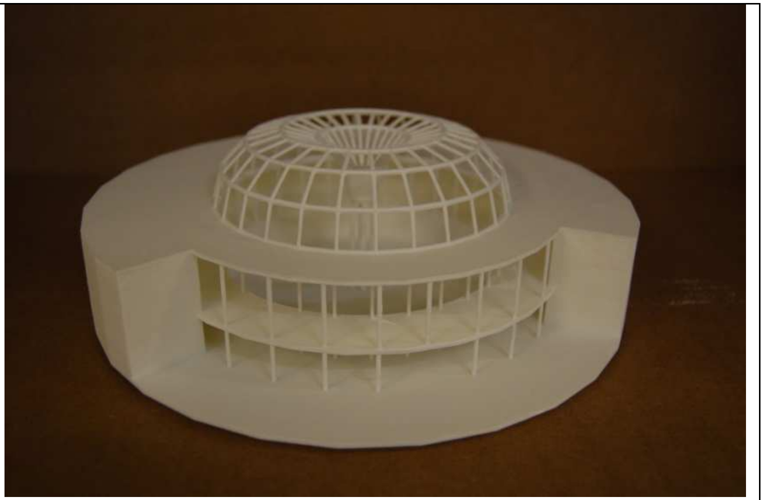

Figure A.11 Architectural model
Source: The Author

Case 5 Exhaust Tool

Additive Manufacturer	LittleCo	**Annual Volume**	1
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Tooling	**Visibility**	High – customer visits
Machine Supplier	3D Systems	**Variation of Demand**	High
Material Supplier	3D Systems	**Time Window**	2 weeks
Customer	Exhaust Manufacturer	**Approach**	MTO

Case Overview

Additive technologies have been shown to offer a major benefit is in the creation of tooling, which typically constitutes a major time and cost burden for manufacturers (Gibbons et al. 2003). The use of Additive Tooling has been shown to enable complex shaped tooling inserts, jigs, and fixtures to be manufactured rapidly and efficiently to support conventional manufacturing processes (Dimov et al. 2001; Ma et al. 2007). Designs for tools can be created based on the 3D CAD model of the original product, and quickly fabricated using a selected Additive Manufacturing technology. Leadtimes can be reduced by over 80% (Oakham 2002), which can reduce the time-to-market of new products and thereby offer firms a competitive advantage. The paradox exists that whilst Additive Manufacturing does not need tooling for its own operation, one of its strengths is its capabilities to create tooling for rival conventional manufacturing processes.

This case concerns the production of a hydroform tool for the production of automotive exhaust systems. There are three principal hydroforming methods: shell, sheet, and tube hydroforming, all of which are employed in the creation of lightweight components using a range of forming techniques (Lang et al. 2004). This case concerns the tube hydroform process, which has increased in popularity for automotive applications in recent years, leading to a shift from conventional stamping processes to the tube hydroforming alternative. In tube hydroforming, sheet metal is placed within two halves of a tool, which is then closed and subjected to fluids at a very high pressure which forces the material into the shape of the tool, enabling the production of complex shaped metal parts (Figure A.12)

Using Additive Manufacturing for tooling processes may be categorized as being either direct or indirect. The direct approach produces a metal part directly using an Industrial Additive Manufacturing machine capable of metal processing (e.g. DMLS), using a very high powered laser to fuse the metal powder achieving an almost 100% dense part. LittleCo does not posess such equipment, and so used an indirect process where a polymer coated metal powder is fused in its 3D Systems HiQ machine.

Using a CAD model of the required part (Figure A.13), a laser sintered porous skeleton part (known as a Green Part) was produced in the same manner as other parts produced in Industrial Additive Manufacturing Systems. However, this part required much post-processing, requiring subsequently infiltration with a low melting point alloy (e.g. bronze) in an infiltration furnace to achieve a fully dense part (Figure A.14). Whilst this is therefore a more manual and laborious process to perform compared to direct approaches, it does enable the use of the commonly available laser sintering processes (e.g. SLS), rather than the less common and considerably more expensive metal processing machines.

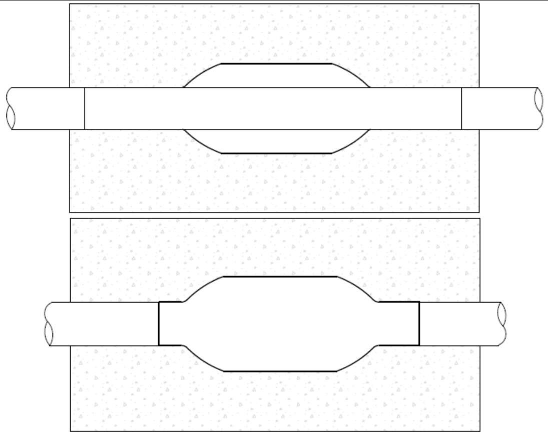

Figure A.12 Hydroform process – before (top) and after (bottom)
Source: The Author

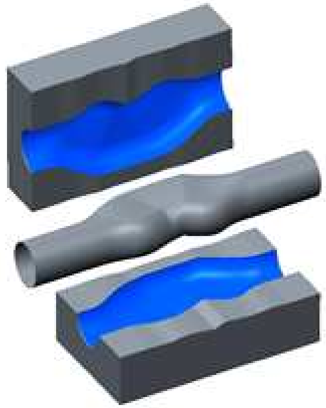

Figure A.13 CAD model
Source: LittleCo

Figure A.14: Manufactured insert
Source: LittleCo

Case 6 LittleCo Fixtures			
Additive Manufacturer	LittleCo	**Annual Volume**	1
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Tooling	**Visibility**	Medium – telephone updates
Machine Supplier	3DSystems	**Variation of Demand**	High
Material Supplier	3DSystems	**Time Window**	1 week
Customer	Medical Manufacturer	**Approach**	MTO

Case Overview

In the production of many conventional products, fixtures are an essential resource that are utilized whenever a component must be located and held with respect to a machine-tool or measuring device, or with respect to another component, as for instance in assembly or welding. Conventionally, fixtures are made of plastic or metal and are produced by machining processes. The lead times are variable and can often extend to several weeks for production of moderately complex fixtures. For these conventional processes, lead time and costs increase as the fixture becomes more complex. Further limitation arises since both design for manufacturability and design for assembly rules apply to fixtures, and resultantly optimal fixture designs are often sacrificed to satisfy machining or fabricating constraints. In the design of new products for manufacture, consideration of fixtures is therefore often an important consideration.

This case concerns the development of fixtures for a new toothbrush product, for which LittleCo were required to produce fixture plates and mounts (Figures A.15-A.18). LittleCo had previously produced the toothbrush through Additive Manufacturing, and to create the fixture used an inverse of the CAD model to create an exactly fitting fixture design. Produced using a 3D Systems HiQ machine, the part was built in six hours at a cost of £250. Alternative options using CNC machining of an aluminium billet was identified by LittleCo as costing £760, and taking 24 hours to complete.

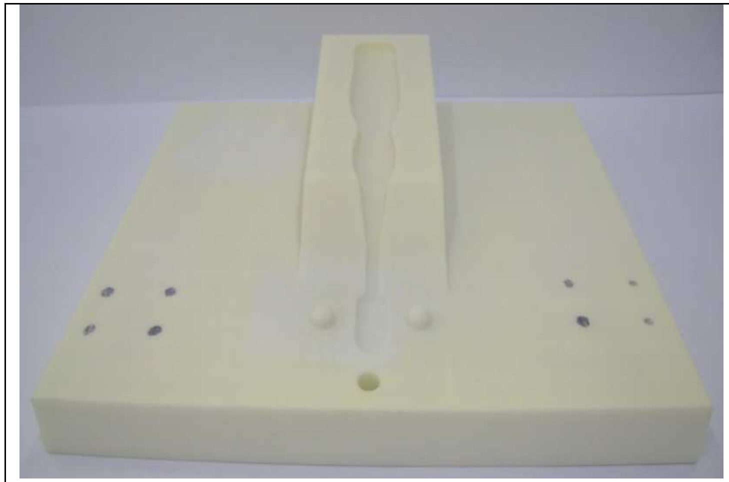	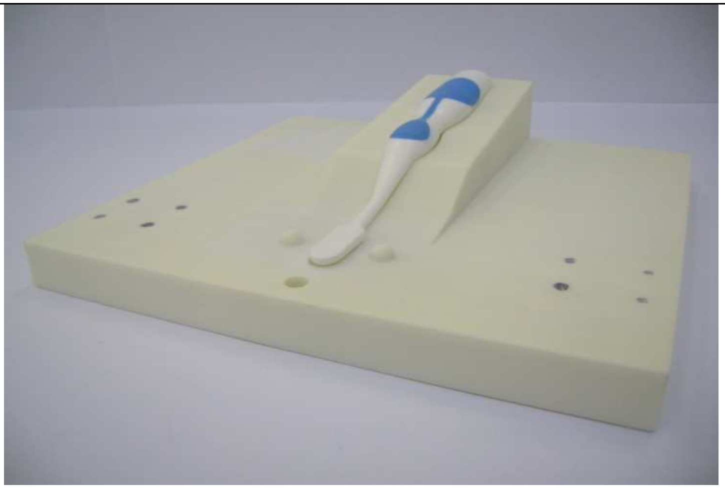
Figure A.15: Toothbrush fixture plate Source: The Author	**Figure A.16: Toothbrush fixture plate with product** Source: The Author
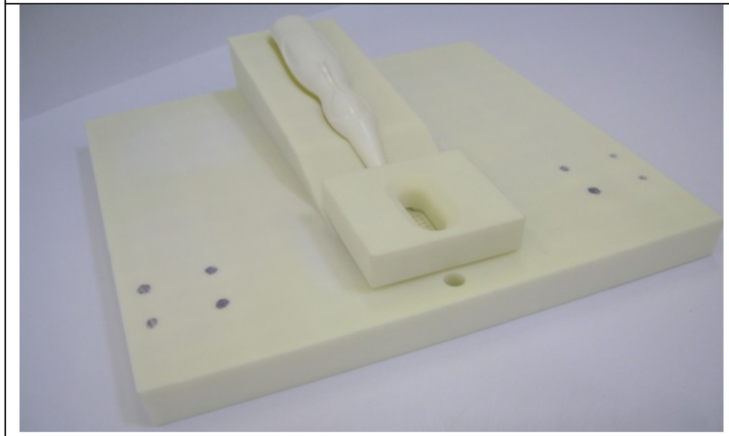	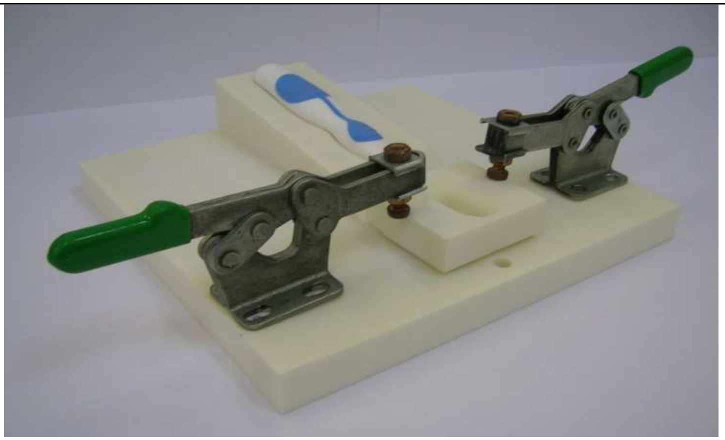
Figure A.17 Toothbrush fixture plate with product and assembly mount Source: The Author	**Figure A.18 Toothbrush fixture plate with product and assembly mount clamped** Source: The Author

Case 7 Sensor Tool

Additive Manufacturer	LittleCo	**Annual Volume**	3
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Prototyping	**Visibility**	Medium – telephone updates
Machine Supplier	3DSystems	**Variation of Demand**	High
Material Supplier	3DSystems	**Time Window**	1 week
Customer	Exhaust Manufacturer	**Approach**	MTO

Case Overview

Exhaust systems for modern domestic automobiles typically include a Lamba sensor which measures the emissions of the vehicle's engine in terms of a fuel/air ratio. Through a closed loop control system, this sensor provides feedback to the car to in order to maintain the optimal mixture of gases entering the catalytic convertor of the car. In the manufacture of exhaust systems a hole is laser cut in the exhaust tube (Figure A.19), in which the lambda sensor will later be inserted. Under normal circumstances the metal slug offcut will be ejected through the open end of the exhaust; however, the potential exists that the part will remain attached as a result of metal melting and re-solidifying.

This case concerns a project involving LittleCo and an exhaust system manufacturer in the development of a prototoype tool to test for the presence of an undetached metal slug in the tube. The customer designed an inspection tool (referred to as 'sensor tool') to mechanically test for the presence of the metal slug (Figure A20). LittleCo received 3D CAD files for this part, which were refined to afford manufacturability. The evaluation part (Figure A.21) was manufactured using an EOS P700 Laser Sintering machine, for conformance testing and evaluation by the exhaust manufacturer (Figure A.22).

Figure A.19: Hole for lambda sensor
Source: The Author

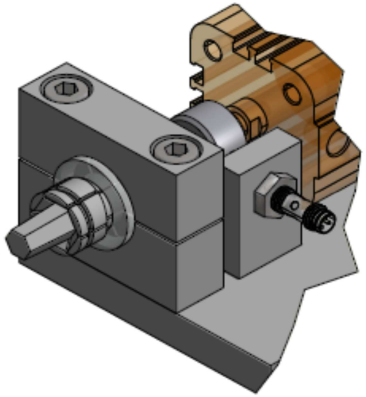

Figure A.20 Inspection tool envisaged design
Source: Exhaust Manufacturer

Figure A.21: Laser sintered part
Source: The Author

Figure A.22: Sensor tool in situ
Source: The Author

Case 8 Surgical Guides			
Additive Manufacturer	BigCo	**Annual Volume**	Tens of thousands
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	Medium – telephone/email updates
Machine Supplier	EOS	**Variation of Demand**	Low
Material Supplier	EOS	**Time Window**	3 weeks
Customer	Assembler & orthopaedic surgeon	**Approach**	MTO

Case Overview

This case concerns the production of surgical guides, which are medical products used by surgeons when operating on patients. Surgical guides are prepared in advance of operations, and are customized to the individual requirements of each patient. A detailed appraisal of the nature of these products has previously been provided (Bibb et al. 2009), to which the interested reader is directed.

BigCo identified that one of the major challenges for this application is the need to achieve high accuracy in the geometry of the products produced, for which two principal strategies are identified:

- Using CT data from the patient, the company works closely with the consultant/surgeon in the development of a 3D CAD model for production. To assist in this process, BigCo has developed specialist configurator software to simplify some of the operations, reducing time and development effort.
- A dedicated production line exists, producing only these medical parts. This allows the company to ‘tune’ machines to an optimum configuration, and to engage specialist staff most familiar with the pre- and post-processing activities.

This accuracy is confirmed within post-processing, where each surgical guide is subject to enhanced quality assurance checks prior to despatch.

Case 9 Custom Lamps

Additive Manufacturer	BigCo	**Annual Volume**	Hundreds
Manufacturing Technology	Laser Sintering	**Variety/Customization**	Medium
Classification	Rapid Manufacturing	**Visibility**	Medium –email updates
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	1-2 weeks
Customer	Various B2B and B2C	**Approach**	MTO

Case Overview

The ability to produce highly complicated geometries has led to the application of Industrial Additive Manufacturing technologies in the production of a wide range of artistic and design applications. One such example is that of lamps, which comprise a combination of parts made using conventional and additive technologies. A detailed review of this case is provided in Chapter 5, based on interviews and observations at BigCo.

The provision of this product by BigCo was motivated by an observed demand for customized lighting products, but an acknowledgement that customers typically lacked the ability to independently create their own designs. Prior experience had shown that some customers struggled to design manufacturable products, and/or were dissatisfied with their own efforts when realized in production. As a result it developed a single lamp design for which the lampshade with a limited range of options. By restricting the potential customization to different shade textures (3), different typefaces (3), and up to 140 characters of text that could be integrated into the shade design.

Lamps are designed using an online configurator developed by BigCo and hosted on its website, alongside its normal product range. Customers are able to configure their lamp using a series of drop-down options, and provide their customized message for inclusion on the lamp in a free text box. Orders are received and processed at the company’s central European facility, and normally orders are fulfilled within 2 weeks.

Case 10 Standard Lamps

Additive Manufacturer	BigCo	**Annual Volume**	Hundreds - Thousands
Manufacturing Technology	Laser Sintering	**Variety/Customization**	Low
Classification	Rapid Manufacturing	**Visibility**	Medium – telephone updates
Machine Supplier	EOS / 3D Systems	**Variation of Demand**	Medium
Material Supplier	EOS / 3D Systems	**Time Window**	2 weeks
Customer	Various B2B and B2C	**Approach**	MTS

Case Overview

This case concerns the production of standardized lamps using Industrial Additive Manufacturing, made popular as a result of the wide range of complex geometries possible from these technologies. BigCo produce a wide range of different lamp designs from their own catalogue range, and sell these both online and though retail distributors. This case was developed as a result of interviews and observation at BigCo.

One of the most interesting characteristics about this case is the approach taken to the fulfilment of demand. As illustrated in Section 2.9, most research has focused on the production of products in response to individual customer orders, normally as a result of customization requirements. This example is different, since the standardized nature of the product means that it can be produced to stock, based on forecast demand requirements. BigCo identified that such products made for easier planning and scheduling of production, particularly in terms of utilizing spare capacity. Additionally, such an approach was described as improving responsiveness, with orders fulfilled from retailers' shelves and normally replenished with new stock on a fortnightly basis.

Case 11 Modular Fixture System

Additive Manufacturer	BigCo	**Annual Volume**	Hundreds - Thousands
Manufacturing Technology	Laser Sintering	**Variety/Customization**	Medium
Classification	Rapid Tooling	**Visibility**	Medium
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	3 days
Customer	B2B	**Approach**	MTO

Case Overview

This case concerns a system developed by BigCo for the production of fixtures for assembly and testing purposes. As identified in Case 6, fixtures are an important component in conventional manufacturing, particularly during the launch of new products. In response to market requirements, BigCo developed a modular system to suit a wide range of applications, representing a more sophisticated approach than that employed in Case 6.

The modular system comprises of two conventional modules (known as the ‘beam’ and ‘plate’), which are standardised aluminium components that may be used in all fixture applications. As shown in Figure A.23, these connect to the product using contact elements (Figure A.24), each of which is shaped to exactly fit the target geometry. These contact elements are created automatically based on a 3D model of the designed product (which can either originate from a designer’s 3D model, or from 3D scan of the physical product), and manufactured by BigCo in polyamide to a tolerance of 0.1mm.

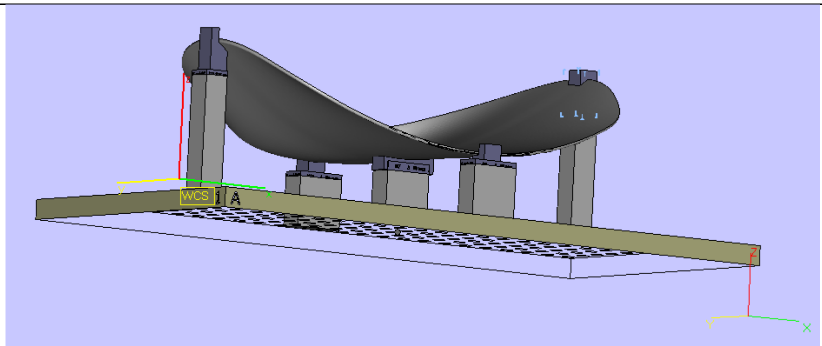

Figure A.23: Modular beams and contact elements holding curved seat profile

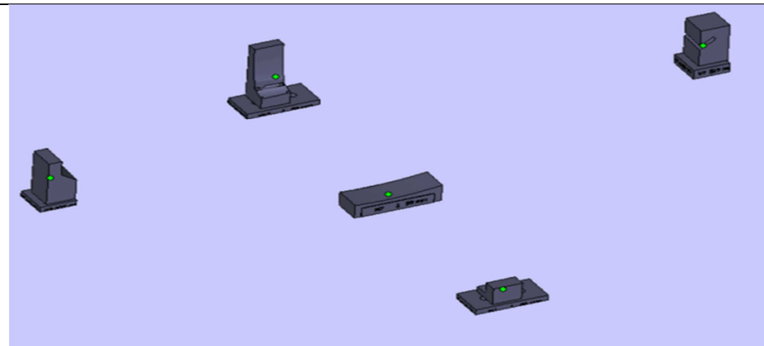

Figure A.24 Contact element designs for production

Case 12 Furniture			
Additive Manufacturer	BigCo	**Annual Volume**	1
Manufacturing Technology	Laser Sintering	**Variety/Customization**	High
Classification	Rapid Manufacturing	**Visibility**	Medium – telephone updates
Machine Supplier	EOS	**Variation of Demand**	High
Material Supplier	EOS	**Time Window**	1 week
Customer	Designer	**Approach**	MTO

Case Overview

This case concerns the production of a furniture item that was designed by a professional Additive Manufacturing designer, and subsequently fabricated by BigCo. It was a large item, requiring production in several pieces in multiple builds, and extensive post-processing to achieve desired surface characteristics. Confidentiality constraints prevent the author from providing a discussion of the nature of this part.

Appendix B Research Ethics

B1.1 Established protocol for Operations Management research

The nature of the research conducted in this study necessitates consideration of potential ethical implications. Research ethics are important in the protection of all research participants (including the investigator); one of the "Ten Commandments" for ethics is that investigators should not even consider accepting a research project where professional or ethical standards may be violated (Sarantakos 2013).

For established disciplines such as medicine, explicit communication of the ethical design and conduct of the research is normal, and often a confirmatory statement of this is requisite for the publication of research. However for Operations Management, comparatively little has been written concerning the issues of ethics in the conduct of research; as Svensson and Bååth (2008) recognize this observation extends also Supply Chain Management Research. This is not to indicate that this research is unethical, but as with the earlier consideration of research philosophies, it is a notable omission at this stage of the development of Operations Management. Karlsson (2008) identify four key principles of ethics in Operations Management, the emphasis for which are primarily legalistic:

- Emphasis should be placed on consent
- Research should have clear utility (i.e. the benefits should outweigh burdens)
- Caution should be exercised, and risks evaluated
- Justice should be obeyed, and benefits shared (with intellectual property rights upheld)

The absence of ethical consideration is somewhat surprising for two reasons. Firstly, in recent years ethics has been a growing concern for both business and academia. In academic research, ethical frameworks have increased in their prevalence, leading to a "globalisation of ethics" (White 2009) where the agenda is set by national and international committees (e.g. funding councils), rather than at a local/institutional level. Secondly, from a more practical perspective, Operations Management research often involves extensive contact with employees, handling of sensitive data and dissemination to a range of audiences, all of which have the potential to raise considerable ethical implications.

In the neighbouring discipline of Operations Research (OR), a small body of research is growing into the conduct of ethical OR, particularly with regards to modelling and is therefore relevant to elements of this study. In traditional OR, models create "objectively optimal" solutions which exclude ethical concerns to "ensure the formal validity of their solution" (Le Menestrel and Van Wassenhove 2004). However, since modelling is an abstraction of reality, modellers make choices in how they model data, and therefore there is an obligation on them to be honest and accurate in their claims (Le Menestrel and Van Wassenhove 2004). However, there are influences which may act counter to this ethical approach. White (2009) observes that researchers both in OR and other disciplines have multiple conflicting interests including: conducting high quality research, completing the work expediently, protecting research participants, obtaining funding, and also the advancement of their career. This study therefore observes ethical research to be a multi-faceted and challenging pursuit.

B1.2 Ethical considerations in this study

In the absence of a framework for Operations Management Research Ethics, a synthesis of pertinent ethical issues has been developed, and their relevance to this study discussed in Table B.1.

The research involved the interview of a number of individuals, chosen according to their job description, and not on any other measures (including age, gender, race, religious beliefs etc). When negotiating access with gatekeepers, efforts were made to ensure that selected respondents were willing to take part (rather than feeling obligated). From the commencement of the research it was be made clear that all participation was voluntary, and that the individual or organisation may withdraw their involvement at any time. This statement was reiterated periodically through the conduct of the research.

The research has been conducted in accordance with Cardiff University Research Ethics procedures, and a copy of the relevant consent forms are included in this appendix.

	Ethical Consideration	Approach taken in this study
Design	Identify applicable codes for ethical research already in existence	This research is underpinned by the ethical policies of ESRC (2005), Cardiff University (2010), and Engineering Council UK (Royal Academy of Engineering 2012)
	Evaluate objective approaches to data collection to ensure quality	Qualitative research is employed that has been designed to promote validity and reliability.
	If deception is part of the research, is it justified and to what degree?	Not applicable; all research participants will be fully informed on the nature of the study.
	Identify measures to minimize/eliminate physical & mental stress for research participants	Case studies are developed with research participants, informed by multiple methods. The participatory nature of interviews merits particular attention: these shall be conducted at the informants premises for which they are familiar and comfortable. Where the interviewer perceives interviewee discomfort (or where it is stated), the interview topic will be changed or the interview terminated.
	Identify likely benefits of research for participants, and whether the research is justified	Participants will have the opportunity to discuss and develop ideas concerning their Additive Manufacturing operations with the researcher. Participants will have access to copies of published research if desired.
	Evaluate potential benefits relative to harm to assess study justification	The most likely harm that may arise as a result of this research is identified to be a breach of confidentiality. As a result, all responses are held anonymously and procedures in place to secure data to minimize the potential harm. Any material that could cause harm to the research participants will not be published. The main benefit for the research participant is an increased awareness of the implications of Additive Manufacturing on their operations and supply chain management.
	Balance consideration of internet usage	As far as possible data shall be collected in-person; where this is not possible VOIP telephony may be employed in the conduct of interviews. The asynchronous tool of email will be used only for arranging research meetings, or for exchanging documents.
	Identify how data will be stored, and who will have access	The author shall solely have full access to data; where it is considered appropriate this will be extended supervisors. All data held electronically (interview recordings, typed transcripts, company data, research text) shall be stored on an encrypted hard disk, and regular encrypted backups made. All paper-based research shall be stored in a locked cupboard for which only the researcher has access.
	How will data be verified, and by whom	Data shall be verified by follow-up interviews or discussions with the research participants.
	Identify effective measures for anonymity & confidentiality	All respondents and the organizations for which they are employed will be anonymised in any publications.
	How will results be disseminated, and to whom?	Research will be disseminated in scholarly publications (conference and journal papers), trade journals, and in case examples for teaching in Higher Education.
	Assess potential legal implications	The principal legal implications relate to the secure storage of the data in accordance with the UK Data Protection Act (1998)

Preparation	Identify potential participants who are able to adequately respond to the research question	Research participants are invited to contribute to this research based on their job descriptions, and initial screening discussions are employed to identify the extent of their knowledge. It is recognized that their technical understanding of Additive Manufacturing is largely irrelevant.
	Provide adequate upfront information	In exploratory studies it can be difficult to provide sufficient upfront information, and so the researcher must explain, to the best of their knowledge, the nature of enquiry at each point of data collection.
	Explain consequences of research	Research participants are advised that they will contribute to qualitative interviews, and this may be complimented with other data that are achieved through techniques such as process mapping. It is made clear that this is a scholarly activity, and the dissemination outlets explained.
	Achieve informed consent	The Cardiff University approach to Informed Consent is employed.
	Minimize and explain harmful aspects of the research	The researcher will maintain confidentiality and be sensitive to any concerns expressed by participants.
	Minimize participation coercion to participate	The researcher will aim to build a relationship of trust between himself and the research participants, in which the value of their participation is made clear, but the voluntary nature of the participation stressed.
	Present the benefits of participation honestly	Participants will be advised of the potential benefits arising from participation in the research in an honest and frank manner.
	How far should the researcher's own agenda influence the research?	The researcher shall be clear about their intentions to use the research for scholarly publication in the form of a PhD and related academic publications. The main research objectives of the research will be explained to the participants in an accessible manner.
	Establish degree of reciprocity	Research participants will have access to the general publications of the research, however the identification of participants, together with any sensitive/unpublished will not be permitted.
	Utilize developed code for ethical research	The practices explained in this table are employed in the research process.
Execution	Do not cross-contaminate execution of research between participants	The research shall take great care not to discuss the contribution to research made by other participants. Any questions from respondents concerning other contributors shall be rebuffed.
	Uphold professional standards in research conduct	The researcher shall make frequent reference to the professional standards and uphold them in the conduct of this research.
	Discontinue research where resistance or discomfort is evident	Whilst every attempt is made to ensure the research does not cause discomfort, the researcher will discontinue his investigation at the request of the research participant.
	Ensure results are disseminated only to those intended and in the manner planned	The researcher will clearly explain the potential outlets for dissemination of the research to participants, and abide by these.
Dissemination	Uphold professional standards in research conduct	The researcher shall make frequent examination of the professional standards for research, and reflect upon these in the analysis and preparation for dissemination of the research.
	Ensure benefits are not withheld	The researcher will honour any requests for copies of publications, and make themselves available to discuss the implications of Additive Manufacturing for their organization's operations and supply chain management.
	Honour anonymity	The identity of the research participants will not be divulged beyond the immediate supervisors of this Doctoral research.
	Avoid invasion of privacy	The researcher will not ask questions that infringe the privacy of the individual respondent.

Table B.1 Pertinent issues for Operations Management research

Source: The Author based on (Bryman and Bell 2011; Karlsson 2008; Saunders et al. 2012)

B1.3 Cardiff University Research Ethics Approval

CARDIFF BUSINESS SCHOOL ETHICAL APPROVAL FORM:
PHD THESIS RESEARCH
(For guidance on how to complete this form, please see http://www.cf.ac.uk/carbs/research/ethics.html)

For Office Use: Ref **Meeting**

Does your research involve human participants? Yes ☒ **No** ☐
If you have answered 'No' to this question you do not need to complete the rest of this form, otherwise please proceed to the next question

Does your research have any involvement with the NHS? Yes ☐ **No** ☒
If you have answered **Yes** to this question, then your project should firstly be submitted to the NHS National Research Ethics Service. Online applications are available on http://www.nres.npsa.nhs.uk/applicants/ . It could be that you may have to deal directly with the NHS Ethics Service and bypass the Business School's Research Ethics Committee.

Name of Student: DANIEL EYERS

Student Number: 991423468

Section: CARDIFF BUSINESS SCHOOL

Email: EYERSDR@CF.AC.UK

Names of Supervisors: DR HARTANTO WONG, DR ANDREW POTTER

Supervisors' Email Addresses: WONGH@CF.AC.UK, POTTERAT@CF.AC.UK

Title of Thesis: AN ASSEMENT FOR THE ENABLEMENT OF MASS CUSTOMISATION

Start and Estimated End Date of Research: **OCTOBER '08 – SPRING '11**

Please indicate any sources of funding for this research: STAFF CANDIDATE

1. Describe the Methodology to be applied in the research

This research will develop a framework to classify different levels of Mass Customisation (MC) in terms of definition and techniques of enablement. The definition of MC in the literature is vague and has evolved with the literature since inception in 1987. Consequentially, it is difficult to assess which companies are performing MC, to what extent they are achieving MC, or for those aspiring to MC how it may be achieved. The framework will initially be developed using extant definitions and examples from the literature. The objective is to establish the attributes common to the definition and enablement of MC, and to propose a means of assessing the varying levels of MC achievement.

A number of case examples will be used to verify the framework. In confirmation of the framework, an assessment will be made using secondary data (sourced from the internet) of current examples of MC products. Following this, a number of manufacturing organisations will participate in case study research. These organisations will be manufacturers of consumer goods of varying types, potentially from industries such as clothing, food and automotive. Such case studies will be both quantitative and qualitative in nature, utilising interviews (structured and semi-structured), archive data and observation of manufacturing processes. The questions and data achieved shall be based on the attributes of the developed framework.

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2. *Describe the participant sample who will be contacted for this Research Project. You need to consider the number of participants, their age, gender, recruitment methods and exclusion/inclusion criteria*

The case examples will require the involvement of several manufacturing organisations providing customised consumer products from various industries. The number of companies involved will be less than five. The companies will be selected to allow comparison across a range of possibilities defined in the framework. For example, if 'financial cost of end product' was identified as a characteristic of the framework, companies would be selected which produced examples reflecting attributes of the framework (e.g. low cost t-shirts vs high cost automobiles). Participants from organisations will be chosen according to their job description, with key positions being sales/marketing manager, manufacturing manager, engineering/technology manager and director. The number of participants from each company is likely to be low (i.e. less than five), assuming adequate experience and knowledge is held by the identified personnel. This study will not select participants on other measures (including age, gender, race, religious beliefs etc).

Manufacturing organisations will be invited to join the research project in writing. The researcher will send a letter, together with the project flyer which will provide initial information about the project, including the key objectives. Prior to becoming involved with the research, interested organisations will be able to achieve further detailed information from the researcher by telephone, fax, letter or email. It will be made clear (both at the outset and in ongoing research) that all participation with the research project is voluntary, and that the organisation may withdraw their support/involvement at any time.

3. *Describe the consent and participant information arrangements you will make, as well as the methods of debriefing. If you are conducting interviews, you <u>must</u> attach a copy of the consent form you will be using.*

Following the invitation letter, any companies which have indicated their interest in the research will be visited by the researcher. A presentation will be made outlining the aims and objectives of the project, the research methods to be employed and the possible outputs which will result. It is the responsibility of the researcher to ensure informed consent is achieved; namely that participants are aware the nature of the research, the researcher, the funding body, the reason for the research and how the results will be disseminated. Attention will be drawn to the rights and responsibilities of the researcher, the University and the collaborating organisation and issues such as confidentiality. Such information will be conveyed in appropriate detail and using terms which are accessible to participants. There will be opportunities for the company to ask questions or seek clarification. Agreement to participate in the project will be achieved using the signed consent form attached, which will be fully explained. If necessary, a confidentiality agreement (as arranged by RACD) could be provided for organisations involved with this research,

Debriefing will be achieved through the provision of a case study report, which will provide a synthesis of the research output, together with copies of any publications which result from this research.

4. *Please make a clear and concise statement of the ethical considerations raised by the research and how you intend to deal with them throughout the duration of the project*

This research activity's ethical considerations focus primarily on the achievement of informed consent for the organisation, together with the need to maintain confidentiality and secure storage of data achieved. All research undertaken shall be in accordance with English and Welsh law and administrative regulation. Such regulations include, but are not limited to, Data Protection Act 1998, Copyright, Designs and Patents Act 1988, and the Copyright (Computer Programs) Regulations 1992.

Informed consent will be achieved both at the initiation of the research with an organisation, but also on a continual basis. The research aims, objectives and methods will be reiterated throughout the project, with opportunity for involved parties to ask questions at any time. Contact details for the researcher (email, telephone & fax) will be made available to all persons involved in this research.

Data and interview coding will be held in such a way that it is not possible to identify individuals or organisations. Data achieved will not be published or made public in any other way which would be incompatible with the confidentiality arrangements made in this research. Data held electronically will be secured using password systems and shall not be held unencrypted on other media (e.g. backup tapes/discs).

At all times the research will be conducted in accordance with both the CARBS ethical guidelines (as published on the website) and the ESRC Research Ethics Framework.

PLEASE NOTE that you should include a copy of your questionnaire

NB: Copies of your signed and approved Research Ethics Application Form together with accompanying documentation must be bound into your Dissertation or Thesis.

5. ***Please complete the following in relation to your research:***

		Yes	No	n/a
(a)	Will you describe the main details of the research process to participants in advance, so that they are informed about what to expect?	☒	☐	☐
(b)	Will you tell participants that their participation is voluntary?	☒	☐	☐
(c)	Will you obtain written consent for participation?	☒	☐	☐
(d)	Will you tell participants that they may withdraw from the research at any time and for any reason?	☒	☐	☐
(e)	If you are using a questionnaire, will you give participants the option of omitting questions they do not want to answer?	☐	☐	☒
(f)	Will you tell participants that their data will be treated with full confidentiality and that, if published, it will not be identifiable as theirs?	☒	☐	☐
(g)	Will you offer to send participants findings from the research (e.g. copies of publications arising from the research)?	☒	☐	☐

PLEASE NOTE:
If you have ticked **No** to any of 5(a) to 5(g), please give an explanation on a separate sheet.
(Note: N/A = not applicable)
There is an obligation on the lead researcher to bring to the attention of Cardiff Business School Ethics Committee any issues with ethical implications not clearly covered by the above checklist.

Two copies of this form (and attachments) should be submitted to Ms Lainey Clayton, Room F09, Cardiff Business School.

Signed

Print Name
DANIEL EYERS

Date
17th December 2008

SUPERVISOR'S DECLARATION

As the supervisor for this research I confirm that I believe that all research ethical issues have been dealt with in accordance with University policy and the research ethics guidelines of the relevant professional organisation.

Signed (Primary supervisor)

Print Name
DR ANDREW POTTER 12/1/09

Date

STATEMENT OF ETHICAL APPROVAL

This project has been considered using agreed School procedures and is now approved.

Signed (Chair, School Research Ethics Committee)

Print Name

Date 17-02-09

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CARDIFF BUSINESS SCHOOL
RESEARCH ETHICS

Consent Form - Anonymous data

I understand that my participation in this project will involve participation in one or more interviews to discuss how my organisation achieves Mass Customized manufacturing, and the associated implications which arise from this practice.

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. The student conducting the research can be contacted at any time:

Email: eyersDR@cf.ac.uk
Telephone: 02920 874516
Fax: 02920 879633
Post: Daniel Eyers, Cardiff Business School, Colum Drive, Cardiff CF10 3EU

If for any reason I experience discomfort during participation in this project, I am free to withdraw or discuss my concerns with the student's supervisors Dr Andrew Potter (potterat@cf.ac.uk) or Dr Hartanto Wong (wongh@cf.ac.uk).

I understand that the information provided by me will be held totally anonymously, so that it is impossible to trace this information back to me individually. I understand that, in accordance with the Data Protection Act, this information may be retained indefinitely.

I also understand that at the end of the study I may request some additional information and feedback about the purpose and results of the study by applying to the University.

Name of student conducting the research: Daniel Eyers

Name of student's supervisors: Dr Andrew Potter, Dr Hartanto Wong

B1.4 Cardiff University Research Ethics Approval Supplement

SURNAME: EYERS

ETHICS 1

Cardiff Business School
Cardiff University

Ysgol Fusnes Caerdydd
Prifysgol Caerdydd

STANDARD ETHICAL APPROVAL FORM

This form should be completed for every research project that involves human participants. It can also be used to identify whether a full application for ethics approval needs to be submitted. The researcher or, where the researcher is a student, the supervisor, is responsible for exercising appropriate professional judgement in this review. This checklist must be completed **before** potential participants are approached to take part in any research.

APPLICATION APPROVED
RESEARCH ETHICS COMMITTEE
CARDIFF BUSINESS SCHOOL
CARDIFF UNIVERSITY

SECTION 1 - RESEARCH CHECKLIST

1.1	**Does the study involve holding personal information (names, attributable information or personal identifiers of any form) on a database?**	**NO**
1.2	**Does the study involve participants who are particularly vulnerable or unable to give free and informed consent (children, people with learning disabilities, students in academically dependent relationships)?**	**NO**
1.3	**Will it be necessary for participants to take part in the study without their full knowledge and explicit consent (perhaps through covert observation)?**	**NO**
1.4	**Will the study involve discussion of sensitive topics (political or religious views, illegal activities, sexual activity, drug use and so forth) that could be uncomfortable to participants or harmful if divulged to others?**	**NO**
1.5	**Will the study involve potentially harmful procedures of any kind or be conducted in a hazardous environment that could expose the researchers or participants to higher risk than is encountered in normal life?**	**NO**
1.6	**Will financial inducements (cash, vouchers or a prize draws) be offered to participants?**	**NO**
1.7	**Will the study involve patients or patient data in the NHS?**	**NO**

If you have answered 'NO' to all questions 1.1 to 1.7 above, please complete this form and submit TWO copies to Lainey Clayton in room F43. Both forms will be stamped as evidence of submission. One copy will be retained by the School for audit/office purposes and the other by the researcher/s. Undergraduate and postgraduate students should include/bind their copy of the form with their research report or dissertation.

If you have answered 'YES' to any of the questions above, you will need to complete a full ethical review form (ETHICS 2, available on Learning Central – CARBS RESEARCH ETHICS)

ETHICS 1

SURNAME: EYERS

SECTION 2 PROJECT DETAILS

Title of Project:	Additive Manufacturing Supplier Questionnaire The researcher already has ethical approval for his doctoral study on the "Additive Manufacturing Supply Chain", based on case research methods. This application is made for a survey in addition to the prior approval.
Name of Lead Researcher:	Daniel Eyers
Status (please circle) :	Post Graduate Researcher
Names of other Researchers:	
Department:	LOM
Email:	eyersDR@cf.ac.uk
Contact Address:	B07 Aberconway Building, Colum Drive, Cardiff
Telephone number:	02920 874516
Start and Estimated End Date of Project:	November 2011 – January 2012

SECTION 3 STUDENTS ONLY

Module name and number	PhD Operations Management
Supervisor's or Module Leader's name	Dr Andrew T Potter
Email address	potterAT@cf.ac.uk

SECTION 4 SUPERVISORS ONLY

• Have you seen the students Questionnaire?	Yes
• Has the student prepared a consent form to leave with participants	Yes
• Has the student given a brief list of interview questions	Yes

APPLICATION APPROVED
RESEARCH ETHICS COMMITTEE
CARDIFF BUSINESS SCHOOL
CARDIFF UNIVERSITY

ETHICS 1

SURNAME: EYERS

SECTION 4

Briefly describe the study design to be applied in the project including methods of data collection and data analysis

A short survey is to be administered to organizations which supply machines and materials into the Additive Manufacturing supply chain. The purpose of the study is to understand how the operations of these suppliers affect overall supply chain flexibility.

A list of these suppliers (by dominance in the market) has already been published (Wohlers 2008), and this will be used to identify potential participant companies. The top ten companies dominate over 90% of the market, and so these are identified as likely to be the most representative sample to study. The researcher already has appropriate contact details for most of these companies (gathered from attendance at trade shows). The remainder will be identified by browsing the company websites. All companies will be telephoned to explain the research, and invited to participate in the study. If they agree, a survey will be sent by email or post for their completion. It will be made clear that all participation with the research project is voluntary, and that the organization may withdraw their support/involvement at any time. It is the responsibility of the researcher to ensure informed consent is achieved; namely that participants are aware the nature of the research, the researcher, the funding body, the reason for the research and how the results will be disseminated. Attention will be drawn to the rights and responsibilities of the researcher, the University and the collaborating organization, especially on issues such as confidentiality. Such information will be conveyed in appropriate detail and using terms which are accessible to participants. There will be opportunities to ask questions or seek clarification.

Completed surveys will be analysed both qualitatively and quantitatively. Qualitative data will be used to support the development of existing case studies, explaining through text how the operations of the suppliers affect the supply chain. Quantitative modelling (using Geographical Information Systems) will be used to model material and information flows in the supply chain.

The data will be held confidentially and anonymously. Data held electronically will be secured using password systems and shall not be held unencrypted on other media (e.g. backup tapes/discs). At all times the research will be conducted in accordance with both the CARBS ethical guidelines (as published on the website) and the ESRC Research Ethics Framework. Debriefing will be achieved through the provision of a short report of the researcher's findings which will be offered to the participating company free of charge and without obligation.

SECTION 5 DECLARATION

I/we hereby agree that I/we have read the Cardiff Business School's Ethics Code of Practice and taken reasonable steps to ensure the independence and transparency of this research project. There are no significant conflicts of interest or partiality that may impact on the findings and outputs of my/our research activities.
I/we confirm that all participants will be recruited on the basis of informed consent.

SIGNED: [signature] **PRINCIPAL RESEARCH INVESTIGATOR**	**DATE:** 4/11/11
SIGNED: A Potter **SUPERVISOR (WHERE APPROPRIATE)**	**DATE:** 4/11/11

APPLICATION APPROVED
RESEARCH ETHICS COMMITTEE
CARDIFF BUSINESS SCHOOL
CARDIFF UNIVERSITY

NB: Safety Guidelines for researchers working alone on projects – please go to this University's web link to learn about safety policies - http://www.cf.ac.uk/osheu/index.html

ETHICS 1

**Sample cover email **

<<date>>

Dear X,

Further to our earlier telephone conversation I am pleased to enclose the brief questionnaire which I am using as part of my research into the effects of Additive Manufacturing on the supply chain. The purpose of this questionnaire is to explore the contribution machine and material suppliers make to the supply chain, for which your assistance is extremely valued.

As discussed on the telephone your involvement in this research is wholly voluntary, and you may answer as many or as few questions as you choose. Your responses will be held confidentially, and will be anonymized so that neither you, nor your company are identifiable from the results.

The questionnaire should take no more than ten minutes to complete, but will provide very valuable material to my research. If you have any questions or comments about either the questionnaire or need clarification on any aspect of the research, please contact me by any of the methods below. Similarly if you would be happy to participate in future research I would be very pleased to hear from you.

Once again my sincere thanks for your participation in my research,

Daniel Eyers
Cardiff Business School
Cardiff University
Colum Drive
Cardiff CF10 3EU
United Kingdom

Tel: +44 (0)29 2087 4516
Mob: +44 (0)75 2277 8444
Web: www.cf.ac.uk/carbs/lom
Email: eyersDR@cf.ac.uk

APPLICATION APPROVED
RESEARCH ETHICS COMMITTEE
CARDIFF BUSINESS SCHOOL
CARDIFF UNIVERSITY

CARDIFF BUSINESS SCHOOL
RESEARCH ETHICS

Consent Form - Anonymous data

I understand that my participation in this project will involve the completion of a survey regarding my organization's operations, with a specific focus on the supply of machines and/or materials to Additive Manufacturing companies.

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. The student conducting the research can be contacted at any time:

Email:	eyersdr@cf.ac.uk
Telephone:	02920 874516
Fax:	02920 879633
Post:	Daniel Eyers, Cardiff Business School, Colum Drive, Cardiff CF10 3EU

If for any reason I experience discomfort during participation in this project, I am free to withdraw or discuss my concerns with the student's supervisor Dr Andrew Potter (potterat@cf.ac.uk).

I understand that the information provided by me will be held totally anonymously, so that it is impossible to trace this information back to me individually. I understand that, in accordance with the Data Protection Act, this information may be retained indefinitely.

I also understand that at the end of the study I may request some additional information and feedback about the purpose and results of the study by applying to the University.

Name of student conducting the research: Daniel Eyers

Name of student's supervisors: Dr Andrew Potter

APPLICATION APPROVED
RESEARCH ETHICS COMMITTEE
CARDIFF BUSINESS SCHOOL
CAR F UNIVERSITY

Additive Manufacturing Machine & Material Supplier Questionnaire

- *Your participation is voluntary and **all questions are optional**: you may choose to skip any question(s) however please ensure you return the questionnaire even if part completed.*
- *Your responses will be held anonymously and will not be identifiable in the finished research.*
- *If you would like a summary report of the research findings (without charge or obligation), or have any questions about this research please contact the researcher (details below)*

1. Which of the following products does your organization supply?
Please tick and then answer the appropriate section(s) of the questionnaire

Additive Manufacturing Machines ☐ *includes all layer manufacturing machinery directly involved in the Additive Manufacturing processes*	**Materials for Additive Manufacturing Machines** ☐ *including all powders, liquids, and solid materials used in Additive Manufacturing machines as part of the manufacturing process*	**Both Machines & Materials** ☐
*Answer Section **A** ONLY*	*Answer Section **B** ONLY*	*Answer Sections **A AND B***

Thank you for taking the time to complete this questionnaire

When you have completed the activity, please return it by email to eyersDR@cf.ac.uk or by post to
Daniel Eyers, Cardiff Business School, Aberconway Building, Cardiff, CF10 3EU, Wales, UK
Telephone 0044 2920 874516 Mobile 0044 7522 778444

Section A: Supply of Additive Manufacturing machines by your organization to customers

A1. How many **different** machine models are currently offered in the standard product range?

A2. What is the **typical** production lead-time to supply a machine in response to a customer order?
Do not include transportation time

A3. What is the **typical** product life-cycle length for a machine from the standard product range?

A4. Is it possible for these machine models to be customized to meet specific customer requirements? **If so,** what are the main customizable features?

A5. Which of the following statements **best** describes how machines are normally supplied? *Tick one only*

- ☐ Machines are produced in response to an individual customer order. All raw materials are purchased to satisfy this order (no stocks are held)
- ☐ Machines are made in response to an individual customer order, using raw materials and component parts which are held in stock.
- ☐ Components and sub-assemblies are asesmbled in response to an individual customer order (there is no stock held of finished machines, but may be stocks of part-assembled machines)
- ☐ Finished machines are held in stock and sent to customers on receipt of an order
- ☐ Machines are manufactured and distributed to stock points which are located close to the customer

A6. In which country/countries are the Additive Manufacturing machines normally manufactured?

A7. Approximately how many different customers are there for an **average selling** model from the standard range?
It is acceptable to give a wider range if this is a sensitive question (e.g. "between 50 and 100")

A8. What is the **typical average** quantity of machines sold to each customer?
It is acceptable to give a wider range if this is a sensitive question

A9. What is the **average** delivery distance to the customer from the manufacturer? *Tick one only*
km ***or*** *if not known specify whether customers are* ***usually***:

0-250km ☐ 251km-1000km ☐ 1000km-3000km ☐ 3001km+ ☐

A10. Is it possible to expedite supply of machines to meet urgent customer requirements? *Tick one only*

Yes ☐ How do you achieve this?

No ☐ What are the main constraints?

A11. Are purchasers of machines obliged to use **only** materials which are approved by the company? *Tick one only*

Yes ☐ Does the company offer to supply these materials? Yes ☐ No ☐ *Tick one only*

Approximately how many other suppliers which are not part of the company (or its subsidiaries) are approved to supply materials?

No ☐

A12. Are spare parts supplied **directly** to Additive Manufacturing machine users? *Tick one only*

Yes ☐ What is the **typical** supply lead-time (excluding transport time)

No ☐

A13. Are spare parts supplied to resellers/service agents (for subsequent resale to Additive machine users)? *Tick one only*

Yes ☐ What is the **typical** supply lead-time (excluding transport time)

No ☐

Section B: Supply of materials (resins/powders etc) by your organization to customers

B1. How many **different** materials does the company offer in its standard range?
Do not include development materials or products customized for specific customers in this number

B2. Which of the following statements best describes the **majority** of materials offered by the company? *Tick one only*

- ☐ Materials are wholly manufactured as part of the company's operations
- ☐ Raw materials are purchased from suppliers, and are then further processed to meet requirements
- ☐ Bulk materials are purchased and split into smaller quantities to satisfy multiple customer orders
- ☐ Materials are purchased from suppliers and re-sold in the same quantities to satisfy orders
- ☐ None of the above - please provide alternative

B3. Which of the following statements **best** describes the **majority** of materials offered by the company? *Tick one only*

- ☐ No stock is held. Individual orders are satisfied by purchasing the required amount of raw materials for processing or direct supply to customer
- ☐ Individual customer orders are manufactured using raw materials already held in stock
- ☐ Individual customer orders are satisfied from pre-prepared material stocks
- ☐ Finished materials are held in stock and sent to customers on receipt of an order
- ☐ Materials are manufactured and distributed to stock points which are located close to the customer for immediate supply in response to a customer order

B4. In which countries are manufacturing and/or warehousing facilities located?
Manufacturing: Warehousing:

B5. Overall, what is the **average** production lead-time for material products?
Do not include transportation time.

B6. For materials supplied to the **UK market** what is the typical production lead-time and origin for the **three most popular** materials from the standard range? *If less than three materials are supplied insert "n/a" where there is no appropriate data.*

Material No.	Typical production location		Typical storage location		Typical supply lead-time
	Country	Region/City	Country	Region/City	*Do not include transportation time*
1					
2					
3					

B7. Is the data provided in B6 **representative** for the following countries? *Tick all that apply*

Austria ☐ Belgium ☐ Denmark ☐ Finland ☐ France ☐ Germany ☐ Greece ☐
Ireland ☐ Italy ☐ Luxembourg ☐ Netherlands ☐ Portugal ☐ Spain ☐ Sweden ☐

B8. In what manner are the three popular materials given in Question **B6** supplied to customers?

Material No.	Stock Keeping Unit (SKU) *e.g. 10kg bag/100litre tub*	Normal Minimum Order Quantity	Average Customer	
			Order Quantity	Order Frequency
1				
2				
3				

B9. As a percentage what is the estimated **typical** monthly variation in the quantity of materials ordered by **average** customers?
%

Thank you for taking the time to complete this questionnaire

Appendix C A Technical Review for Industrial Additive Manufacturing

C1.1 Introduction

This appendix is included as a technical reference in support of the main thesis. It provides an overview of the principal Industrial Additive Manufacturing technologies as considered in this study, and provides a novel classification framework to support academic and practitioner appraisal of the different manufacturing approaches. This text has been developed and updated from a published paper, for which the full citation is:

- Eyers, D. R. and Dotchev, K. D. Rapid Manufacturing for Mass Customisation Enablement. Assembly Automation 2010 30 (1) pp. 39-46.

This paper was awarded a "Highly Commended" prize at the 2011 Annual Emerald Literati Awards.

C1.2 An overview of different manufacturing processes

The basic function of any manufacturing system is to affect the value of the product flow as it moves from its input state to its output state (Henry et al. 2012). This change can be achieved through physical and chemical processes to alter its properties (e.g. geometry), or as an assembly process to combine multiple parts in the formation of products (Groover 2007). From a management perspective manufacturing can be considered in terms of the generic transformation model in which resources to be transformed are worked on by transforming resources to produce the desired outputs (Figure C.1)

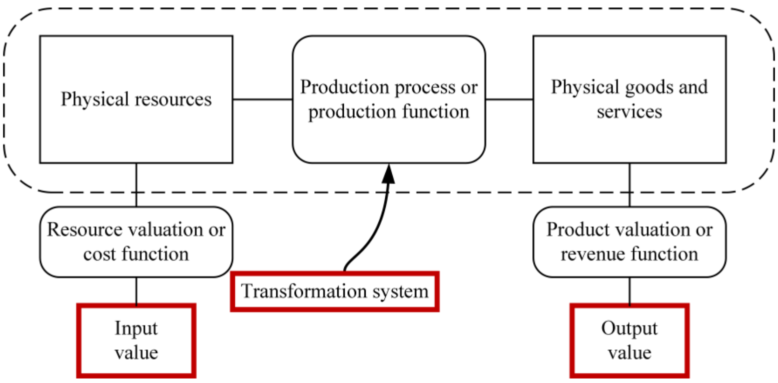


Figure C.1: Schematic of a transformation system
Source: de Neufville and Stafford (1971)

The processes that afford the transformation of raw materials into finished products may be classified on their principal fabrication *modus operandi*. Burns (1993) identified such approaches to manufacturing can be considered as additive, subtractive, and formative (Figure C.2). Additive processes join materials together to create a larger product. For example, the production of plywood is performed through the successive adhesion of thin sheets of wood to form a strong manufactured wood product. Subtractive processes create products through the removal of material from a larger block (e.g. slabs or billets) of raw materials, using techniques such as milling, drilling, chiselling, and other acts of abrasion. Formative processes are used to create products by forming them around a tool to meet their desired shape, using techniques such as injection moulding.

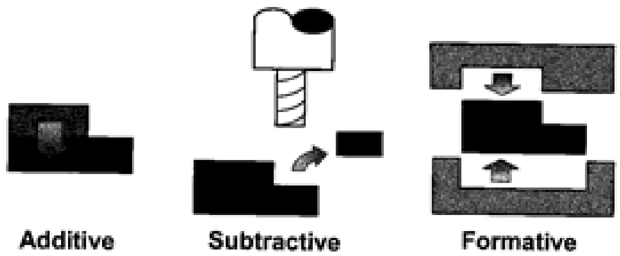


Figure C.2: Additive, subtractive, and formative manufacturing processes
Source: Burns (1993)

C1.3 The nature of Additive Manufacturing

C1.3.1 Additive Manufacturing Terminology

The term "*Additive Manufacturing*" is defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM International 2009). In Additive Manufacturing processes, parts are typically produced through the successive addition of layers of liquid, powder, or sheet material, building the overall structure in an incremental layer-wise approach. Additive Manufacturing uses computerized 3D model data to directly create physical artefacts from a range of materials, including plastics and metals. This is achieved by successive addition of layers of materials that are joined or fused together by the machine, which negates the requirement for tooling or moulds in the production process. As a result, Additive Manufacturing is able to produce highly complex geometries (e.g. Figure C.3) without many of the cost implications inherent in other manufacturing techniques. This capability has previously been identified as offering "geometry for free" (Hague et al. 2003a). Additive Manufacturing is therefore a general manufacturing process descriptor, within which a number of different Additive Manufacturing technologies may be classified.

It is recognized that the term “3D Printing” (or 3DP) is frequently used in many texts as a synonym for Additive Manufacturing, particularly in media and non-technical articles. For some, the term has been considered to have the same meaning as ‘Additive Manufacturing’ (Brookes 2014; Grimm 2012). However, 3DP is a specific process created by Massachusetts Institute of Technology, and trademarked by Z Corporation as an inkjet-based technique for the incremental, additive approach to manufacturing (Z Corporation 2005). In this study “Additive Manufacturing” shall be used to maintain overall clarity in the communication of some complicated concepts.

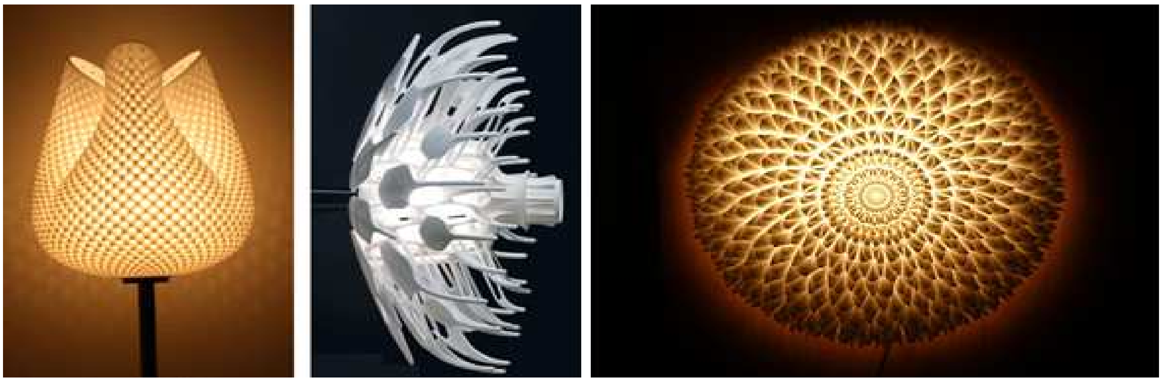


Figure C.3: Complex geometries in lighting products produced using Additive Manufacturing
Source: Materialise NV

As a process descriptor, Additive Manufacturing is a subset of the additive processes explained in Section 4.3. There are three important distinctions between the superset and subset of processes:

1. Additive Manufacturing processes utilize 3D computer data as the source information from which the product is fabricated, whereas other additive processes may use designs from a range of sources. Typically (and hereafter in this text), this data file is known as a Stereolithography (STL) file. It is acknowledged that current research is working on a successor to STL, known as the Additive Manufacturing File format (AMF).

2. Additive Manufacturing processes utilize computer-controlled machines in the fabrication of products based on the 3D design files, which is not requisite in all additive processes.

3. When fabricating, Additive Manufacturing machines either do not need support structures (e.g. polymer-based Laser Sintering), or are able to build their own (e.g. Stereolithography). This is not a feature typically inherent in additive processes as normally there needs to be some external intervention to produce these.

It is further observed that the use of the "Additive Manufacturing" term within both academia and commercial enterprises is subject to some liberal interpretation. The term is often used interchangeably to describe either the manufacturing processes or the manufacturing process technologies, for which distinction is usually apparent from the context of discussions. In this thesis, *Additive Manufacturing* is taken to refer to the concept of the Additive Manufacturing process (the totality of operations performed by which the part(s) or product(s) are produced), and *Additive Manufacturing Technologies* to refer to the specific machines by which Additive Manufacturing is implemented.

C1.3.2 Rapid Prototyping, Rapid Tooling, and Rapid Manufacturing: The Emergence of Additive Manufacturing

The first Additive Manufacturing technology patent was for an "Apparatus for production of three-dimensional objects by stereolithography" by Charles Hull (1986), and commercialized by his company 3D Systems. The concept of Additive Manufacturing has evolved since the development of this first technology, during which time three distinct categorizations based on application may be identified as follows:

On initial commercialization, these technologies were used for rapid fabrication of physical prototypes for concept modelling and design validation during the product development phase, and hence termed *'Rapid Prototyping'* (RP). Traditionally a time-consuming, labour intensive, and costly process, the application of RP enabled comparatively quick manufacture of prototypes for evaluation, offering the potential to enhance the overall speed at which new products could be developed (Nyaluke et al. 1995). Furthermore, RP offered the critical advantage to enable direct manufacture from the designer's 3D model, eliminating much of the preparation time inherent in conventional prototyping techniques, and offering the potential to positively affect the phase of New Product Development (NPD) (Gunasekaran 1998).

A second applications category for Additive Manufacturing technologies is their utilization to rapidly build complex patterns or mould inserts and thus to assist the conventional forming processes such as casting and moulding. For this application the term '*Rapid Tooling' (RT)* was coined as being the development of Rapid Prototyping in the creation of patterns for casting, direct tooling, and indirect tooling (Rosochowski and Matuszak 2000). This leads to the application of Additive Manufacturing technologies in the creation of tooling for vacuum casting, vacuum forming, die casting, investment casting, and injection moulding, capable of surviving from a few dozen to tens of thousands of cycles (Dimov et al. 2001; Ma et al. 2007). Similar to RP, the main advantages of accelerated production time and lessened costs have made RT an attractive option for the mould manufacturing industry (Oakham 2002). Wohlers (2012) identified in an appraisal of the market that over one-fifth of current Additive Manufacturing output is used for tooling applications.

As the technologies matured on a range of attributes including quality, accuracy, speed, and cost, new applications opportunities emerged for which a third distinct categorization may be identified. These improvements, combined with enhancements in the variety of materials available (and their performance characteristics) enabled several companies to successfully employ Additive Manufacturing technologies in the manufacture of finished production parts or end-use parts in quantities of one to thousands (Wohlers 2012). Another term, *'Rapid Manufacturing' (RM)* was consequently adopted for this application (Pham and Dimov 2001), for which a plethora of definitions have been offered. Hopkinson et al. (2006b, p. 1) defined Rapid Manufacturing as a "CAD-based automated additive process to produce finished end use parts or components". Within Rapid Manufacturing parts of extreme geometric complexity may be directly fabricated from 3D CAD designs, releasing designers from the "design for manufacturing" constraints (Hague et al. 2004) and freeing their creativity for innovative products. As Rapid Manufacturing does not require tooling or moulds to create products, the elimination of these fixed costs promotes the technologies for low volume and customized production, and Hopkinson et al (2006) identified these characteristics may eventually make manufacturing of a single part viable. This emphasizes Rapid Manufacturing as being commercially feasible, which could compete with traditional manufacturing on the standard operations performance attributes of cost, quality, speed, dependability, and flexibility.

Some authors consider Additive Manufacturing an extension of Rapid Manufacturing, excluding consideration of tooling or prototyping. For example, Nottingham University's Additive Manufacturing and 3D Printing Research Group (2013) identified Additive Manufacturing to relate only to 'direct fabrication of end-user products and components using technologies that deposit material layer-by-layer'. There is little consensus over this exclusion; the ASTM International (2009) definition does not make this assertion, and major research sponsors such as TSB (2012) adopt a broader perspective where "the production of tangible products made using a growing set of digitally controlled machine tools... the approach differs radically in that products are produced through the selective addition of materials layer-upon-layer, rather than through machining from solid, moulding or casting".

The three principal applications definitions as shown in Figure C.4 represent the majority of uses for Additive Manufacturing technologies, and as a result within this study Additive Manufacturing is therefore taken to be a term which serves to unify these three definitions. Each application has different characteristics that present different challenges in the management of Additive Manufacturing, and so whilst this research concerns "Additive Manufacturing", in its conduct and analysis the difference between prototyping, tooling, and manufacturing is acknowledged.

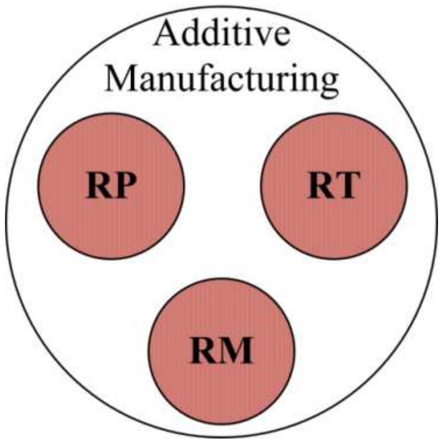


Figure C.4: Additive Manufacturing as a collective noun for three distinct concepts
Source: The Author

C1.3.3 Classification of Additive Manufacturing types

Whilst early Additive Manufacturing machines were used for prototyping and research purposes, the increasing number and variety of applications have led to the development of a wide range of Additive Manufacturing implementations by a range of machine manufacturers. Within this study these are classified by their intended application:

- **Industrial Additive Manufacturing machines** concentrate on the production of manufactured items that are produced on a commercial basis. These machines may produce finished products, components for products, tooling, or prototypes. Importantly, these machines operate in competition with other manufacturing process types, and must therefore meet commercial requirements. Depending on the expected usage, they may be operated in-house, or alternatively may be outsourced to an Additive Manufacturing "Service Bureau", Ruffo et al. (2007) provided one of the few studies that evaluate of the suitability of each approach.

- **Educational Additive Manufacturing machines** are utilized for both research and teaching activities, with a bias tending towards research. 52% of UK Additive Manufacturing capacity within Universities is utilized for research (Dickens et al. 2013). These machines may be similar to those found in industrial applications, but may lack some of the advanced features, and/or some of the processing capabilities.

- **Small Office / Home Office and Domestic (SOHOD) Additive Manufacturing machines** are the most recently established type of Additive Manufacturing machine.

These are priced considerably cheaper than the other machine types (sub £5,000) to be accessible to smaller firms and individual users. Currently these machines tend to have a small build platform, and use relatively inexpensive materials. These machines may be offered by established Additive Manufacturing suppliers as an extension to their existing ranges (e.g. 3D Systems' Cube), or as 'Open Source' products (e.g. RepRap). These limitations constrain the types of products which can be produced and the quality which can be achieved, however this is a fast-growing sector of the Additive Manufacturing market. Wohlers (2013) reported that annual growth in this sector averaged 346% during 2008-11; in 2012 this annual growth rate had dropped to 46.3% with most machines being sold to hobbyists, DIY enthusiasts, and some educational users.

As this study explores the implications for manufacturing and supply chain management, this research focuses principally on the usage of Additive Manufacturing for **industrial** purposes, rather than educational or SOHOD. At present SOHOD has received considerable media attention for consumer products, but there is little evidence for these as currently rivalling conventional approaches to manufacturing, and so it is premature to attempt the practical observation of implications for manufacturing undertaken in this study.

It is however recognized that the SOHOD market may have significant implications for the future of manufacturing as a result of user-manufacturing (e.g. Burns and Howison 2001; Fox 2013), particularly as technologies mature and commercial patents expire. Within the current study, industrial manufacturers acknowledged the potential for a competitive threat from SOHOD machines, but noted this would not arise in the short term. Whilst a detailed consideration of SOHOD implications is therefore identified as outside the scope of the current study, developments in this area suggest it to be a viable opportunity for future exploration as discussed in Section 8.5.1.

C1.3.4 Industry size

The Additive Manufacturing industry has demonstrated significant and on-going growth (Figure C.5), with most growth arising through SOHOD sales. For Industrial Additive Manufacturing the principal suppliers are Stratasys, Z-Corp, 3D Systems, Solidscape, Objet, EnvisionTEC, and EOS who between them dominate the market (Wohlers 2012). During the conduct of this research a series of mergers and acquisitions has reduced the overall number of vendors and concentrated the majority of supply to a few large organizations. The principal applications for these technologies is shown in Figure C.6.

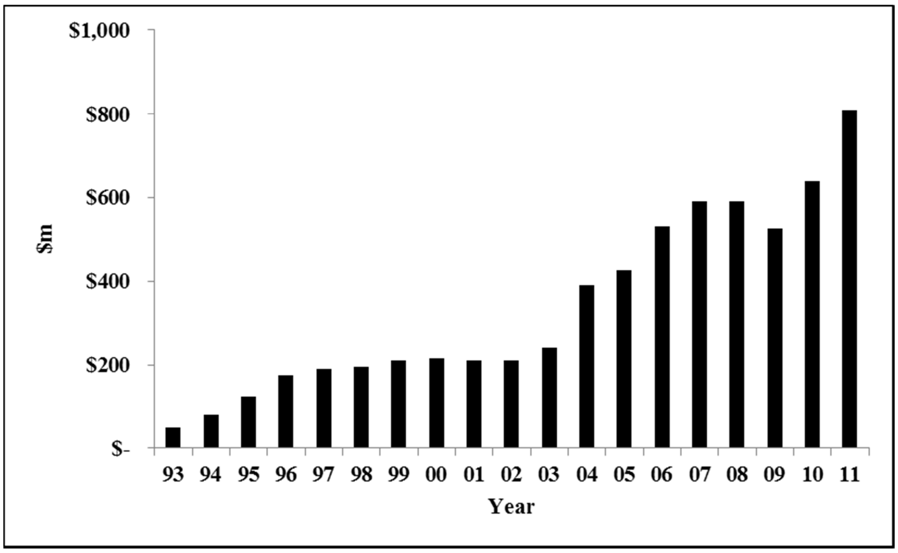


Figure C.5: Additive Manufacturing industry size (excluding services)
Source: The Author, adapted from Wohlers 2012

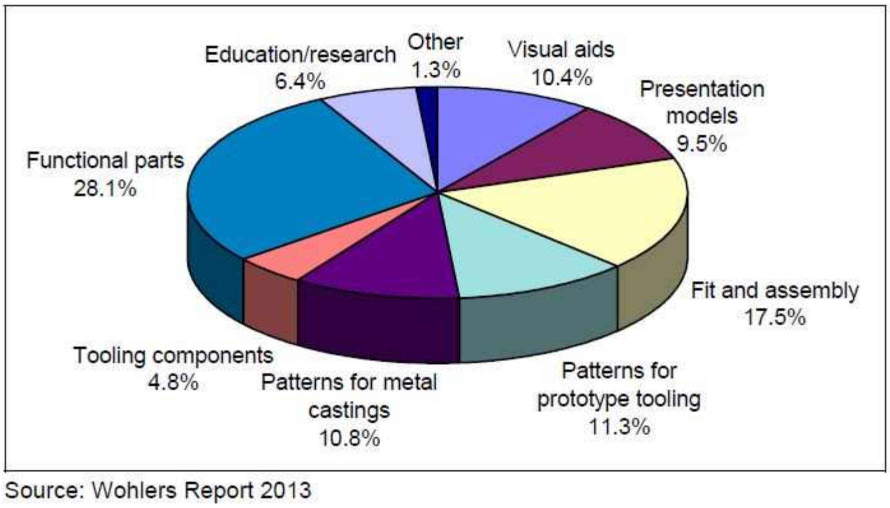


Figure C.6: Industrial uses of Additive Manufacturing
Source: TCT Magazine / Wohlers 2013

C1.4 A classification of Industrial Additive Manufacturing Technologies

Several classification schema have been proposed in order to categorize Additive Manufacturing processes. According to early work by Kruth (1991), RP may be divided into technologies involving material addition *or* material removal, and hence it may be identified that not all processes which have been termed RP follow the current ASTM Additive Manufacturing definition. Based on Kruth's first division, the accretion processes may be subsequently subdivided on the basis of the raw material state before part formation: namely liquid, powder, or solid sheets. A similar approach to classifying Additive Manufacturing based on raw material is offered by Chua et al. (2010, p. 18), though this more recent publication benefits of an updated listing of technologies.

An alternative categorisation for RP was proposed by Pham and Dimov (2003), and is based on the mechanism employed for transferring data from the sliced 3D models into physical structures. This approach therefore focuses on the transformation actions undertaken by the Additive Manufacturing process. The transfer mechanisms proposed include 1D channel (laser beam or nozzle); multiple 1D channels (two laser beams), array of 1D channels (array of nozzles), and 2D channel (a photo mask, layer projection).

In the context of modern Additive Manufacturing, these existing classifications have several limitations. Aside from their relative complexity for interpretation, their focus on either the raw material (input) or transformative machine type (transformation) lacks alignment with the needs of product developers or manufacturers. By focusing principally on either the raw state of materials or their transformation mechanism, they do not reflect the nature of the desired part for which the processes are employed: the output (in terms of the material characteristics relevant to the part) is therefore overlooked. As a result, selecting a viable Additive Manufacturing technology for a specific application is a challenging task that requires knowledge not only of the currently available Additive Manufacturing processes, but also understanding of their capabilities, advantages, and drawbacks in the attainment of these.

Eyers and Dotchev (2010) observe that for Rapid Prototyping applications, process selection is normally based on production speed and cost, with part quality often a secondary priority. However, for finished products (i.e. Rapid Manufacturing), the requirements are much more complex and design driven, and as a result it is important to reflect these in the development of a classification schema. In such design, the important criteria are product functionality, appearance, and shape/geometry, which are the outputs of the manufacturing process. The achievement of these for Additive Manufacturing is strongly correlated to the properties of the materials chosen by the designer.

The limited variety of materials available for Additive Manufacturing compared to the vast choice in conventional manufacturing remains a constraint of the technologies. However, this limitation does make it practical to classify Additive Manufacturing technologies based on their material characteristics in terms of their capabilities to meet the design requirements. A general classification of the most popular and already proven Additive Manufacturing technologies arranged by the desired output material type is developed in Table C.1.

Required Material Type	Manufacturer	Technology	AM Process Phenomena	Materials
Photopolymer Resin	3D Systems	Stereolithography (SL)	UV laser scanning/curing	Variety of epoxy resins, nano-composite resin
	EnvisionTEC	Perfactory™	Photopolymer resin	Epoxy-acrylic resins, nano-composite resins, acrylic resin (investment casting)
	3D Systems	ProJet™	Printing/Multi-jetting of UV sensitive resin	Variety of proprietary UV curable acrylic resins Wax-like polymers (casting patterns)
	Objet Geometries	PolyJet™	Multi jet printing of UV sensitive resin	Proprietary photopolymers, biocompatible resins
Engineering Plastic	EOS	Laser Sintering (LS)	CO_2 Laser scanning of thermoplastic powder	Polyamide 12 Various filled polyamide (Glass, aluminium, carbon fibre), polystyrene (investment casting), PEEK HP3
	3D Systems	Selective Laser Sintering™ (SLS)	CO_2 laser scanning of thermoplastic powder	Polyamide 12, GF polyamide, Aluminium filled polyamide, composite plastics, polystyrene powder/wax system for casting patterns
	Stratasys	Fused Deposition Modelling (FDM)	Molten plastic extrusion	ABS, PC-ABS, PC plastics, biocompatible ABS plastics
Metal	EOS	Direct Metal Laser Sintering (DMLS)	Laser beam metal powder sintering	Direct Steel H20, Stainless Steel GP1 (industrial), Stainless Steel PH1 (medical), Cobalt Chrome MP1, SP2, Titanium Ti6, Ti6 ELI, Maraging Steel MS1, Nickel Alloy IN625, Aluminium
	Renishaw (formerly MTT)	Selective Laser Melting (SLM)	Laser beam metal powder sintering	Stainless steel 316L and 17-4PH, H13 tool steel, aluminium Al-Si-12, titanium CP, Ti-6Al-4V and Ti-6Al-7Nb, cobalt-chrome (ASTM75), Inconel 718 and 625
	Concept Laser	LaserCusing (LC)	Laser beam metal power fusing (complete melting)	Stainless Steel, Cobalt chrome, ALSi10Mg Aluminium alloy, TiAl6V4 Titanium alloy, Inconel 718
	Arcam	Electron Beam Melting (EBM)	Electron beam melting of metal power	Titanium alloy Ti6Al, Titanium, Cobalt Chrome (ASTM75)

Table C.1: Principal Additive Manufacturing technologies & materials based on commercial popularity

Source: The Author, developed from Eyers and Dotchev (2010)

C1.5 Photopolymer resin based processes

Photopolymer resins used in Additive Manufacturing exist in a liquid-like state, and are cured on exposure to light in the UV range in order to form the desired solid part in a photo-polymerization process. Resin-based processes are very popular for Additive Manufacturing, though the integrity and durability of the parts may be less than plastic or metal based approaches. A fundamental challenge for photopolmerized parts is longevity; the auto-oxidation of parts (thermal- and photo-oxidation) has been experimentally demonstrated by Troger et al. (2008) as degrading the part, which is particularly relevant for Rapid Manufactured applications in which the part is likely to have a requirement for a longer life-expectancy than a prototype.

Stereolithography (SL) was the first Rapid Prototyping technology, developed from the patent of Hull (1986), and uses photopolymer resins to form parts. In SL an ultraviolet (UV) laser beam scans thin (typically 0.1mm) layers of the UV curable resin to solidify exposed cross sections, leaving all other areas as a liquid resin for subsequent draining in the post-processing phase of production (Figure C.7).

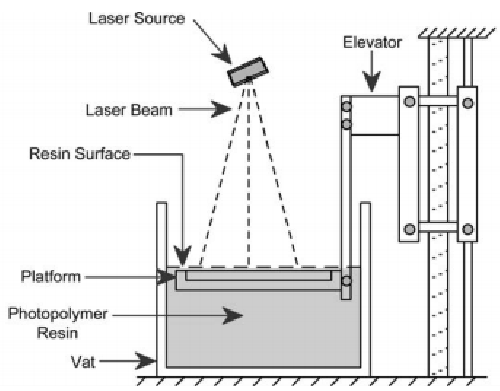


Figure C.7: Stereolithography process
Source: Zhang et al. (2000)

Among the advantages of SLA are: reliability, very good accuracy, repeatability, good resolution, and the availability of a wide variety of different resins. Many commercially available epoxy resins simulate the mechanical properties of moulded plastics such as Acrylonitrile Butadiene Styrene (ABS), polycarbonate (PC), polypropylene (PP), etc. Notably the longevity of parts produced using SL can be compromised depending on their intended application; for example Ribeiro et al. (2004) identify that high-temperature applications may result in unintended post-curing of the resin, leading to deformation of the part.

There are several weaknesses relevant to SL, affecting design, manufacture, and post-processing. One of the principal weaknesses is its reliance on ‘support structures’ in the fabrication process, which serve to support overhanging features. Whilst modern software is able to largely create these automatically, they still take time to build and must be removed in the post-processing activity, and as Canellidis et al. (2013) observed, they promote challenges in the optimization of build layouts. The draining of unused liquid resin is an additional time-consuming activity, which Pham and Gault (1998) observed may take several hours depending on viscosity. After draining has occurred the part is typically placed in a UV oven to ensure complete photo-curing, which is another post-processing activity that takes time and resource to achieve.

envisionTEC Perfactory Systems form parts through the projection of bitmaps onto photosensitive liquid resin, using Texas Instrument's Digital Light Processing technology. Each slice of the STL file is projected as a mask onto the resin; the illuminated portion will cure the resin whilst the masked area will not (Chua et al. 2010). The envisionTEC process is unusual compared to other Additive Manufacturing processes as it builds the model top-down, with the build platform raised between each layer of production. Through this approach the need for a recoating mechanism is eliminated, with gravity causing the resin to fill the space between the cured part and the window (Gibson et al. 2010).

The envisionTEC Perfactory process is relatively quick, and is well suited to the accurate production of small components (Hopkinson et al. 2006a), particularly those with micro features/fine resolution/surface finish. A number of different resins are used to make fully functional components, mould inserts, and vacuum/investment casting patterns for medical and dental applications. The technologies are particularly exploited in the production of hearing aids (Eyers and Dotchev 2010; Petrovic et al. 2011; Wohlers 2012).

The jetting of photopolymer materials forms the basis of **ProJet** and **PolyJet** technologies, through which layers of photosensitive liquid resin and support material are simultaneously jetted. This approach allows the fabrication of parts with very fine and intricate features. The advantages of this technology are high production speed and accuracy, fine resolution, easiness in part cleaning, and reliability thanks to the absence of lasers.

C.1.6 Engineering plastics based processes

One of the main constraints for all additive manufacturing processes is the size of components which they can fabricate. Several technologies have been developed in order to produce large parts, including Stereolithography (SLA), Fused Deposition Modelling (FDM), and Laser Sintering (LS).

Laser Sintering (LS) and Selective Laser Sintering (SLS) are similar to SLA in their layer-based approach, but instead of liquid resin they employ thermoplastic powder which melts when exposed to thermal energy. Parts are fabricated within a pre-heated build chamber, and a focused CO_2 laser beam traces the part sections, adding more heat to selectively sinter or fully melt the powder. There is much commonality between SLS and LS; the principal difference is the variety of materials that each machine may process.

For LS, the EOS P700 machine was the first to implement a dual 50 watt laser system, resulting in increased productivity in the manufacturing process. Figure C.8 highlights the main components of the system, with powder entering the machine from two tanks via a helical coil. This approach allows for new (virgin) material to be added to powder reclaimed (recycled) from previous builds. For each build layer, powder is spread across the part bed within the exchangeable frame by the recoater, and preheated in advance of sintering. Heaters at the side of the frame serve to hold the whole build chamber is held at a consistent temperature for the duration of the build; however thermal inconsistencies have been identified by the author as leading to inaccuracies in fabricated parts (Soe et al. 2013).

In the production of plastic items, LS offers a major advantage over its rivals by negating the requirement for support structures when building parts, which simplifies the design process and facilitates flexibility in the placement of parts within the build chamber (including part nesting). This can therefore increase productivity and output of the machine, which in turn will lower the associated cost of production for each part. Furthermore, LS can produce parts with similar mechanical properties as those produced using conventional manufacturing processes (Dingal et al. 2008). It is possible to produce fully functional components in PA12, filed nylons (glass fibres/beads, aluminium, carbon), flame retardant nylons, and high temperature plastics (Polyetheretherketone) for automotive, aerospace and military industries, Formula1, and research equipment applications (Eyers and Dotchev 2010). The LS process has the capability to process a variety of thermoplastics, thermoplastic composites and ceramics. As a result, LS is one of the most popular additive manufacturing processes: in terms of the number of units in service, LS is second only to SLA (Plunkett Associates 2008) and it is the most popular additive manufacturing technology that commercial vendors are considering to add to their manufacturing portfolios in the future (Wohlers 2012). In spite of this popularity, LS is inferior to some competitors in terms of the accuracy of the products produced, with inaccuracies being introduced at various stages of product fulfilment (Senthilkumaran et al. 2012), particularly as a result of the thermal non-uniform shrinkage investigated by the author (Soe et al. 2013). Whilst it is acknowledged by Relvas et al. (2012) that research considering accuracy for additive manufacturing technologies is extremely limited, some details do exist to compare LS to its competitors. For example, SLA offers much higher degrees of accuracy during the build process (Kim and Oh 2008), though it should be noted that the tendency of parts to absorb moisture over time leads to post-manufacturing distortions in SLA (Dulieu-Barton and Fulton 2000).

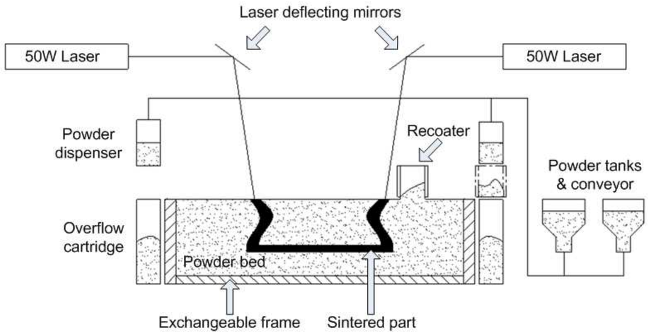


Figure C.8: Laser sintering process
Source: Soe et al. (2013)

Fused Deposition Modelling (FDM) is a process developed by Scott Crump and commercialized by Stratasys based on a 1992 patent. The expiry of this patent in 2009 led to a number of low-cost providers developing FDM machines, and today FDM underpins the principal SOHOD 3D printer market (including RepRap and Makerbot).

The principal of FDM is the use of solid-based materials (in filament form), which are heated to become molten and passed through an extrusion head. This head moves in both X and Y directions, depositing material on a base plate, layer-upon-layer, each of which solidify at the ambient temperature to form the desired part. Figure C.9 provides a basic overview of the process.

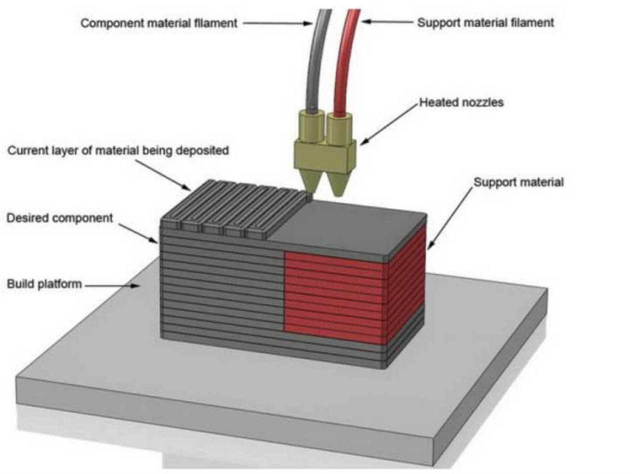


Figure C.9: Fused Deposition Modelling process
Source: Novakova-Marcincinova et al. (2012)

For FDM separate nozzles deliver different materials that either contribute to the part, or are used in the production of support structures. The use of multiple heads has been demonstrated to enable simultaneous multi-material production through the FDM process (Espalin et al. 2014). The way in which FDM utilizes materials is one of the main advantages of the process. FDM is able make efficient use of materials that are similar to comparable ‘conventional’ manufacturing technologies, with little wastage (Eyers and Dotchev 2010). For ABS, it is identified that FDM achieves 85% strength of a conventionally moulded part (Chua et al. 2010), making it particularly suitable for manufacturing applications. Furthermore, removal of support structures is easy, and can be automated. However, the parts have rough surface finish, and reduced mechanical strength due to cold weld between layers and treads (Eyers and Dotchev 2010). Additionally, accuracy is constrained by the layer thickness, and the circular nozzles lead to ‘rounding’, making the achievement of sharp corners difficult (Gibson et al. 2010).

C1.7 Metal based processes

Whilst this study does not explore Additive Manufacturing in the context of direct metal-based processes, for completeness Table C1 includes the principal technologies. Direct metal-based Additive Manufacturing remains extremely expensive in terms of machines and materials, and as a result indirect methods are often employed in the fabrication of metal parts. Indirect processes use a polymer coated metal powder which is fused by exposure to a much lower laser power in an Additive Manufacturing machine, producing a porous skeleton part. This “green part” is then manually infiltrated in a furnace using a low melting point alloy such as bronze to create the finished part. This is a comparatively laborious process, and cannot achieve parts of the same material as metal-processing machines (e.g. titanium), but does allow the utilization of the more common laser sintering processes (e.g. LS/SLS), rather than the less common and considerably more expensive metal processing machines (e.g. DMLS).

C1.8 Summary

This appendix has presented an up-to-date review of the principal commercial Industrial Additive Manufacturing technologies, highlighting the principal characteristics of each. In contrast to many earlier works, this review has provided an outputs-focused classification of these technologies, which is intended to support both the current research, and also the selection of processes by practitioners.

Appendix D Supporting data

This section provides resources to support the main thesis:

D1 contains a copy of the structured interview protocol used in the collection of data at an industry conference.

D2 contains an IDEF0 diagram for Case 2 (LittleCo Model Ship). This is included as a sample of the twelve IDEF0 diagrams that have been used in this work.

D1 Structured Interview Protocol

Preamble

The purpose of the research activity is to learn more about the supply of Additive Manufacturing machines and materials, particularly in terms of enablers and constrains within the physical supply of materials. The researcher should introduce themselves to the participant, explaining that this work is being conducted for a doctoral study, that their identity will remain anonymous, and to overview the purpose of the research. It is important to stress at the beginning and end of the questioning that there are only six questions, all participation is voluntary, all questions are optional, and that the participants are free to withdraw from the interview at any time.

1. Are you today…

a) employed by an Additive Manufacturing machine supplier

b) acting in a reseller capacity

c) acting in another capacity *if so, what?*

The respondent should be clearly identifiable by the trade stand at which they are standing, and/or their ID badge. If this is not clear ask the respondent which company they are representing.

2. Which Additive Manufacturing technology/technologies does your organization represent?

Important to note all technologies and to collect data for each – so the following questions might need to be asked multiple times.

3. For each these technologies you have just outlined, does your company supply…

a) Machines?

b) Materials?

c) Both?

d) Neither?

If neither enquire about the nature of the company's involvement, thank respondent, and cease structured interview. If appropriate check whether respondent would like to contribute to other areas of the research.

4. Thinking about the materials (*insert resin/powder/filament etc as appropriate)* used in the machine, is there a requirement for customers to purchase only from suppliers already approved by the company?

IF YES: Can you please tell me why is this a requirement? <Then go to question 5>

Important! Don't use direct prompts – let the respondent give their own reasons. This is a really important part of the questioning, so let the respondent talk for an extended time if necessary. If nothing is forthcoming, use the follow-up question

4a. So what would be the implication if a company did use material from another supplier?

IF NO, can you please tell me why this is? <Then go to question 6>

Important! Don't use direct prompts – let the respondent give their own reasons. If nothing is forthcoming, use the follow-up question

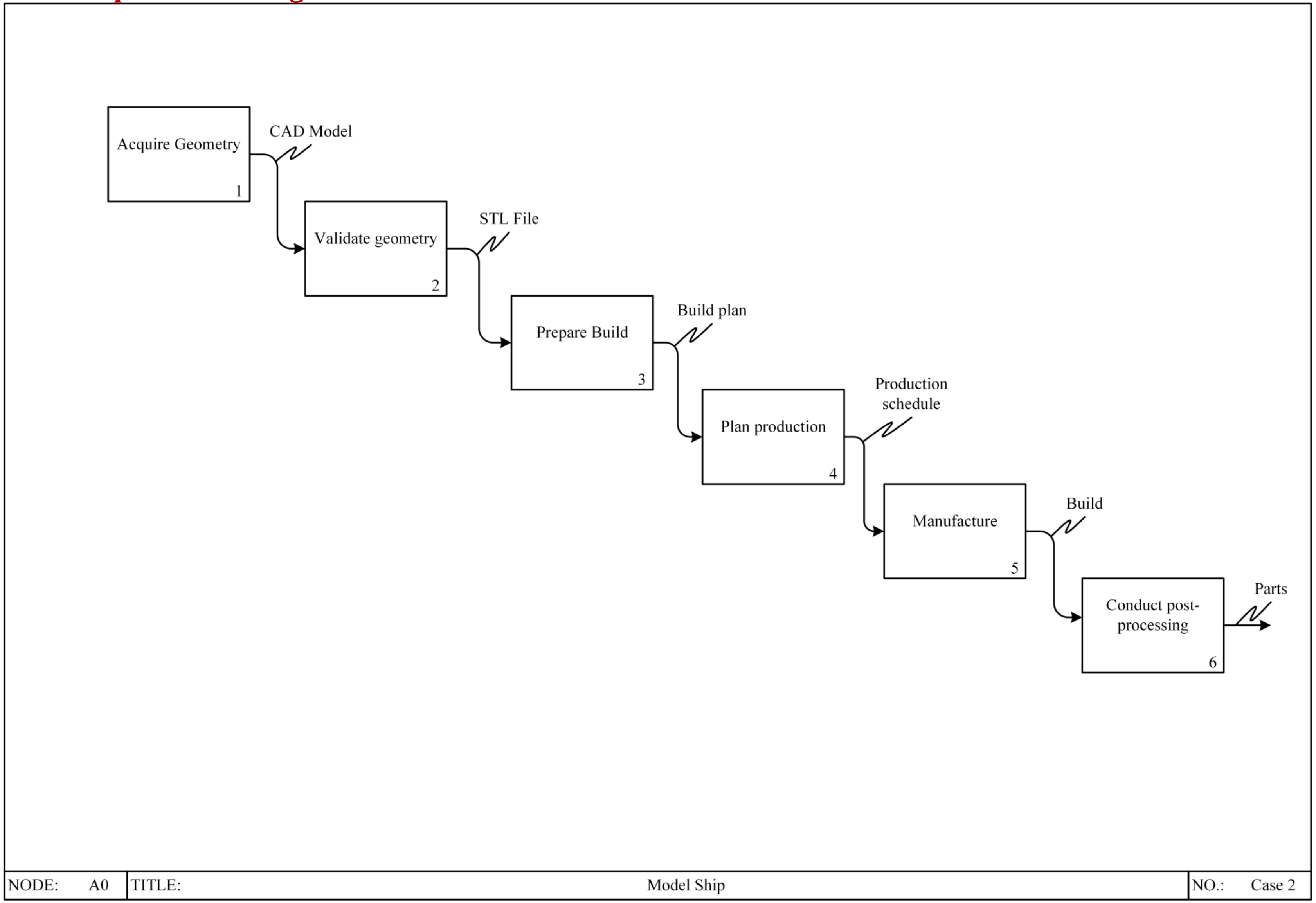
4b. So are there no consequences for companies using material from other suppliers?

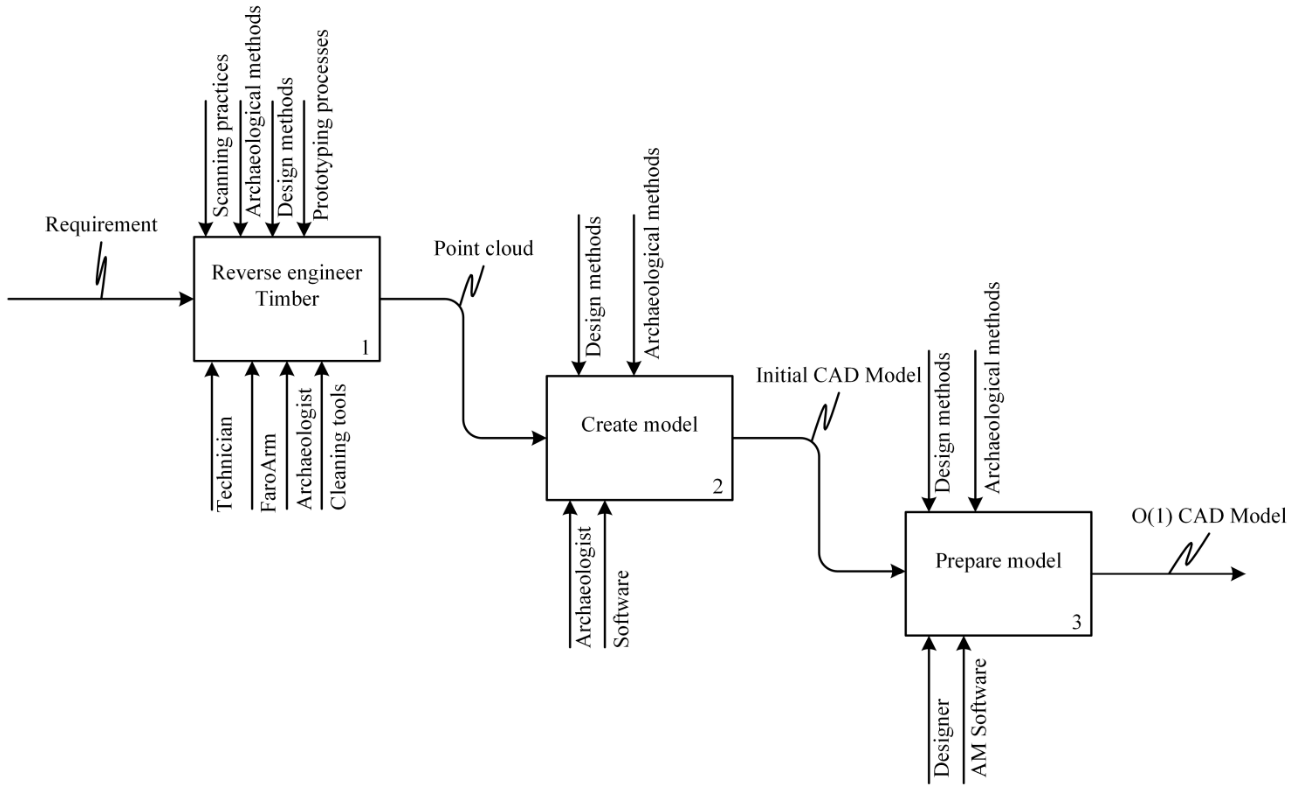
5. Could you tell me which companies are approved suppliers for these technologies?

6. Do you think that the situation regarding approved providers will change in the future (and if so how, when, and why)?

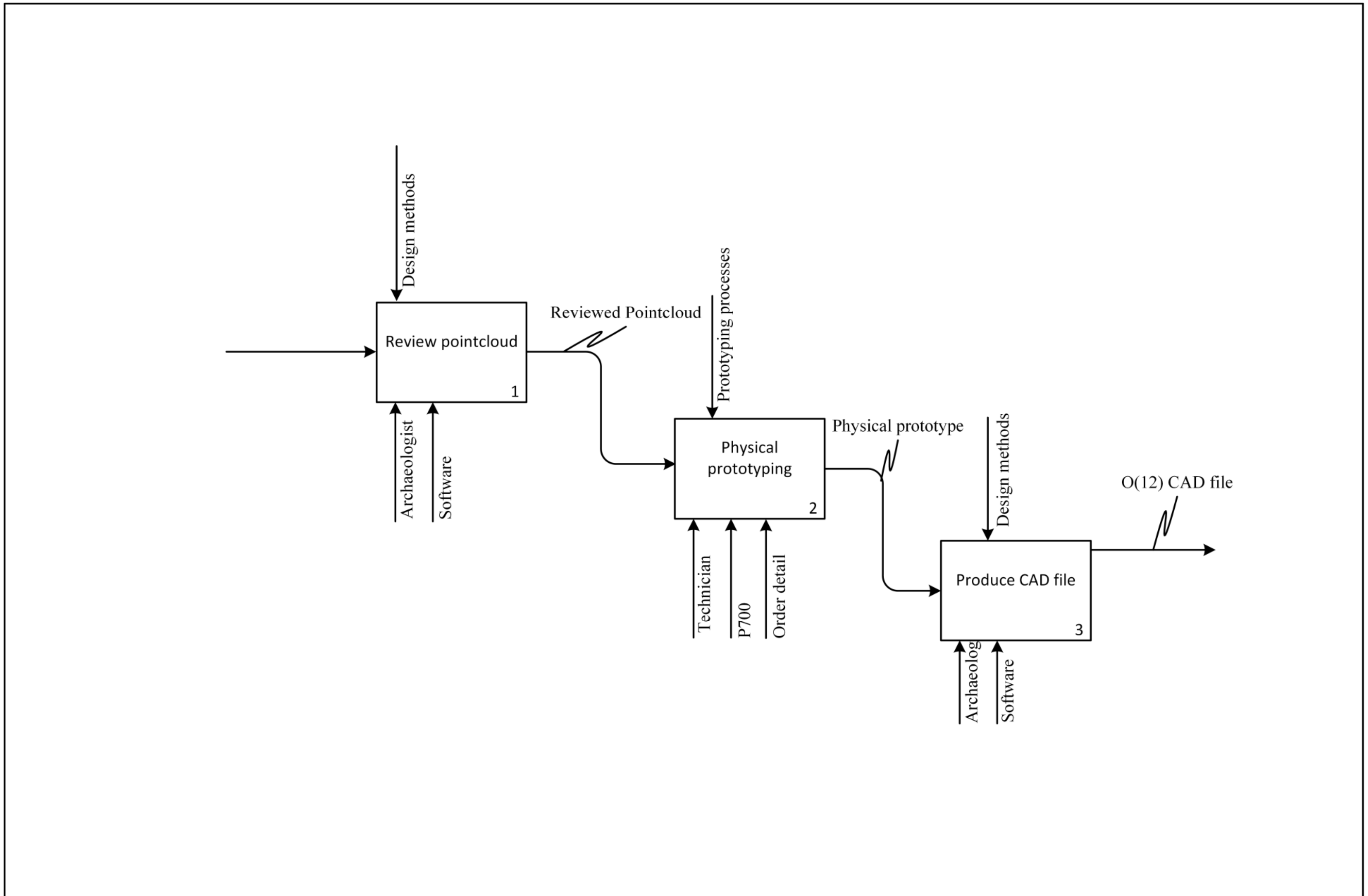
CLOSE: Thank respondent for their time, and reiterate the opening discussion concerning their participation.

D2 Sample IDEF0 diagram

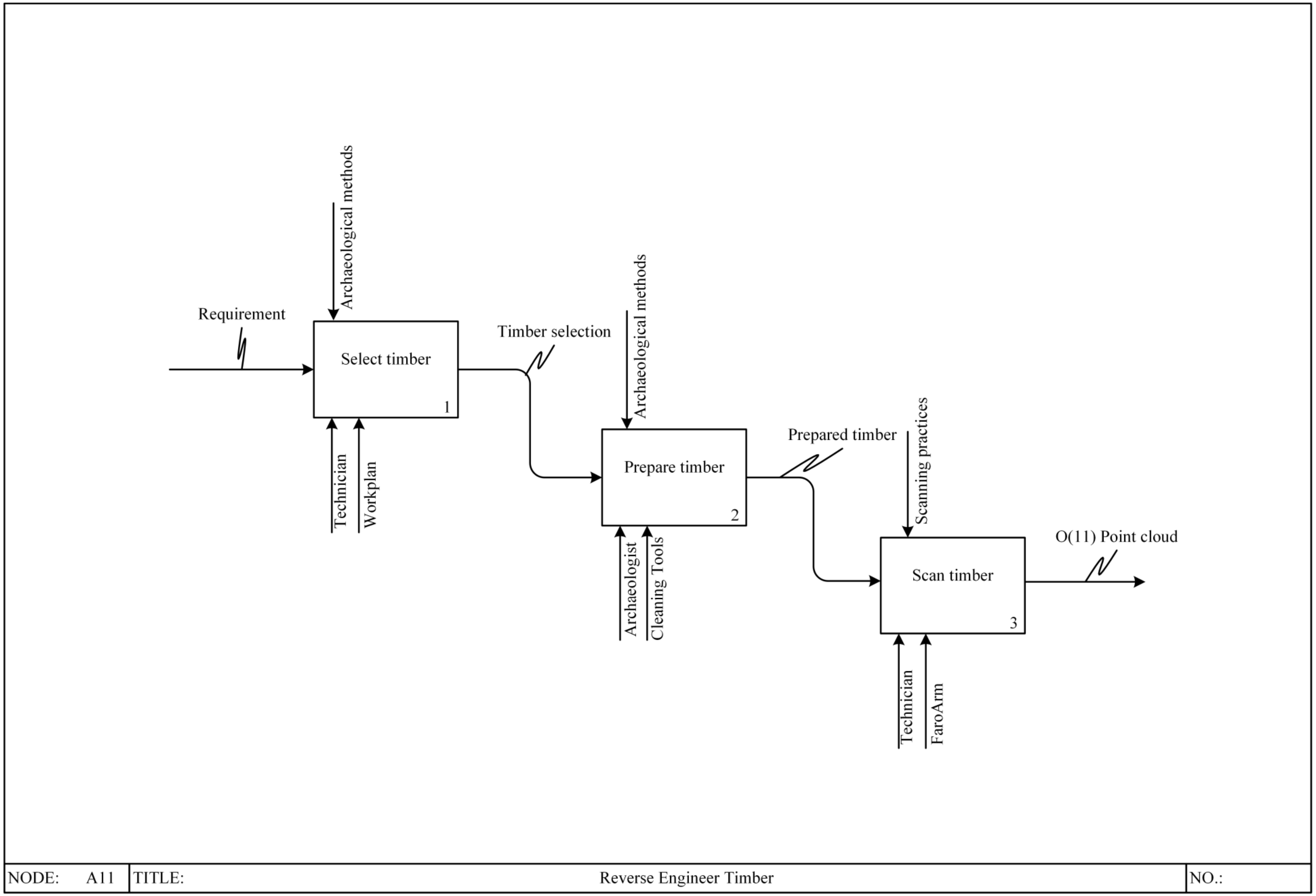


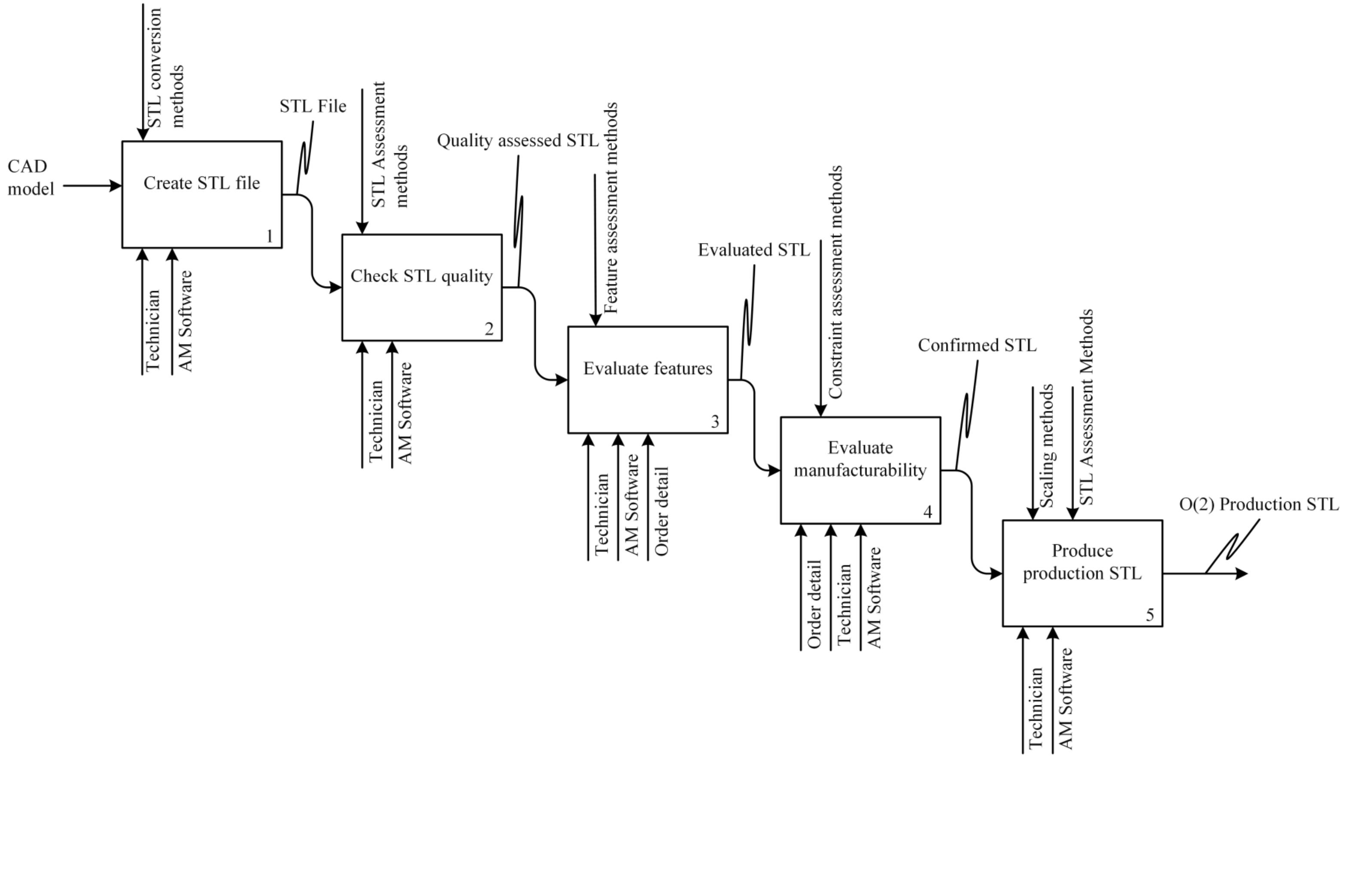


NODE: A1	TITLE: Acquire Geometry	NO.: Case 2

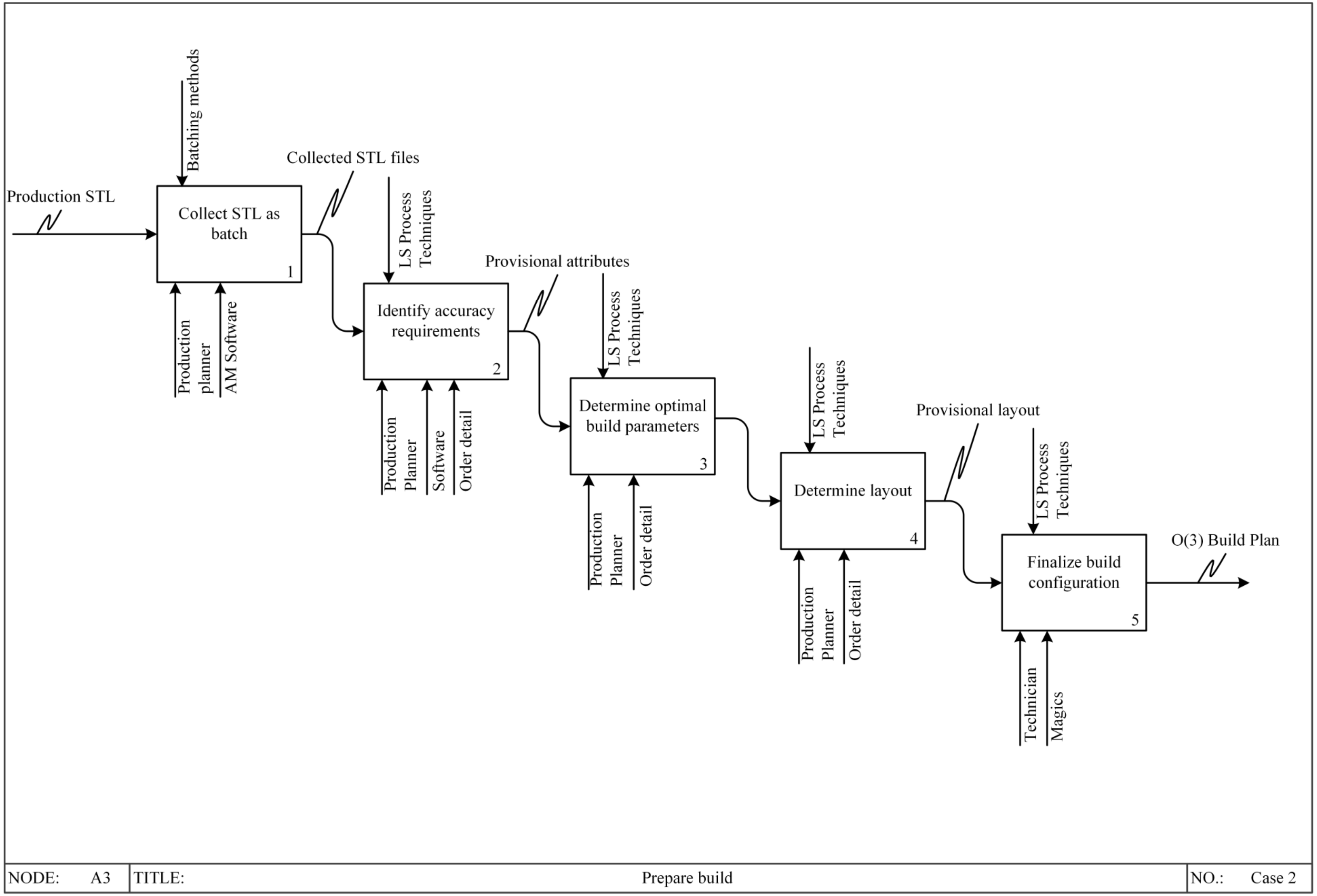


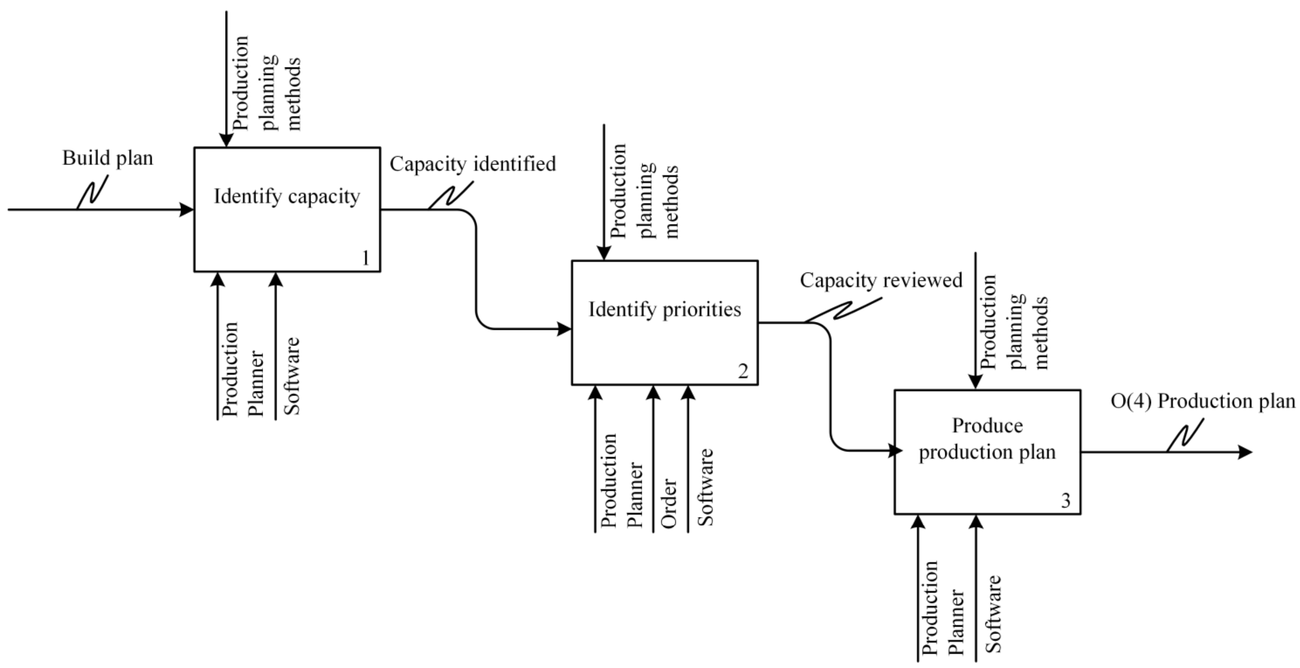
NODE:	A12	TITLE:	Create CAD model	NO.:	Case 2


Archaeological methods
Requirement
Select timber
1
Technician
Workplan
Timber selection
Archaeological methods
Prepare timber
2
Archaeologist
Cleaning Tools
Prepared timber
Scanning practices
Scan timber
3
Technician
FaroArm
O(11) Point cloud
NODE: A11
TITLE: Reverse Engineer Timber
NO.:

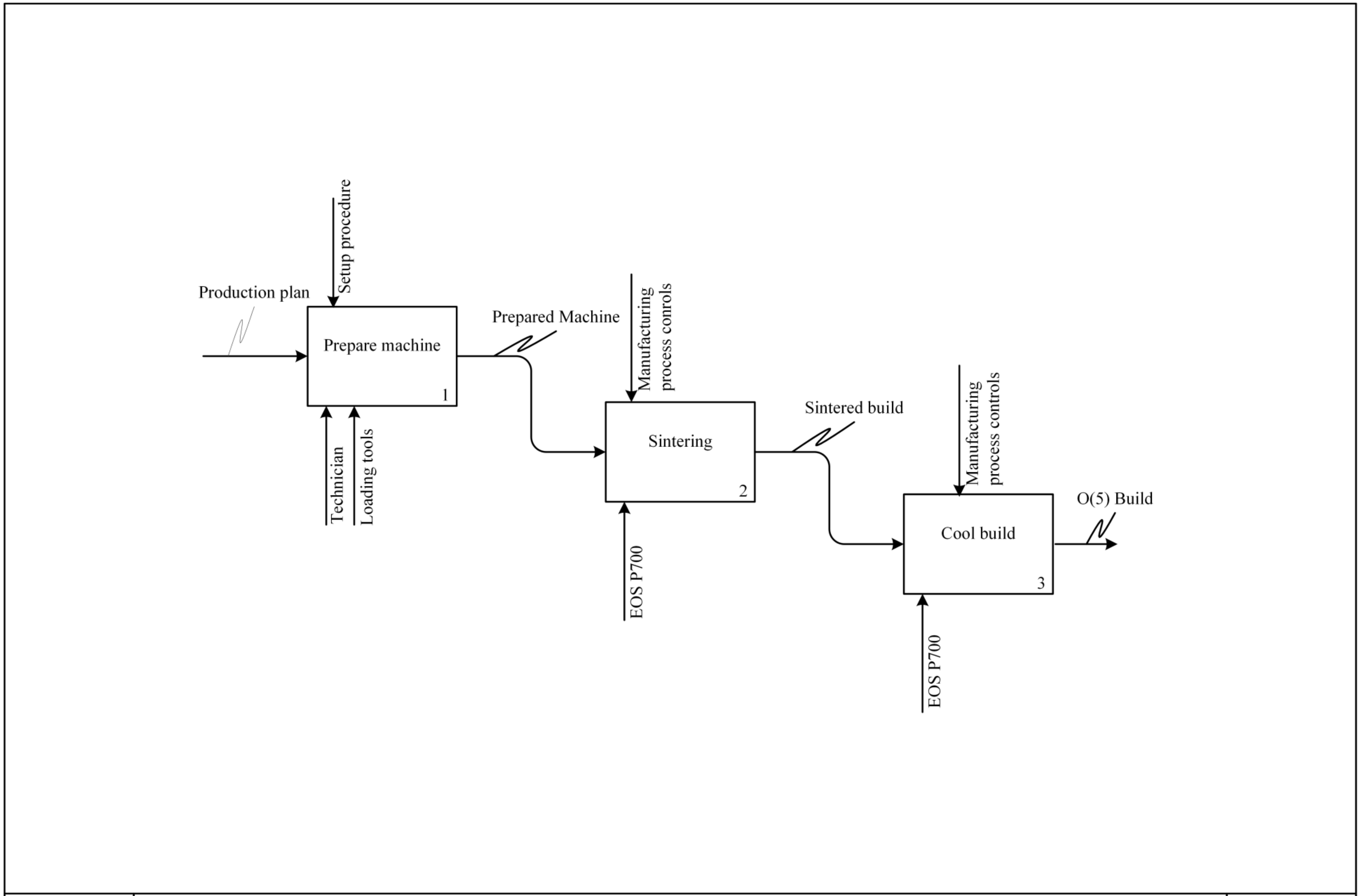


NODE: A2	TITLE: Validate Geometry	NO.: Case 2

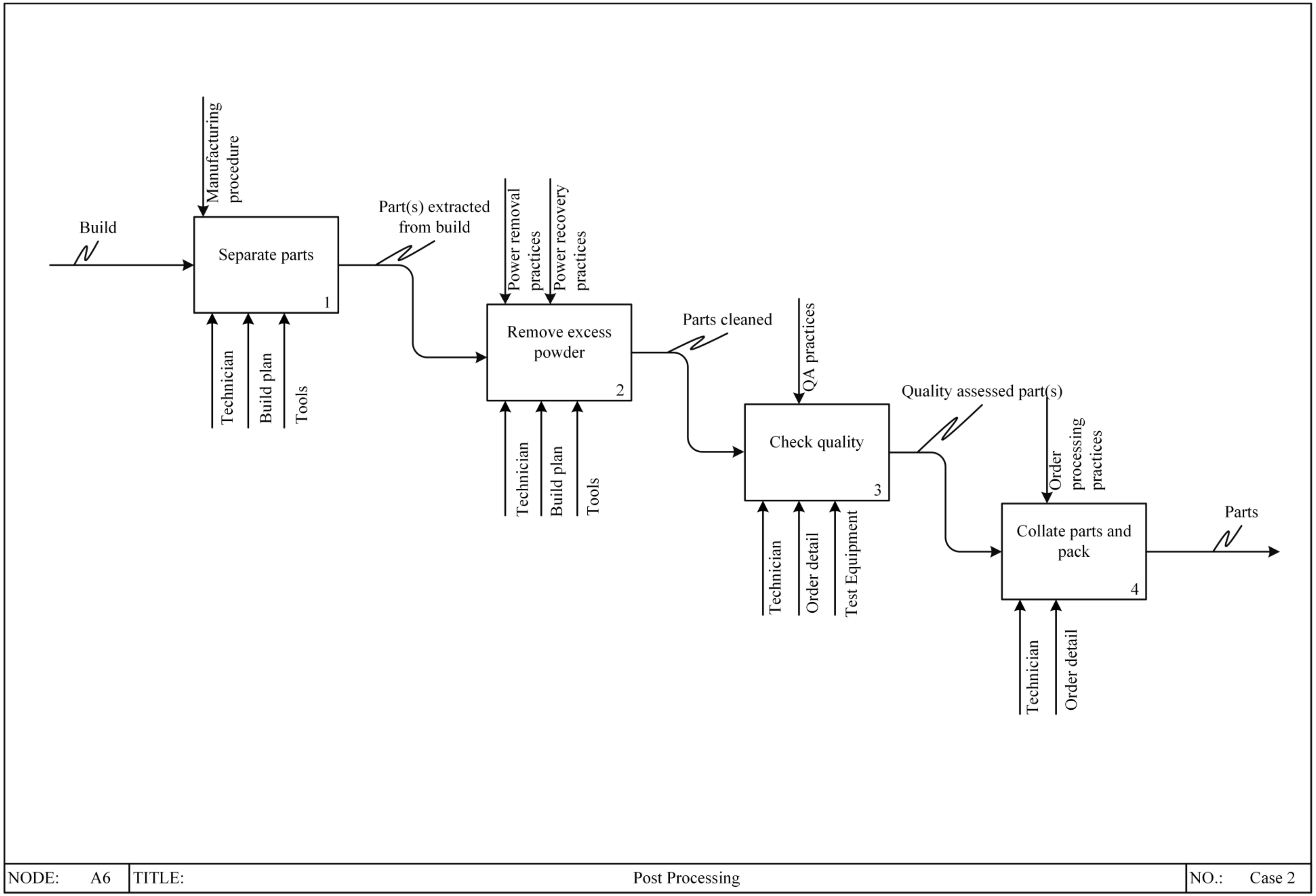

Production STL
Batching methods
Collect STL as batch
1
Production planner
AM Software
Collected STL files
LS Process Techniques
Identify accuracy requirements
2
Production Planner
Software
Order detail
Provisional attributes
LS Process Techniques
Determine optimal build parameters
3
Production Planner
Order detail
LS Process Techniques
Determine layout
4
Production Planner
Order detail
Provisional layout
LS Process Techniques
Finalize build configuration
5
Technician
Magics
O(3) Build Plan
NODE: A3
TITLE: Prepare build
NO.: Case 2



NODE: A4	TITLE: Plan production	NO.: Case 2



NODE: A5	TITLE: Manufacture	NO.: Case 2


Manufacturing procedure
Build
Separate parts
1
Technician
Build plan
Tools
Part(s) extracted from build
Power removal practices
Power recovery practices
Remove excess powder
2
Technician
Build plan
Tools
Parts cleaned
QA practices
Check quality
3
Technician
Order detail
Test Equipment
Quality assessed part(s)
Order processing practices
Collate parts and pack
4
Technician
Order detail
Parts
NODE: A6
TITLE: Post Processing
NO.: Case 2