An Implementation Framework

for Additive Manufacturing

Submitted by Stephen Mellor to the University of Exeter as a thesis for the degree of
Doctor of Philosophy in Engineering

March 2014

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

Signature: ....

ACKNOWLEDGEMENTS

The undertaking of the works contained in this thesis has been a privilege and a pleasure. I am tremendously grateful to all who have made this possible. It has been through the help of many people this thesis has come to completion, and although the following is not extensive, it provides a list of those who have extended significant and invaluable assistance during the course of this study:

- I would like to thank my supervisors, Dr Liang Hao and Professor David Zhang, for their guidance and support throughout the years of my study.

- To my friends and family, particularly mum and dad, Claire and Yinka, John and Hazel, and all the children. Your support during the years of my research has provided me with the confidence and the desire to persevere particularly in the difficult times.

- Much gratitude is extended to the staff and students at the University of Exeter, College of Engineering, Mathematics and Physical Sciences (CEMPS). Both the financial and academic support of the college has provided the support necessary to conduct these investigations.

- To my colleagues at CEMPS who have made the last few years so enjoyable, particular thanks to Ahmed Hussein, Matthew Johns, Robert Allen, Marc-Antoine Boucher, Giovanni Stranno, Asmi Rizvi and Pierre Aumjaud.

- I would also like to thank the informants at each of the case study companies, their openness and willingness to share their experiences made this research possible. I am particularly grateful for my work colleagues at HiETA.

- To the many friends in Exeter who have made life as a PhD student in the City so much fun, Matt Dorrington, Paul Dorrington, Luke Dorrington, Sue Dorrington, Mike King, William Stewart, Rachel Burrows, Jack Dyer, friends at Belmont Chapel and the Bowling Green. Special thanks to Toby Wood, who has been a great friend and given invaluable support over the years.

ABSTRACT

The study presents a normative framework for the Additive Manufacturing (AM) implementation process in the UK manufacturing sector. The motivations for the study include the lack of socio-technical studies on the AM implementation process and the need for existing and potential future project managers to have an implementation model to guide their efforts in implementing these relatively new and potentially disruptive technologies.

The study has been conducted through case research with the primary data collected through the in-depth semi-structured interviews with AM project managers. Seven case studies were conducted representing AM implementation practice at different stages of the implementation cycle. The first stage involved a pilot study at a post-implementer to identify the main areas of interest for AM implementation research. The second involved a wider study of AM implementers at the post-implementation stage with cross case analysis of implementation practice. The final stage involved an investigation into pre-implementation of AM, applying the proposed framework in three companies yet to fully implement AM as a production method.

Contribution towards the existing body of literature was in the form of a normative framework for AM implementation in a variety of industrial sectors. The framework describes the main activities in the implementation process and supports a taxonomy of implementers.

PUBLICATIONS

The following publications were produced during the course of this study.

- S. Mellor, L. Hao, D. Zhang, (2014) Additive manufacturing: A framework for implementation, *International Journal of Production Economics*, Volume 149, pages 194-201.

- S. Mellor, L. Hao, D. Zhang (2010), An Overview of Business Models and Strategy of Additive Manufacturing, *In Proceedings of the Eleventh National Conference on Rapid Design*. *Prototyping and Manufacturing*. Eleventh National Conference on Rapid Design. Prototyping and Manufacturing. Lancaster: CRDM Ltd, pages 153-162.

- P. Li, S. Mellor, J. Griffin, C. Waelde, L. Hao, and R. Everson, (2014) Intellectual property and 3D printing: a case study on 3D chocolate printing, *Journal of Intellectual Property Law & Practice*, published online.

- L. Hao, S. Mellor, O. Seaman, J. Henderson, N. Sewell, M. Sloan, (2010), Material characterisation and process development for chocolate additive layer manufacturing, *Virtual and Physical Prototyping*, 1745-2767, Volume 5, Issue 2, pages 57 – 64.

LIST OF CONTENTS

ACKNOWLEDGEMENTS I

ABSTRACT II

PUBLICATIONS III

LIST OF CONTENTS IV

LIST OF FIGURES X

LIST OF TABLES XIII

CHAPTER 1 INTRODUCTION 1

1.0 Introduction to Additive Manufacturing 1

1.1 The Additive Manufacturing Industry 2

1.2 The Research Problem, Aim and Objectives 4

1.3 The Research Scope 7

CHAPTER 2 LITERATURE REVIEW 10

2.0 Introduction 10

2.1 Additive Manufacturing Defined 10

2.2 Additive Manufacturing Technologies 12

2.2.1 Liquid-based processes 13

2.2.2 Powder-based processes 15

2.2.3 Solid-based processes 18

2.3 The Additive Manufacturing Industry and Applications 18

2.3.1 Medical 21

2.3.2 Aerospace 23

2.3.3 Automotive 25

2.3.4 Consumer goods 25

2.4 Additive Manufacturing Implementation Research 26

2.5 Manufacturing Technology Implementation 32

2.6 Technology Strategy 32
2.6.1 Technology as a Competitive Weapon 32
2.6.2 Terminology and Definitions 33
2.6.3 Technological Change 35
2.7 Implementation Defined 36
2.7.1 Models of Manufacturing Technology Implementations 37
2.8 Manufacturing Strategy 44
2.8.1 Content of Manufacturing Strategy 45
2.8.2 The Process of Manufacturing Strategy Formulation 50
2.9 Conclusions 51
CHAPTER 3 RESEARCH METHODS 53
3.0 Introduction 53
3.1 Philosophical Basis of the Study 53
3.2 Selection of Method 54
3.2.1 Case studies 56
3.3 Developing the Research Framework, Constructs and Questions. 58
3.3.1 Research questions 58
3.3.2 Research framework 59
3.3.3 Defining the unit of analysis 60
3.4 Choosing Cases 62
3.4.1 The typical case: The RP Convertor 65
3.4.2 The typical case: The Conventional Manufacturer 65
3.4.3 The typical case: The New Start-up 66
3.5 Developing the Research Instrument and Protocols 66
3.6 Conducting the Field Research 67
3.6.1 Sources of evidence 67
3.6.2 Gaining site access 68

3.7 Approach to Data Analyses 71
3.7.1 Within-case analysis 71
3.7.2 Cross - case analysis 74
3.8 Summary of the Chapter 75
CHAPTER 4 DEVELOPMENT OF THE IMPLEMENTATION FRAMEWORK 77
4.0 Introduction 77
4.1 The Proposed Research Framework 77
4.2 The Research Constructs 77
4.2.1 Contextual factors – Organisational and supply chain constructs 78
4.2.2 Technical factors – AM technology factors 78
4.2.3 Additive manufacturing strategy and operations 79
4.3 The Framework Factors 79
4.3.1 Strategic Factors 79
4.3.2 Organizational Factors 82
4.3.3 Operational Factors 88
4.3.4 Supply chain factors 92
4.3.5 Technological Factors 96
4.4 Summary 99
CHAPTER 5 THE PILOT STUDY 103
5.0 Introduction 103
5.1 Background information of the company and informants 103
5.2 Pilot Case Study Results 104
5.2.1 Strategic factors 105
5.2.2 Organisational Factors 111
5.2.3 Supply Chain Factors 114
5.2.4 System of Operations 116
5.2.5 AM Technology 119

5.3 Discussion.......... 121

5.4 Conclusions 125

5.4.1. Framework refinement based on pilot study 126

5.4.2 Research methodology implications.......... 129

5.5 Summary.......... 130

CHAPTER 6 THE MULTI-CASE STUDY: AM IMPLEMENTATION FOR PRODUCTION APPLICATIONS.......... 131

6.0 Introduction 131

6.1 AM Implementation at Renishaw Plc, Gloucestershire.......... 132

6.1.1 AM Strategy 132

6.1.2 Organisational change 137

6.1.3 AM Technology.......... 140

6.1.4 Systems of Operations.......... 143

6.1.5 AM Supply Chain.......... 145

6.1.6 Summary of case study.......... 148

6.2 AM implementation at Materialise UK, Sheffield 152

6.2.1 AM Strategy 152

6.2.2 Organisational Change 155

6.2.3 AM Technology.......... 158

6.2.4 Systems of Operation 161

6.2.5 AM supply chain 163

6.2.6 Summary of the case study.......... 165

6.3 AM Implementation at Reprap Ltd, Bath.......... 167

6.3.1 AM strategy.......... 167

6.3.2 AM Technology.......... 170

6.3.3 Organisational Change 172

6.3.4 Operational Factors.......... 173

6.3.5 AM Supply Chain 175

6.3.6 Summary of case study 176

6.4 Summary of the Chapter 177

CHAPTER 7 CROSS-CASE ANALYSIS AND IMPLICATIONS OF THE IMPLEMENTATION FRAMEWORK 179

7.0 Introduction 179

7.1 Cross- Case Analysis 179

7.1.1 Contextual similarities and differences 180

7.1.2 Technology similarities and differences 183

7.1.3 Similarities and differences in implementation activities and issues 185

7.2. Implications of the Framework 188

7.2.1 The framework revisited - process of AM implementation 189

7.2.2 Developing the business case 190

7.2.3 Developing the systems of operations 192

7.2.4 Building a supportive structure and culture 196

7.2.5 Developing the AM supply chain 199

7.3 The Framework Applied in the Pre-implementation Cases 201

7.3.1 BAE Systems 202

7.3.2 HiTA Technologies Ltd 206

7.3.3 Choc Edge Ltd 209

7.4 Summary of the Chapter 213

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK 215

8.0 Conclusions 215

8.1 Contributions of the Study 216

8.2 Limitations of the Study 217

8.3 Implications of the Study 218

8.4 Future Research Direction 219
REFERENCES 221
APPENDIX A RENISHAW INTERVIEW TRANSCRIPTS 231
APPENDIX B 3T RPD INTERVIEW TRANSCRIPTS.. 242
APPENDIX C MATERIALISE UK INTERVIEW TRANSCRIPTS 243
APPENDIX D REPRAP LTD INTERVIEW TRANSCRIPTS................................... 244
APPENDIX E BAE SYSTEMS INTERVIEW TRANSCRIPTS 245
APPENDIX F CHOC EDGE LTD INTERVIEW TRANSCRIPTS............................ 246
APPENDIX G HITA SYSTEMS INTERVIEW TRANSCRIPTS 247

LIST OF FIGURES

Figure 1.1 Hype cycle for emerging technologies 2012 produced by Gartner Inc. . 2

Figure 1.2 Breakeven analysis performed by Atzeni and Salmi comparing high pressure die casting and SLS 4

Figure 2.1 The stereo-lithography process 13

Figure 2.2 The fused deposition modelling process. 14

Figure 2.3 The inkjet printing process. 15

Figure 2.4 The selective laser sintering process 16

Figure 2.5 The direct metal laser sintering process 17

Figure 2.6 AM industry growth worldwide year on year in millions of dollars. . . . 19

Figure 2.7 The revised technology adoption cycle proposed by Moore 20

Figure 2.8 Percentage of AM services provider revenues generated by industry . . 21

Figure 2.9 Accetabular cups produced in titanium alloy using electron beam melting. 22

Figure 2.10 Aerospace brackets manufactured via metal additive manufacturing . . 24

Figure 2.11 SLS lamp shades produced by FOC 26

Figure 2.12 Economics of SLS production presented by Ruffo 27

Figure 2.13 Life-cycle model of the process of implementation proposed by Voss 37

Figure 2.14 The process of implementation proposed by Voss. 38

Figure 2.15 The proposed AMT implementation integrated planning model 41

Figure 2.16 The FMS technology diffusion model proposed by Bellassi and Fadlalla. 43

Figure 2.17 Framework of effective factors on AMT implementation performance. 44

Figure 2.18 Three paradigms of manufacturing strategy proposed by Voss 46

.

Figure 2.19 Hayes and Wheelwright manufacturing strategy framework. 47

Figure 2.20 Hayes and Wheelwright product process matrix 48

Figure 2.21 Appropriate productions systems for technical complexity/technical flexibility proposed by Kim and Lee 49

Figure 3.1 Conceptual framework of factors influencing the success of Additive Manufacturing technologies implementation. 60

Figure 3.2 Paths to Additive Manufacturing. 61

Figure 3.3 Scenario 1 - direct implementation of Additive Manufacturing. 61

Figure 3.4 Scenario 2- Implementation of RP/RT followed by implementation for Additive Manufacturing. 61

Figure 3.5 The replication approach to multiple-case studies. 63

Figure 3.6 Axial coding diagram redrawn from Matsumoto and Wilson. 73

Figure 3.7 Selective coding diagram adapted from Matsumoto and Wilson. 74

Figure 3.8 The research methodology employed in the study. 76

Figure 4.1 Conceptual model of factors influencing the success of AM technologies implementation. 78

Figure 4.2 Conceptual Framework of Technological Change and Posited Relationship. 88

Figure 5.1 The proposed framework of AM implementation (initial). 105

Figure 5.2 Technological and market maturity determine the marketing process. . 110

Figure 5.3 RP process chain (top). AM process chain (bottom). 118

Figure 5.4 The refined AM implementation framework. 129

Figure 6.1 Dental copings produced at Renishaw on DMLS M270 134

Figure 6.2 Comparison of dental copings produced via casting and DMLS 135

Figure 6.3 AM implementation stages at Renishaw 151

Figure 6.4 Reprap "Mendel" printer with printed components in red coloured

ABS. 171

Figure 7.1 AM technologies included in the study. 183

Figure 7.2 Implementation stages for Additive Manufacturing. 189

Figure 7.3 The typically AM process chain. 192

Figure 7.4 The fragmented AM supply chain. 199

Figure 7.5 Overview of Choc Creator 1 3D printer. 209

LIST OF TABLES

Table 2.1 AM processes categorised according to supply material state. 12

Table 2.2 Five steps in formulating a manufacturing strategy. 51

Table 3.1 Matching research purpose with methodology. 57

Table 3.2 Six sources of evidence: strengths and weaknesses 67

Table 3.3 Additive manufacturing companies involved in the study 72

Table 4.1 A comparison between the characteristics of large, medium and small organisations. 82

Table 4.2 Process planning parameters in AM systems. 91

Table 4.3 The four main cost factors used in AM costing. 91

Table 4.4 Summary of framework constructs and factors. 100

Table 5.1 Summary of strategic factors at the pilot case Study. 111

Table 5.2 Summary of organisational factors at 3T RPD 113

Table 5.3 Summary of supply chain factors at 3T RPD 115

Table 5.4 Summary of the operational factors at 3T RPD 119

Table 5.5 Summary of technology factors at 3T RPD. 121

Table 6.1 The three typical cases classifications 131

Table 6.2 Summary of AM strategic issues and activities at Renishaw 136

Table 6.3 Summary of organisational issues and activities at Renishaw 139

Table 6.4 Summary of technology issues and activities at Renishaw 142

Table 6.5 Summary of operational issues and activities at Renishaw 144

Table 6.6 Summary of supply chain issues and activities at Renishaw 147

Table 6.7 Summary of strategic issues and activities at Materialise. 154

Table 6.8 Summary of organisational issues and activities at Materialise 157

Table 6.9 Summary of technology issues and activities at Materialise 160

Table 6.10 Summary of operational issues and activities at Materialise 165

Table 6.11 Summary of supply chain issues and activities at Materialise 165

Table 6.12 Summary of strategic issues and activities at Reprap 170

Table 6.13 Summary of technology issues and activities at Reprap 172

Table 6.14 Summary of organisational issues and activities at Reprap 173

Table 6.15 Summary of operational issues and activities at Reprap 175

Table 6.16 Summary of supply chain issues and activities at Reprap 176

Table 7.1 Main study case classification 180

Table 7.2 Contextual similarities and differences of the cases 183

Table 7.3 The operational issues and suggested activities for the typical cases . . . 196

Table 7.4 The organisational issues and suggested activities for the typical cases . 198

Table 7.5 The supply chain issues and suggested activities for the typical cases . . 201

Table 7.6 Characterisation of the pre-implementation case studies including informants. 202

CHAPTER 1

INTRODUCTION

1.0 Introduction to Additive Manufacturing

"Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [1] With over 20 years of history, Wynn Kelly Swainson [2] filed the first associated patent in 1977 and the pioneering technology, stereolithography, was commercialised by 3D systems in 1987. In the early years of AM the more commonly used term to describe the process was Rapid Prototyping (RP), reflecting its main use at the time; the manufacture of prototypes more quickly and easily than conventional means such as CNC but at a cost and speed not competitive for production. These prototypes were most commonly used as communication and inspection tools, where producing several physical models in short time directly from computer solid models helped to shorten production development steps [3].

The terminology and definitions within the field in question have been in much debate since the early years of AM [4–6], and still today, depending on the realm of commentary the reader may find a number of terms used interchangeably. In the realm of technical research, AM has been taken as the dominant representation of the field in question, illustrated by its use by authoritative authors such as Terry Wohlers along with standards committees such as the ISO and ASTM. Whereas in popular press, the more commonly used term has become 3D printing, reflected in its common use in press articles such as the Economist [7,8]

As the industry has evolved, encompassed within this definition are a large number of technologies, some of the more widely used including, stereolithography (SL), fused deposition modelling (FDM), selective laser sintering (SLS) and direct metal laser sintering (DMLS). Since the development of many of these technologies has occurred simultaneously, there are various similarities as well as distinct differences between each process [4]. A review of the currently available systems will be provided in the following chapter; however, as an introduction to the process some general steps may be defined. Gibson et al. [9] define eight key steps in the generic process of Computer Aided Design (CAD) to production:

1. Conceptualization and CAD
2. Conversion to Stereolithography (STL) file
3. Transfer and manipulation of STL file on AM machine
4. Machine setup
5. Build
6. Part removal and cleanup
7. Post-processing of part
8. Application

1.1 The Additive Manufacturing Industry

The additive manufacturing industry has been dominated by over estimation and hype since its early years, and this has continued throughout recent press [9,10]. The Gartner Hype Curve or 'Hype Cycle for Emerging Technologies' is annually produced by a leading information technology research and advisory company, Gartner Inc. Their most recent estimate shows 3D printing on the 'peak of inflated expectations'. Though many have labelled these technologies as being 'disruptive' and suggest they are key enabler for a 3rd industrial revolution [5], their impact to date in terms of global manufacturing have been at best modest.

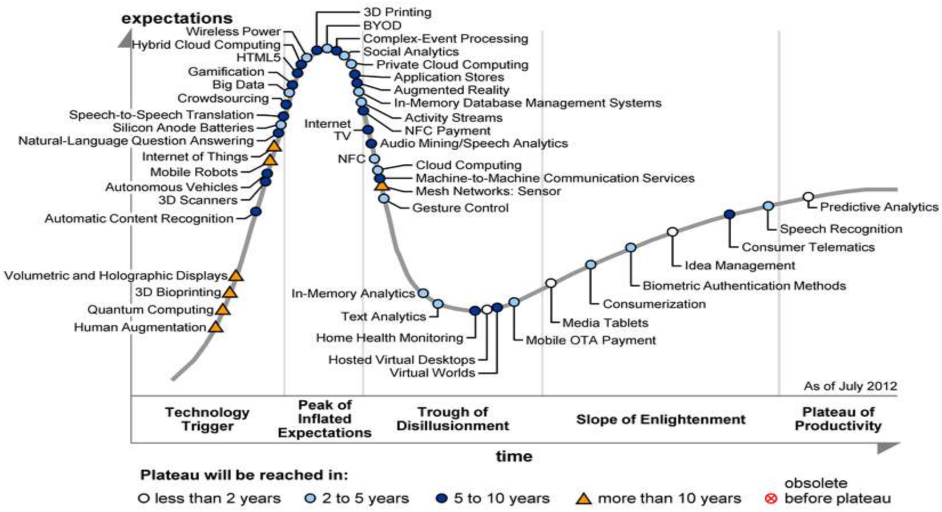

Figure 1.1 Hype Cycle for Emerging Technologies 2012 produced by Gartner Inc.

Holmstrom et al. [11] suggest the unique characteristics of AM production lead to the following benefits:

- No tooling is needed, significantly reducing production ramp-up time and expense.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Allows product to be optimized for function (for example optimized cooling channels).
- Allows economical custom products (batch of one).
- Possibility to reduce waste.
- Potential for simpler supply chains; shorter lead times, lower inventories.
- Design customization.

These benefits have been captured in a variety of applications spanning a number of industries, and different stages of the product development life cycle. Examples include, titanium aerospace parts where only 10% of the raw material is required when compared to the original machined part [8]. Atzeni and Salmi [12] showed the economics of additive manufacturing for end-use parts through comparing the production of landing gear aircraft assemblies, through high pressure die casting (HPDC) and selective laser sintering (SLS). The authors showed the cost benefit at low to medium production volumes, illustrated in the breakeven analysis shown in Figure 1.2. The benefits of AM have also been captured in the production of race car gearboxes, as AM facilitates the manufacture of smooth internal path ways, providing faster gear changes and reducing component weight by 30% [8]. Similarly, Cooper et al [13] illustrate the potential for improved functionality in their study of formula one technology, applying AM to hydraulic component manufacture gaining efficiency of fluid flow of 250%. With such proposed benefits one may assume there are a vast number of organisations adopting AM and products on the market, however, this is not the case.

As previously stated the current dominant application for AM processes remains RP. Rapid Tooling (RT) also makes up some of the current AM activity which involves the fabrication of moulds and dies. Regarding manufacturing applications of AM processes, notable areas of success include the production of medical devices such as dental crowns and hearing aids, driven by customer requirements for individualised products and AM processes having the benefit of design customization. AM has also been applied to the production of low volume consumer products, including high value lighting goods and electronics. The aerospace sector has also found a number of applications, often driven by the possibility of improving buy-to-fly ratios, as some AM processes have high material utilisation (most notably metal-based process) and reducing the weight of components through design optimisation [14]. Other sectors include, automotive, jewellery, architecture and defence applications.

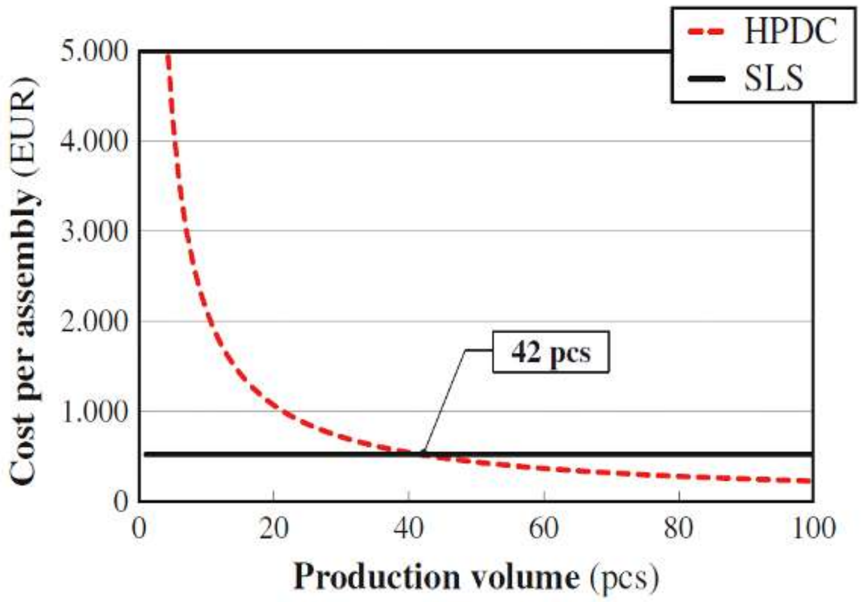

Figure 1.2 Breakeven analysis performed by Atzeni and Salmi comparing High Pressure Die Casting and SLS processes [12]

1.2 The Research Problem, Aim and Objectives

With some notable exceptions [15–20] the studies to date in the AM stream of research have mainly focused on process and materials development. This focus, particularly when concerning metal AM, reflects the current view in terms of applications there is significant scope for production applications with technical barriers preventing further adoption. However, it is clear from a scan of AM literature and industry reports that a number of companies are already achieving production with AM technologies, yet the research from an operations management perspective is disappointingly absent.

There have been a number of articles that have studied the use of RP technologies in the implementation of new manufacturing paradigms such as agile manufacturing [21–23]. Though these studies provide an insight into the use of RP technologies, this area of research does not consider the processes as a manufacturing technology. This study proposes that the use of these technologies for manufacturing creates a new area of research; a proposition that has been supported by the study results.

As previously stated, there are few-large scale applications of AM, many of which are for producing personalised products in the medical field [25]. Ruffo et al [17] provided a summary of the pitfalls which exist for companies looking at the use of AM as a solution for current manufacturing problems or wishing to take advantage of this emergent technology, suggesting they are concentrated in three specific areas:

- Manufacturing processes and materials; and
- Design
- Management, organisation and implementation

These issues are inter-related, and this study centres on the third of these areas, specifically focusing implementation of AM technologies for production applications. As Voss suggested in his seminal work on manufacturing technology implementation [24]:

"....there is much evidence that a process innovation can succeed in one attempt at adoption and fail in another".

It is inevitable that some of the factors critical to the implementation of AM technologies are also important to the adoption of other manufacturing technologies (such as flexible manufacturing systems). However, it is not the aim of this study to rediscover these issues. Rather this thesis seeks to build on this understanding, adding insights into factors that are specific or of particular importance to AM technologies due to their unique characteristics, resource requirements, benefits and tradeoffs and so on.

Thus the study focuses on investigating the process of AM implementation, developing a normative framework for AM implementation and building an understanding of the process and the factors influencing success of AM projects. The framework was developed from the investigation of AM implementation in European organisations found to be the most active AM adopters in terms of production applications.

The study poses the following central research question: **How do organisations go about implementing Additive Manufacturing as a manufacturing process, either as a replacement to the conventional approach or for new business opportunities?**

From this central question, the following research sub-questions are posed:

- Is there a normative framework for AM implementation to be used by decision makers at adopting organisations?
- What are the key factors in the AM implementation framework?
- How do these factors combine with technical factors to form the AM implementation framework?
- How do contextual differences influence the implementation process?

In order to answer the research questions posed in this study the following research objectives were developed:

- To develop a normative framework for the implementation of Additive Manufacturing technologies for manufacturing applications
- To capture the key technical and non-technical factors in the process of Additive Manufacturing implementation
- To identify where these key factors have been encountered and managed in different organisations.

In order to achieve these objectives, the research design followed an exploratory/semi-structured approach, using case studies with AM implementers at different stages of adoption. A hybrid research methodology was used during the study, combining case studies and the grounded theory approach. This involved using the body of literature on advanced manufacturing systems along with a pilot case study to develop an initial research framework. Following this pilot stage of analysis, an in-depth multi case study was performed using in-depth interviews with AM project managers in three companies which had already adopted AM for production. Two stages of data analysis were conducted; within and across cases. The analysis produced key factors which formed the normative framework of the AM implementation process. Finally, the framework was then used to propose implementation approaches at three companies who had yet to implement AM for production.

The study offers three possible contributions to the field of AM research. The first and most significant is the normative framework for the implementation of Additive Manufacturing. The framework describes the main activities of AM implementation and describes the how these activities are related to the contextual and technical factors of the process. Moreover, it explains how AM project managers in the manufacturing sector may use the model in developing their own implementation plans along the strategic, technology, organisational, supply chain and operational dimensions.

The second contribution of the study is the comparison of the technology differences of different AM processes and their effect on the implementation process adopted. The comparisons include the contextual differences apparent in the AM industry and definition of three different approaches to AM adoption according to these contextual differences. The explanation highlights the key issues experienced by the three typical cases, how they differ and the contextual and technological reasons for these issues, identifying the areas where more emphasis should be given by the project managers.

Finally, the third contribution of the study is the identification of the research problem in AM implementation. The study highlights the lack of AM implementation studies in the literature, specifically highlighting the lack of socio-organisational aspects of the technology deployment. The study also offers suggestions on the potential research areas of focus in the field of AM implementation.

1.3 The Research Scope

The thesis is structured as follows. The first chapter provides the background to the research problem and the motivation for the study. In this chapter, the study's central research questions are presented and discussed, along with the objectives of the research. The chapter also provides a brief description of the research methods used in the study and a justification for the research through defining its main contributions.

The second chapter presents the literature review used in the formulation of the research questions. The chapter presents the two areas of research study which have been brought together in the formulation of this thesis, AM research and technology implementation research. The chapter describes the types of systems and state of the industry. It also defines the lack of studies on the AM implementation process. It also offers the definition of implementation used in the study and the reasoning behind the selection of the approach for the study. Finally, the chapter combines the selected theories to define the research questions and objectives.

The third chapter describes the research methods employed in this study to answer the proposed research questions and achieve the research objectives. It begins with the explanation of the philosophical underpinnings of the study and therefore the qualitative research approach. The chapter then presents the motivations for combining research strategies, case study research and the grounded theory approach, as the study's research design. The taxonomy used in selecting case studies also presented in this research methods chapter. Finally, the chapter explains the research process employed in the study.

The fourth chapter describes the research framework. It presents the proposed research framework layout and explains how the framework was determined. It then goes onto outline the motivations for grouping of the factors in the chosen constructs. The justifications for including the framework factors are then detailed within each construct description. Finally, the chapter discusses the proposed inter-relationships between factors and a summary of the chapter content.

The fifth chapter in this thesis presents the pilot enquiry. It begins with a background on the case company and the informants interviewed during data collection. The chapter then presents the data and discussion along the framework constructs. It provides a summary of the findings based on the typical case of the RP convertor. The RP convertor being those companies who have a history in prototyping services, implementing AM for production applications. Based on the case analysis, it then describes the refinement of the framework. Finally the chapter presents the lessons learnt for research methodology including data collection methods and selection of case studies.

The sixth chapter presents the multi case study, specifically the within-case analysis of the three main case studies. The chapter presents the three cases sequentially, following the order of investigation. It includes the within case analysis of three typical cases and presents the data along the dimensions of the framework. The chapter also presents a discussion on each of the cases and the issues and activities identified at each of the cases. Finally, a summary of the cases is provided along with some limitations of the study.

Chapter seven presents the cross-case analysis of the multi-case study and the implications of the framework. This chapter provides a comparison of similarities and differences between each of the case studies implementation processes. It presents this comparison with references to the technical and contextual dimensions of the cases. The chapter then goes on to present a revised framework based on the cross case analysis of the three typical cases. Finally, the chapter discusses the implications of the framework through a pre-implementation study of three further cases as outlined in the research methodology.

Finally, the seventh chapter presents the conclusions of the study. This chapter includes the discussion on the major contributions of the study. It also recognises the limitation of the study and the measures taken to enhance the quality of the study findings. The chapter ends with a summary of the study implications as well as proposing directions for future research on AM implementation.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents the literature review performed in the research study. The aim of the literature review was to define the primary research questions that would form the base on which the study would proceed. The chapter is structured as follows; the first section reviews the proposed area of research, AM technologies, the industry, applications, and research. The second section provides a review of implementation research in the context of manufacturing. The third sections provides a review of manufacturing strategy, motivated by the role of technology in manufacturing strategy (MS) and the approach to MS research. Finally, the chapter then summarises the conclusions of the review and how they have defined the study questions.

2.1 Additive Manufacturing Defined

The terminology and definitions related to the field of study have been in much debate over the years, varying worldwide and evolving with the technologies themselves. Synonyms found in the literature include, solid freeform fabrication, direct digital manufacture, 3D printing, layered manufacturing, rapid manufacturing and additive layer manufacturing. Evolving from RP research, which surfaced in the 1980s through the pioneering technology stereolithography, scientific and technological advances have advanced the applications of these processes beyond purely prototyping. Through this development, industry experts advocate the importance of distinguishing between RP and processes that facilitate manufacturing products with long term consistency for the entire product life-cycle [25]. In addition to RP, the group of technologies have also been applied for what has been commonly referred to as rapid tooling (RT). RT involves creating tools that serve traditional manufacturing procedures such as injection moulding, casting, forging and other tooling processes [26]. Kruth at al [27] further defined two sub categories of RT; direct tooling in which moulds are manufactured directly from AM processes, and indirect tooling whereby a master mould is created.

Until recently, Rapid Manufacturing was a popular term in the research community, used to differentiate between the prototyping, tooling and manufacturing:

"Rapid Manufacturing is the direct production of finished products or parts using additive fabrication techniques" [25]

This definition was embraced by a considerable number of experts in the field [5,18,19]. However, although this definition provides an important distinction from rapid prototyping, the characteristics of the process, including short lead times but relatively slow process speed, many recognised that it may be misleading.

Additive Manufacturing (AM) has become the more recently generally accepted in the area of technical research and it defines a methodology of manufacture, rather than an application or grouping of technologies. ASTM F42 committee has to date been the pioneering standards committee for AM process and materials and their definition is often cited within the research community:

"Additive Manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [1]

This definition is used throughout this research study, and unless stated otherwise, the author will be referring to manufacturing applications. However, in performing the literature review presented in this chapter, to ensure potentially important studies were included in the critical study, the research used a number of search terms, including:

- Additive Manufacturing
- Additive Fabrication
- Additive Layer Manufacturing
- Solid Freeform Fabrication
- 3D printing
- Rapid Manufacturing
- Rapid Prototyping
- Rapid Tooling

- Direct Digital Manufacturing

The number of terms used throughout the research community caused some issues with a high number of non-related articles being presented when using basic search tools on e-resources. Therefore, the research used advanced searching techniques to remove non-relevant studies finding success when using combinations of the above terms.

The following section provides a review of the technologies encompassed in this definition of AM.

2.2 Additive Manufacturing Technologies

Reviews of the numerous AM technologies have been performed in some of the key AM readings [4, 5, 28]. Since the development of many of these technologies has occurred simultaneously, there are various similarities as well as distinct differences between each one [29]. The mechanisms and materials introduced along with the technological advancements have resulted in a number of different methods of categorising AM processes. Levy et al [30] used four material categories to group AM processes into RM, RT and RP applications. The material categories used by Levy et al include metals, ceramics, polymers and composites. Kruth [27] identified three basic materials states to categories AM processes, liquid, powder and solid. This form of categorisation was also used Hopkinson et al [5] and is presented in Table 2.1.

Table 2.1 AM processes categorised according to supply material state

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

Concurrent with these references, the systems have been reviewed and presented in the following sub-sections according to the material state during processing, liquid-based, powder-based and solid-based. The following is not an exhaustive list of all available AM technologies, rather there is a focus on those processes which have shown the promise for production applications and are widely used across industry sectors.

2.2.1 Liquid-based processes

2.2.1.1 Stereolithography (SL)

The SL process was the first AM processes to be commercialised and is arguable the most established process in terms of accuracy, controllable parameters, and an in-depth understanding of its mechanics [31]. The process of SL involves: part modelling and conversion into STL file format to create a volumetric mesh and support structure; slicing of STL format of 3D solid model to provide a series of cross-sectional layers; exporting the sliced model to the stereolithography apparatus (SLA); building the support structure and the component layer by layer over a vat of specially designed liquid resin with an argon laser, which traces the outline of the 2D sections and solidifies the resin; removal of support structure; and if required, post-curing of the part to undergo final polymerisation in a post-curing apparatus (PCA), using a controlled furnace or an ultraviolet oven [32]. SL is often used in RP, conceptual and functional polymer prototypes, and for RT to create master patterns for moulding and casting processes. Long term stability of components tends to be an issue, resulting in SL being limited in applications for end-use serial parts. The main limitation of the process is the requirement for supports which consume additional materials and extend the production time [14].

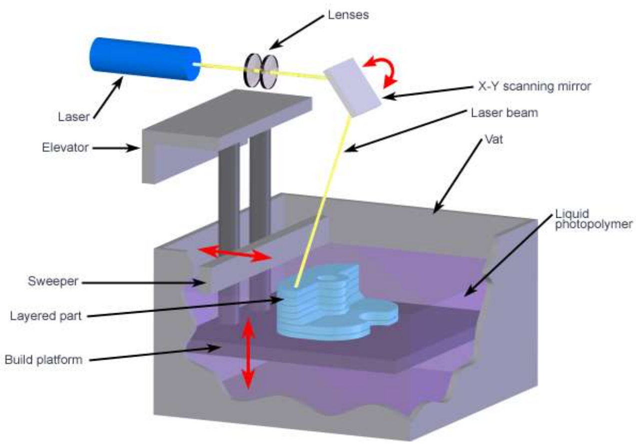

Figure 2.1 The stereo-lithography process [33]

2.2.1.2 Fused Deposition Modelling (FDM)

Similar to the SL process, FDM is one of the most commonly used processes for the manufacture of conceptual and functional prototypes. This deposition based AM process involves extruding polymer filament through a nozzle which traverses in the x and y directions to create each two-dimensional layer (Figure 2.1). The nozzle is heated to melt the material and its movement is controlled by a numerically controlled mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The material cools or cures after extrusion from the nozzle and the part is built as each two-dimensional layer is laid onto the previous. The material used is preferably one which will melt at a pre-selected temperature and rapidly solidify upon adhering to the previous layer [28]. Separate nozzles are used to deposit support structures which allow the creation of complex parts with overhangs. The most commonly used materials are Polylactide (PLA) and Acrylonitrile Butadiene Styrene (ABS), which facilitate fast printing along with dissolvable support structures and coatings to improve surface quality.

The resolution and accuracy of models are limited by nozzle diameter, and the build speed by the need for the nozzle to physically traverse the build area [5]. In deposition based AM processes inferior mechanical properties and surface finish of end products (in comparison to conventionally moulded components), have resulted in its limited application. Much research [34–38] has been devoted to the effects of process parameters on these properties. These discussions reveal that FDM parts exhibit anisotropy of mechanical properties; the uneven heating and cooling cycles due to the inherent nature of FDM process, results in stress accumulation in the built part resulting in distortion which is primarily responsible for weak bonding and thus affect the component strength [34].

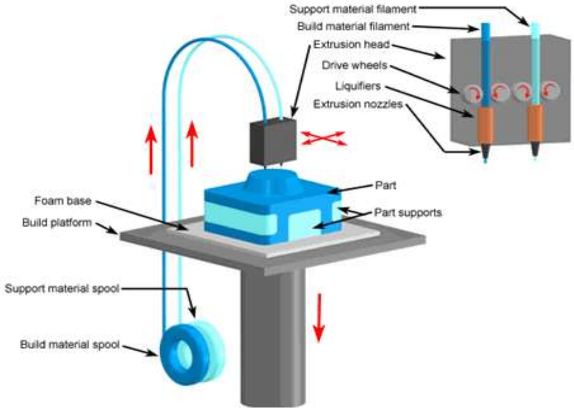

Figure 2.2 The Fused Deposition Modelling Process [39]

2.2.1.3 Inkjet Printing (IJP)

Similar to the SL process IJP involves the printing and curing of photocurable resins, usually acrylic based. Two systems are commercially available include the Objet systems and 3D Systems. These machines print a number of acrylic-based photopolymer materials layers from printing heads containing many individual nozzles, resulting in rapid, line-wise deposition efficiency [4]. Each photopolymer layer is cured by ultraviolet light immediately as it is printed, producing fully cured models without post-curing. It is has been suggested [5] that although accuracy, resolution and speed are high, material properties remain a current weaknesses of inkjet systems. Although, IJT offers improved accuracy and surface quality the slow build speed, the lack of material options and the fragility of finished parts mean they are almost solely suitable for prototyping and investment casting.

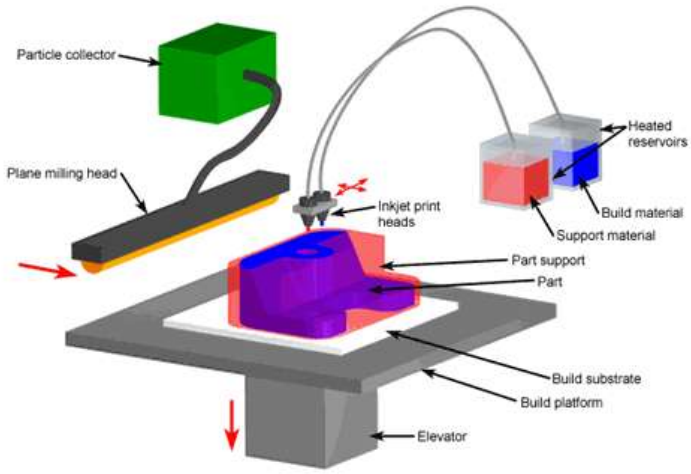

Figure 2.3 The Inkjet Printing process [39]

2.2.2 Powder-based processes

2.2.2.1 Selective Laser Sintering

SLS involves the sintering of powder materials using a laser. As with other AM processes, SLS begins with A CAD model, which is then tessellated and sliced into thin layers to acquire contour information of each layer [40]. This information is used to sinter the selected areas of each layer. The process uses fine powder, spread uniformly by a roller on the machine bed and scanned selectively by a laser (25–100W). This causes the surface tension of the grains to be overcome and they are sintered together [40]. The process does not require the construction of support structure as the un-fused powder acts as support for the model and thermal stresses are reduced through heating of the powder bed. Highly crystalline polymers (notably Nylons) tend to be used for manufacture of end-use parts, sintered to melt temperature, as they give good mechanical properties. Amorphous materials are sintered to glass transition temperatures resulting in weaker properties, therefore have only found application in RT as casting patterns [5]. SLS of metal powder requires the use of polymer binding powders, which are later burnt away during post processing with the pours infiltrated with another metal.

During polymer processes the raw material is heated to a temperature typically a few degrees below the sintering temperature and at the end of the part production the unfused powder is either disposed of or recycled back into the process. Material utilization various between systems, however metal powder typically have a higher percentage of material utilization than polymers. The reason for lower material utilization with polymer SLS, is the thermal cycle which the polymer powder undergoes during the manufacturing cycle. In polymer SLS the whole bed of powdered polymer is heated therefore the excess polymer material has changed in terms of its material properties, and so only a limited amount can be re-used to retain part integrity [41]. Hopkinson et al [5] suggest that the material properties and stability of parts that may be achieved with powder-based processes, such as SLS, means that they will in the long run be more suited to manufacturing than liquid-based systems.

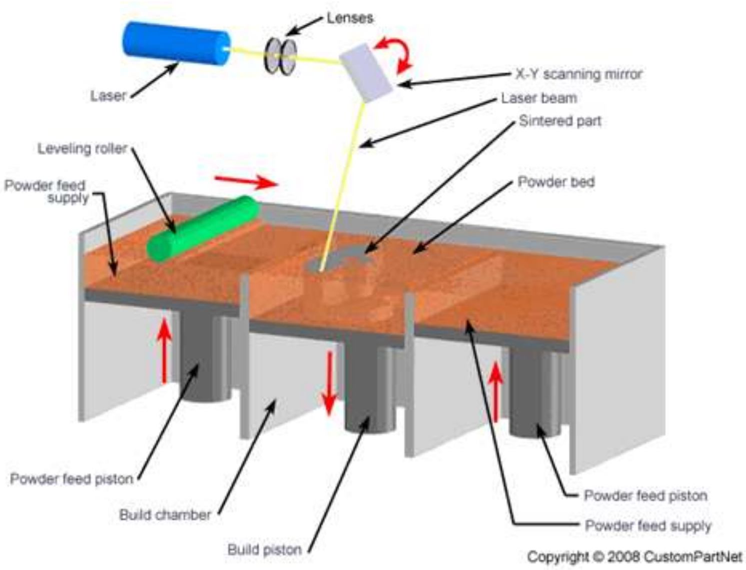

Figure 2.4 The Selective Laser Sintering process [42]

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

Both SLM and DMLS are powder-bed AM melting processes and are grouped together in this sub-section due to their process similarities. Both are laser based powder-bed processes, capable of processing metallic, ceramics and polymers. Metal powders are most commonly used and are supplied in powder distribution size around 10 – 40 microns. The powder is dispersed over a build platform at 20 – 40 micron layers using a powder re-coater. A high power laser (50W – 1kW) driven by the machine software then traces the contour and infill to melt the powder selectively. The process is then repeated each layer, illustrated in Figure 2.5. EOS, machine vendor for the DMLS process, suggest that metallic parts of 99.99% dense are achievable, with reports showing that properties can be comparable those of a cast or machined component. Support structures are required for overhanging features and anchors are required due to the high thermal stresses involve in the process. Similar to SL these support structures require more overall material and post processing [43]. Some of the most commonly used metals include cobalt chromium, titanium alloys, steel alloys and tool steels.

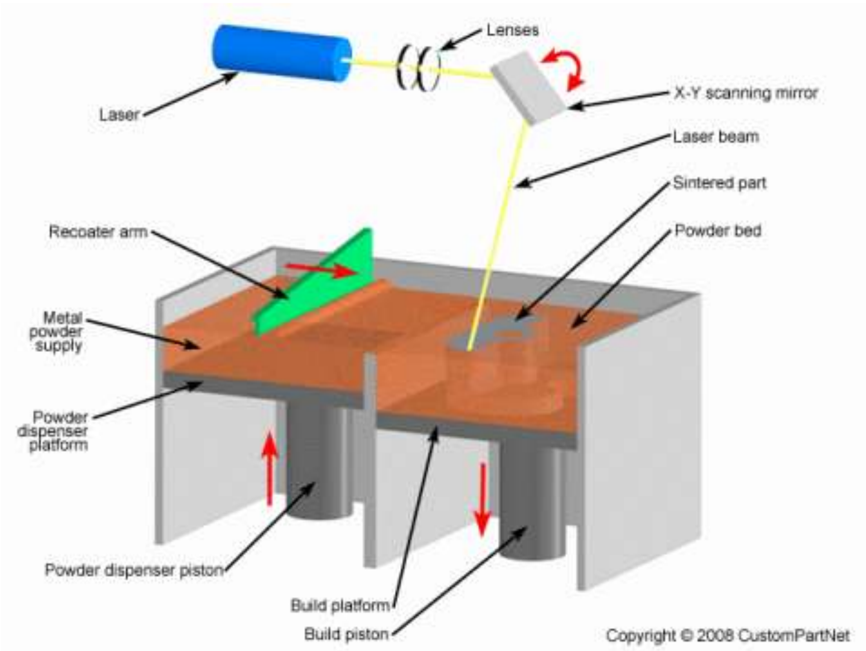

Figure 2.5. The DMLS Process [44]

2.2.2.3 Electron Beam Melting (EBM)

The EBM process was commercialized by Arcam (Gothenburg, Sweden) in 1997 and has similarities to other powder based processes in that powder is fused together selectively. As the name suggests, EBM employs a thermionic emission gun that uses a tungsten filament to produce an electron beam. The EBM process selectively melts metal powder in 70 to 250 micron layers with each layer preheated by scanning the beam at low power and high velocity to lightly sinter the particles [45]. This sintered powder surrounding the part helps support downward facing surfaces and breaks up during post processing allowing for most of the unmelted powder to be recovered and reused. The advantages over laser based processes [5] are; increased scanning speed resulting in reduced build time and reduced thermal stresses of the process due to the scanning technique. However, the available materials are limited to conductive metal powders and surface finish tends to be worst than laser process. The greatest advantage of this process is the vacuum chamber which facilitates an optimal fabrication environment for oxygen reactive materials used for medical implants, similarly in aerospace appliances in which material impurities due to oxygen are strictly prohibited for safety reasons.

2.2.3 Solid-based processes

2.2.3.1 Laminated Object Modelling (LOM)

The LOM system involves the stacking of layers of material cut via laser and binding these layers together to create the component. Post processing usually involves using hand tools to remove the unwanted material, a process known as "decubing". The LOM system has been used for both RP and RT. Although there has been some progress in polymer and metal material development, the system has found little application in manufacture of end-use parts. Some reasons as to why LOM has not been used for the manufacture of end-use parts are presented by Mueller and Kochan [46] such as; a high effort must be applied for decubing; the part accuracy is limited due to the comparably simple machine design; as with other AM systems, mechanical and thermal material properties are inhomogeneous; the detail reproduction and durability of small part features is comparably low.

2.3 The Additive Manufacturing Industry and Applications

One of the key issues or challenges in reviewing the AM industry is where to draw the industry boundaries. This challenge is linked to the differing terminology and definitions. For the purposes of this literature review, the author reviews the AM industry including all applications along the product life-cycle from prototyping, through production (including supportive process such as tooling), use and recycling/remanufacture.

As previously stated, the AM industry has its history in prototyping, and this remains their dominant application. Commercial RP was started by Chuck Hull, who founded 3D Systems to commercialise the liquid resin process Stereolithography described in his patent US 4,575,330, filed in August 1984 [5]. In the late 1980s and early 1990s, a plethora of AM processes appeared and the application range of the processes increased as system improved and new materials could be processed.

The most comprehensive knowledge is collected and regularly reported by a private consultant, Terry Wohlers. The Wohlers report [25] provides a review of the industry year-on year through surveys of AM users and machine manufacturers and is regarded as the key reading when attempting to understand the state of the industry. The most recent report shows the industry growth in terms of AM products and services worldwide. As can be seen from Figure 2.6, the industry has enjoyed significant growth, doubling in size over the past five years. However, in terms of global manufacturing products and services industry size, these figures are very small [47].

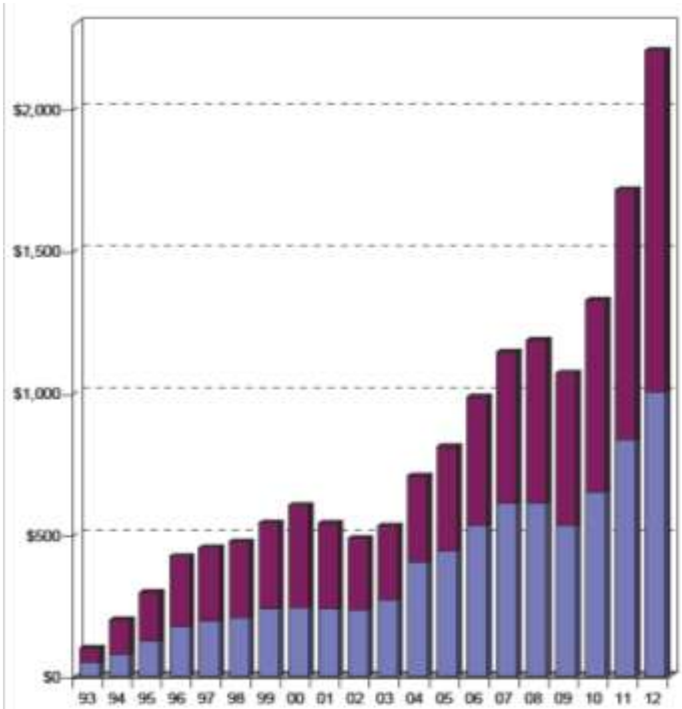

Figure 2.6 AM industry growth worldwide year on year in millions of dollars. The lower (blue) segment being products and the upper (burgundy) segment indicating services, original source [25]

Although RP has become standard practice in many industries, the use of AM for manufacture of end-use products is far from the norm. Rogers [48] presented the Technology Adoption Life Cycle to describe high technology customer's relationship with innovators of new technologies. The smooth bell curve of high tech customers, progresses from Innovators, Early Adopters, Early Majority, Late Majority, and finally Laggards. The model was revised by Moore [49], who suggested cracks existed in the curve, between each phase of the cycle, representing a disassociation between any two groups, Figure 2.7.

Moore suggested that the largest crack, so large it may be considered a "chasm", is between the Early Adopters and the Early Majority and that most high tech ventures fail trying to make it across this chasm. A number of authors [25,50,51] including Wohlers, have identified that although AM technologies have had increasing success in recent years, they have yet to break into the early majority along the technology adoption cycle. The limited uptake of AM shows that the technologies are currently stuck in the early adopters phase of the cycle, finding only limited application within each industry. Terry Wohlers offers the following:

> *"Twenty years is roughly the span of one human generation and is often the time it takes for technology to fully mature, according to futurist Joel Orr. AM is indeed mature for prototyping, but it is still in the "innovators" phase for the production of parts for final products."*

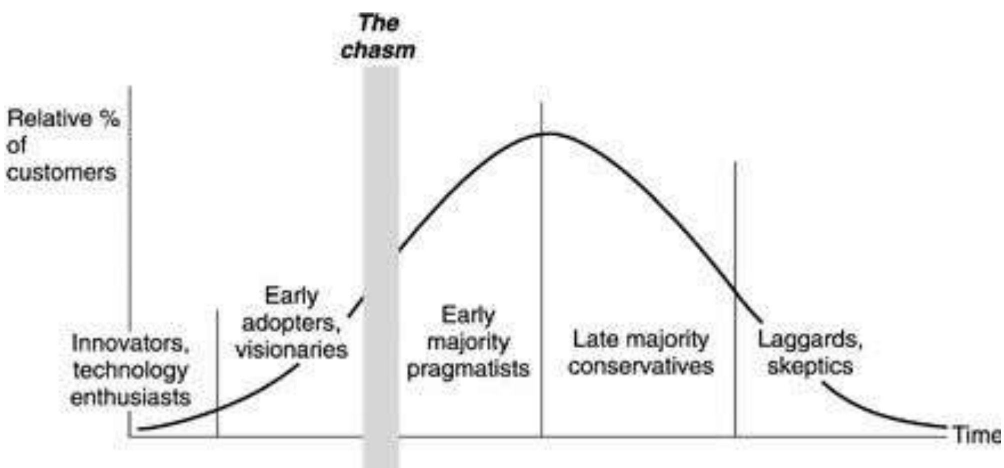

Figure 2.7. The revised technology adoption cycle proposed by Moore [49]

This is a generalised view of the technologies current position in industry. However, for certain market and technology combinations, AM is more established. Wohlers survey analysis also provided a breakdown of products and markets served by AM users and producers, Figure 2.8. The industry sectors where AM technologies are showing the potential for production applications are now reviewed in the following sub-sections.

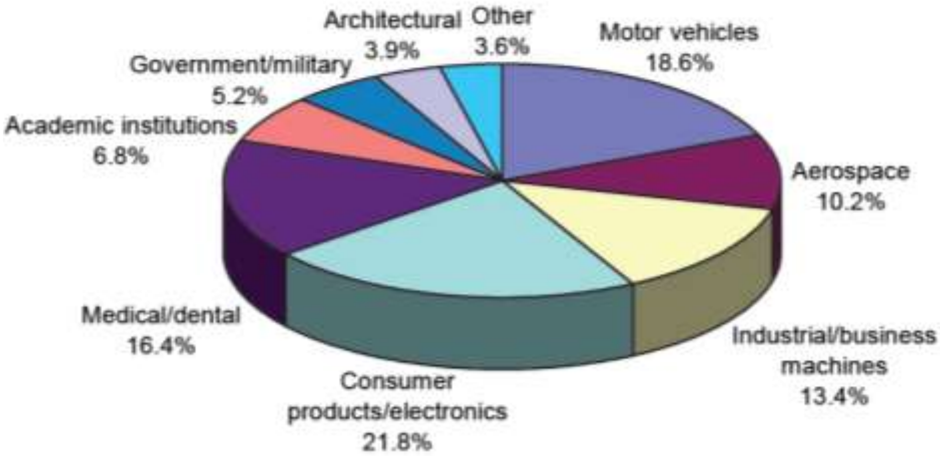

Figure 2.8 Percentage of AM services providers revenues generated by industry [25]

2.3.1 Medical

One area where AM has found particular success has been the medical industry. Each individual is unique, and products in medical applications are often required to be custom-made in shape and functionality. As AM has the potential to allow economic production of personalised production, and provides minimised compromises on product design, it is well suited to application in this sector. Another incentive for the application of AM in the medical industry is the size of the market. For these reason much research has been dedicated to identify opportunities provided by the emergence of AM technologies. Giannatsis and Dedoussis [52] reported medical applications of AM can be classified to the following categories:

- Biomodelling, which involves the fabrication of physical models of parts of the human anatomy and biological structures in general, for surgery planning or testing.
- Design and fabrication of customized implants for prosthetic operations, rehabilitation, and plastic surgery
- Fabrication of porous implants (scaffolds) and tissue engineering

- Fabrication of specific surgical aids and tools
- Drug delivery and micron-scale medical devices.

These areas are in various stages of exploitation, some have become relatively well established whereas others remain subjects of research. Bibb and Winder [53] described the process of biomodelling; a surgeon or clinician who requires a medical model will request a 3D scan of the area of interest using medical imaging technology, usually magnetic resonance imaging (MRI) or computerised tomography (CT); the 3D medical image data is processed; the images are imported into specialist AM software used to isolate the desired anatomical structure; the data is then exported in STL format and utilised by AM machines. D'Urso et al [54] reported on the successful development and testing of customised acrylic cranioplastic implants on 30 patients, manufactured indirectly through stereolithography. It has been argued [5] that biomodelling and surgical planning using AM may not be considered as a true application of the technology, as it is part of process not the end product, this being the same argument for differentiation of RP from AM. Similarly, the indirect manufacture of implants may be viewed as rapid tooling (RT). The volume production of end use parts has been applied in the fabrication of Accetabular cups used as hip joint replacement produced using the Arcam EBM system, the use of AM allows the manufacture of embedded porosity to promote cell ingress, Figure 2.9.

Figure 2.9. Accetabular cups produced in titanium alloy using Electron Beam Melting [25]

The high growth of AM medical applications illustrates the flexibility of AM, enabling high product differentiation to allow surgeons to decide on the most suitable part for each patient and the economic production of customised parts. It also shows the possibility of design optimisation, improving the performance of medical implants. This application also shows the progress made in material development and process reliability. The primary benefit is in the ability to include patient-specific data from medical sources so that customized solutions to medical problems can be found [4].

AM has also been applied for series production of dental components. Again, the potential for cost effective low volume single type products is well suited to this application where the each customer has different requirements. Vanderbroucke and Kruth [55] suggest “dental applications are very suitable to be produced by SLM due to their complex geometry, strong individualization and high-aggregate price. Moreover, the manufacturing of multiple unique parts in a single production run could enable mass customization”.

AM has also found application in the hearing industry, with Siemens and Phonak, industry leading manufacturers of hearing instruments, both using AM systems for series production of customised hearing aids. Similar to other applications in the healthcare industry, the design process begins with capturing data of the customer through either using acquiring physical or electronic impressions of the ear to create a 3D model for manufacture. Two systems are currently being used for the manufacture of customised hearing aids, SLS and SL [5]. The success of AM in hearing industry has been a particularly impressive example of how companies can take advantage of the shape complexity capability of AM technologies to economically achieve mass customisation [4]. The AM replacement offers an almost fully automated solution, with a lead time down to a day and “first-fit” rate of 95% [16].

2.3.2 Aerospace

The aerospace industry has had particular interest in AM since its emergence; the elimination of many conventional design-for-manufacture constraints brings opportunities for optimised designs to increase performance and reduce weight of aerospace components [4,5]. Also, the nature of the market dictates low volume production of high value parts are often required which is suited to the benefits provided by the elimination of tooling.

Details of aerospace applications are in short supply partly due to the industries strict confidentiality culture, but also due to its limited uptake in the industry. The certification requirements inherent in such a demanding application are extensive; where part failure is likely to result in injury or fatalities. However, a number of systems and materials have now been certified, and AM is being used for low volume production of aerospace components. Examples of use on commercial aircraft include, Boeing implemented thermoplastic SLS components on commercial 737, 747 and 777 programs and has several hundred components on the 787 flight test aircraft [10]. In addition, large numbers of SLS components are present on several military derivative aircrafts, such as the Airborne Early Warning and Control (AEWC), C-40, AWACS, and P-8 aircraft.

Freedman [56] has stated that more than twenty thousand parts were additively manufactured by industry giant Boeing and are already flying in military and commercial airplanes.   To illustrate the potential for AM in the aerospace industry, an airline could save more than 2.5 million dollars per year given the fact that AM achieved a 50%-80% weight reduction of metal brackets (up to a thousand per aircraft) used to connect cabin structures [25].

Figure 2.10 Aerospace brackets manufactured via metal additive manufacturing (courtesy of EADS innovation works)

AM has found also found application (though limited) in space instrument development. Rochus et al [23] reported on the possible application of AM technologies for the following:

- Basic prototyping – scale models

- Mock-ups – geometric representations
- Test articles – for testing and qualification
- Real flight hardware.

2.3.3 Automotive

Due to relative high cost and slow throughput of AM, its application in automotive applications tends to be confined to motorsport applications. Similar to the aerospace industry, examples of automotive applications are often protected by non-disclosure agreements; this is particularly true in motorsport. The high volumes and quality requirements of commercial road vehicle production have resulted in AM applications being confined to prototyping and tooling applications. An example of AM applied to an automotive application is presented by CRP technologies, using SLS of carbon fibre filled material to produce 100 headlight washer cover for pre-production models of the Lamborghini Gallardo for immediate delivery to dealers and customers. AM technologies provided an engineering solution to reduce lead times for economic low volume series production of a high value part. However, both RP and RT applications of the technologies can be found throughout the industry, assisting companies to reduce both development and cycle times.

2.3.4 Consumer goods

AM has also found application for the end-user, through production of a variety of home goods and fashion items. Netherlands based company FOC, develops digital furniture like lamp shades, chairs and other decorative items and fabricates the product after it was ordered online, using nylon powder as material for laser sintering [57]. The elimination of many design-for-manufacture constraints allows designers freedom to create unique designs, differentiating the product from others on the market. This value generated in uniqueness allows the manufacturer to charge a premium price for the product. Design freedom can also be passed on to the customer, using the internet with AM technologies allows customers to customise or have complete control of the design of the product. Again this provides value in the form of customer satisfaction.

Figureprint have illustrated the advantage of using AM with the internet, with their World of Warcraft 3D printing service. Customers design their own character or avatar using web-based software, and send their order to the manufacturer, where the product is then made-to-order and shipped to the customer from a centralised manufacturing facility. The gaming industry alone accounts for hundreds of millions of unique 3D virtual creations that consumers may want to have made into physical objects [4] therefore this may be seen as one of the most attractive markets for AM. Shapeways have provided a platform for customers to not only design their own products, but also sell their designs to other internet users through an online shop [57]. This web-based organisation also creates a network between customers and AM organisations, where manufacturing is distributed according to the required resources.

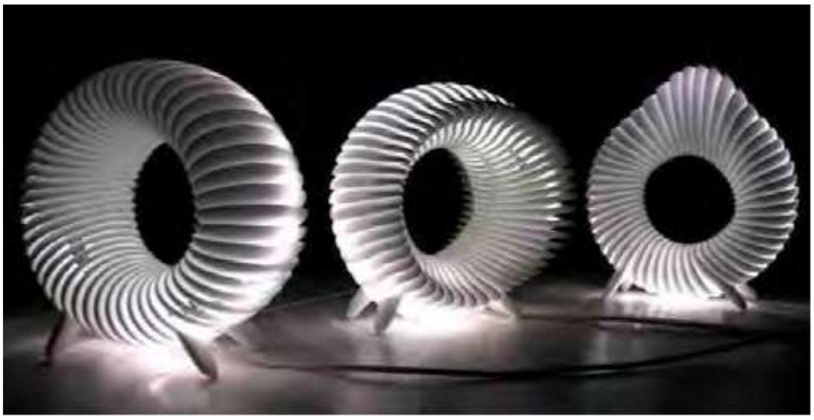

Figure 2.11 Selective Laser Sintered lamp shades produced by FOC (courtesy of FOC)

The previous sections have presented the state-of-the-art of the technologies, the industry and applications. The following sections review the limited literature on AM implementation.

2.4 Additive Manufacturing Implementation Research

As previously stated, research on AM implementation is disappointingly absent, with the majority of research focused on process and materials development. However, there are some works in the literature which may provide a basis for understanding the implementation factors which must be considered when implementing AM for production applications.

Ruffo et al [17] provided seminal work on the cost estimation of AM processes and comparison to traditional manufacturing process. The study provided a cost comparison between the production costs of a part produced through SLS and the same part produced through injection moulding. The study showed that for low volumes AM is the more cost effective option, largely due to the elimination of tooling costs. The costing model presented by Ruffo, Figure 2.12, shows how the cost per part varies according to how the parts are packed into the machine. This analysis shows that packing issues are critical in many AM systems, having a significant effect on part cost.

Ruffo et al [15] also investigated how AM could affect the make or buy decision process, identifying three possible scenarios surrounding the decision to invest in RM; the firm has no experience of RP or RM, the firm has a RP department and the firm already has a RM function. The authors investigate only the later of these scenarios, using two different parts where the decision was assessed according to cost associated with making or buying from two different bureaus (using quantitive data). The authors conclude the make option is favourable for this scenario, and suggest it could also be applied to the second scenario. The authors proposed that the lack of RM bureaus and the consequent RP costing that has further pushed the buy decision. Limitations of the study are that the authors focus solely on the financial cost of investment and only consider one of the implementation scenarios.

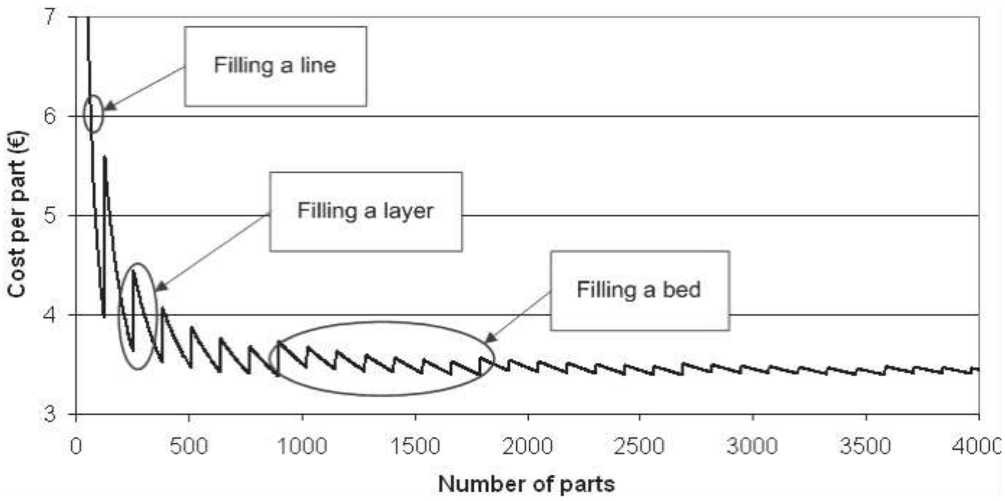

Figure 2.12 Economics of SLS production presented by Ruffo [17]

In other work [16] Ruffo continued the investigation of AM implementation from a management perspective, proposing mathematical methods for the assignment of the full production cost of each single product when producing different parts using SLS. The authors proposed three different cost assignment methodologies, tested on a product mix of two automotive parts, finding only one to be equitable. The results confirmed the concept of cost saving for mixed components production; the production cost curves illustrate the low deflection obtainable by mixing parts during low-volume production (the absorption of indirect costs at one-of or very low volumes).

Munguia et al [58] performed a unique investigation of best practices at various AM service provides based on survey analysis. The authors perform a question based survey on RM service providers and engineering centres in Northern Spain obtaining data on common uses of RM, production volumes used, materials used, percentage of recycled material, process parameters, common practices, quality assurance checks, and finally, manufacturing costs. Best practices included the use of reverse engineering vs CAD, simple visual and tactile quality checks used, and a call for exclusive RM standards. The main factors for RM costing in order of magnitude were found to be annual machine depreciation, maintenance, materials and then labour costs. Most participants mentioned a depreciation period shorter than 6 years. This is not surprising considering the rate of change in the industry. Usual machine operating time was with a range of 10-16h and the results placed manual operation as the bottleneck (i.e. postprocessing). Though labour was not found to be the major cost on small runs, it became more important when volumes increased. A significant criticism of Mungia et al's survey analysis is that rapid tooling made up most of the RM activity analysed and as such the production of end-use parts was not captured in this best practice understanding.

In 2009, Reeves [57] presented commercial applications of AM and summarised the business benefits of its adoption. Reeves also identified the potential for home-based manufacture and its implications on the supply chain and traditional manufacture. Reeves concluded his review by saying that the technology had found applications throughout the supply chain, from concept design to mass production and that there is a clear business case for AM with the advent of the internet, current consumer trends, material utilisation and efficiency, transportation costs and carbon footprint.

Walter et al [59] continued the discussion on the effect of AM on the supply chain, presenting new supply chain solutions made possible by both the centralised and decentralised applications of AM. The authors use a case study of an original equipment manufacturer (OEM) operating in the aircraft industry. The paper provides definition of the advantages and disadvantages of both centralised and decentralised (distributed) application of AM. Walter et al define centralised having the advantage of cutting high inventory costs (of slow moving parts) and reducing the need to subsidise costs with profit of fast moving parts. However, they suggest there will still be warehousing and delivery time cost associated with this application of AM. They also suggest distributed application of AM technologies can be used to eliminate these costs; however, warn there will then be the problem of having enough demand to warrant AM machines on location (i.e. machines running at capacity). From these findings the writers suggest that to maximise the benefit of AM, a hybrid system must be applied but concede that centralised application of AM will be the first to be used, due to the significant changes the distributed manufacture will require. The case study used in their study does not provide quantitive data to support the writer's conclusion, therefore the validity of their results may be questioned. The reason for the descriptive manner of the study may be because at the time of writing, the capacity and limited part range of AM, mean that the business model is not yet feasible. This may still be true in the aerospace sector. However, in other sectors and supply chain scenarios, where part qualification and risk failure are lower, a business model based on a decentralised supply chain approach may already be possible and be an opportunity for competitive advantage through supply chain efficiencies.

Tuck et al [18] extend the research on the effect AM will have on the location of manufacture through focusing on the cost effective production of customised goods. They predicts with manufacture local to customers, there will be a reduction in transport costs and that the burden of part cost will move from skilled labour operating machinery, to the technology and material. This conclusion is supported by the work conducted by Ruffo et al [17]. They also describe the changes that will occur to recognised supply chains; lean, agile and leagile. The authors predict AM will enhance lean supply chains as the only requirements for producing a product will be design parameters and raw material. Tuck et al also suggest that because AM can be used for economic low volume production, there is no requirement to hold stock therefore a fully JIT system is conceivable. They conclude:

"RM could offer the first truly leagile supply chain paradigm, providing goods at low cost through the benefits of lean principles with the fast re-configurability and response time required in volatile markets. The production of goods through RM could lead to reductions in stock levels, logistics costs, component costs (through reduction in

assembled components) and increase the flexibility of production, through the ability to produce products to order in a timely and cost effective fashion."

Their research provides a prediction on the effect AM may have on traditional manufacturing practice. However, to fully understand and predict these effects there is a need to move away from descriptive analysis and base findings on true applications and case studies of AM implementers. AM technologies are being used for the production of customised goods (hearing aids, game avatars, dental copings etc.), therefore there is necessity to understand the strategy employed by these companies, to integrate AM and customisation.

Many of the studies in the existing body of literatrue are based on fictitious cases and highlight the lack of AM applications in the manufacturing sector. The AM literature has provided a number of technical and economic barriers that preclude its widespread use for commercial applications and may explain the lack of AM research from an operations management perspective. The following presents those often cited in the literature;

- High capital investment: although an increase in adoption has resulted in some costs reduction, with new machines entering the market at lower prices, AM machines remain relatively expensive equipment requiring high capital investment for commercial applications. Hopkinson and Dickens [60] suggest, economies of scale coupled with high R&D costs have rendered the AM industry as a high-cost area since its inception. Economies of scale theory suggests unless AM becomes more standard this cost will remain high.

- High material and maintenance costs: Specific material formats such as powder, filaments and resins are required for various AM processes and are much more expensive than conventional material formats such as sheets, bars etc. A study conducted by Hague et al [61] suggested that materials used in AM processes costs are around 100-200 times greater than those used in conventional processes (injection moulding was used as comparison for this data). High maintenance cost result again from the relatively immature nature of the AM systems, with highly skilled staff and complex parts included in running costs. Again, economies of scale suggests that this cost will reduce if there is an increase in uptake of AM processes. Further, the increased uptake of other applications of these material types, such as conventional metal sintering of powders, may contribute to the reduction of these barriers.

- Material properties: The material properties of parts remain a significant barrier to increases in manufacturing applications as many AM processes have not been fully characterised. Studies have shown that parts tend to posses anisotropic material properties due to the inherent layer-by-layer nature of the AM process. Many processes also require secondary machining and polishing to reach acceptable surface finish and tolerances. Choice of materials is also limited with many AM processes, however the number of materials (polymer, metals and ceramics) is increasing. There are some exceptions, materials properties of parts produced through the DMLS process have been found to be similar to wrought properties and better than casting in some cases [61].

- Support material removal: Many AM processes such as SLA and DMLS require the building of support material which not only affects material utilisation, but also results in additional time and resources required for removal. For low volumes this may only represent a small amount of process cost, however as volumes increase this becomes an important consideration.

- Process costs: the literature [15, 60, 61] suggests that at present conventional processes remain more economical than AM systems at high volumes. One of the key reason for this is that process speed of conventional process, such as injection moulding, becomes faster than AM when high volumes are required. As volumes increase the cost of tooling, eliminated through application of AM, becomes less significant to part cost.

An investigation by Hopkinson et al [60] suggests that industries with high capital investment, low volumes of production and complexity in design are more suited to AM and that in these industries the technical barriers become less significant.

From this literature review much of the work can be characterised as predictive research, focused on predicting the likely benefits of AM as a production technology and outlining some costs and tradeoffs with the process. There is a lack of “real” world data in the literature with a small number of “fabricated” cases of applications used to collect data.

2.5 Manufacturing Technology Implementation

The previous section provided a review of AM technology and state of the art research. From this review, the subject of AM implementation was identified as a potential area of novel research. The following sub-sections introduce technology implementation as a research subject, specifically in the context of manufacturing.

AM may be viewed as a process-based innovation which can lead to product-based innovations, thus the aim of this literature review was to understand how organisations manage technological innovations. This review will firstly discuss the research area of technology strategy. The next section presents an understanding of theories around technological change and manufacturing technology implementation. Finally, manufacturing strategy research is reviewed in the context of technology implementation.

2.6 Technology Strategy

2.6.1 Technology as a Competitive Weapon

The concept of technology strategy has been a part of the technology management literature since the late 1970’s [62] and gained momentum as an area of managerial and academic interest in the 1980’s [62–66]. Hayes and Abernathy [67] provided a famous article entitled “Managing Our Way to Economic Decline” where they argued American economic decline could be traced to a lack of technological and management leadership, placing the blame directly on management for failure to use new technologies aggressively to remain competitive.

Skinner [68] was one of the first to propose that innovation in production technology could be used strategically as a powerful competitive weapon, suggesting that it can bring to bear many other strategic factors besides achieving low costs, including; superior quality, shorter delivery cycles, lower inventories, lower investments in equipment, shorter new product development cycles and new production economics. In Porters seminal work on competitive strategy [69], he suggests technology is perhaps the most important single source of major market share changes among competitors and further that it is the prominent cause of the demise of an entrenched dominant firm.

Voss [24] further emphasised the relationship between technology strategy and corporate strategy, proposing that there must be a match between the technology capabilities and the manufacturing and business priorities. Goldhar and Jelnick [70] discussed the organizational, economic and strategic implications of computer integrated flexible manufacturing, suggesting the dominant logic in strategy must change from economies of scale to economies of scope. In their seminal on manufacturing studies, Hayes and Wheelwright [71] suggest that the availability of more than one kind of manufacturing technology gives rise to the following questions:

1. What kind of manufacturing technology is appropriate for a given situation? What particular capabilities must it have and what weaknesses or constraint can it afford to have if tradeoffs are required? How frequently should changes be made in the technology and what circumstances or events are likely to trigger them?

2. What procedures should be adopted to help identify, select and pursue the best opportunities for changing the firm's production technology? How should these changes be implemented and what organisational strengths are required to carry out the firm’s strategy for technological improvement?

These questions have been the subject of technology strategy for many years.

2.6.2 Terminology and Definitions

The terminology and definitions used in technology strategy research have been in much debate. Some authors define technology strategy as specifically focusing on technology development, where others use very broad knowledge-based definitions. As Davenport [72] suggests, this debate on definition mirrors the move in organisational studies to conceptualising the firm as a knowledge system and the resource-based view of the firm. This proposition is further supported by Meyer and Loch [73] who suggest technology strategy encompasses, the translation of the competitive strategy into coherent goals and programs for the organisation responsible for technology development (top down), and also includes the development of technology-based opportunities or options for future competitive advantage (bottom up). Another evolution in terminology can be viewed in the movement from analysis of 'technology' strategy (1980s and mid 1990s) to analysis of 'innovation' strategy (1990s onwards). Dodgson [74] suggests this reflects the change in focus to looking at broader aspects than just technology, beyond operations and engineering management and organizational matters, to encapsulate associated changes in business models and corporate strategies.

Early definitions of technology strategy were specific about framing the content of technology strategy as a set of choices that needed to be made about technology development, broad versus specialised, product versus process and whether to be a market leader or follower [72]. These definitions have been criticised [75] as they do not take into account the enormous variety between firms in sources of technological opportunities and in the rate and direction of their development.

Ford [76] provided the following on the context and definition of technology strategy:

"A good starting point to understanding technology strategy is to affirm that the core of the company is what it knows and what it can do, rather than the products that it has or the market it serves. Technology Strategy centres on this knowledge and these abilities. It consists of policies, plans and procedures for acquiring knowledge and ability, managing that knowledge and ability and exploiting them for profit."

However, as researchers have suggested this definition still remains somewhat broad, therefore this research uses an adapted definition presented by Solomon [77]:

"Technology strategy encompasses the acquisition, management and exploitation of technological knowledge and resources by the organisation to achieve its business and technological goals."

Technology strategy therefore has three main elements; acquisition (or exploration), management and exploitation. Technology itself can be studied from various perspectives and number of authors [77–79] have classified technology into three dimensions:

- Product/ service technologies = Product Technologies
- Manufacturing/service-delivery technology = Production Technologies

- Information/operations technologies = Information Technologies

Within manufacturing, production technology is often further classified into stand-alone, intermediate systems, and integrated systems.

2.6.3 Technological Change

The literature suggests that technological progress constitutes an evolutionary system punctuated by discontinuous changes and that major process technological breakthroughs are relatively rare and tend to be driven by individual genius. Tushman and Anderson [81] offer the following on this subject:

> *"Major technological shifts (discontinuous changes) may be classified as competence-destroying or competence-enhancing, because they either destroy or enhance the competence of existing firms in an industry. The former requires new skills, abilities, and knowledge in both the development and production of the product.*

Rogers [48] presented the most influential model of technology diffusion, which has become a key analytical tool in marketing, organisation and innovation studies. The two main elements of the model on which the model is based are; the technical features of the innovation itself and the social factors that shape the decision to adopt. Rogers suggests that innovations have characteristics which shape their potential for adoption, these characteristics are outlined below:

- The innovations must present significant relevant advantages over existing systems or technologies, the greater the these advantages the more likely and quicker the innovation will be adopted.

- The complexity of an innovation can have a negative effect on an adoption. Innovations that combine different systems often require greater efforts to construct and use them.

- Some innovations can be used before they are adopted, therefore this trailability characteristics of an innovation has a positive or negative effect on adoption.

- As benefits of innovations are hard to determine, the observability of the innovations will also affect adoption. The ease with which the innovations can be evaluated after trial will effect adoption.

- The ability to adapt, refine and modify (reinvention) will also shape an innovations use.
- As innovations are embedded in systems, how closely the innovation fits a system will also impact its use.
- Innovations typically have high levels of uncertainty, therefore the higher the risk involved with adoption, the lower the speed and level of adoption.
- As users have different needs the ability of the innovation to fit the task will effect adoption.
- Innovations often require producers support for adoption, the level of required is another important characteristic in innovation adoption.
- The knowledge required for use is a key determinant of diffusion, with some innovations requiring considerable informal and formal learning and education

2.7 Implementation Defined

Voss [24] provided seminal work on proposing implementation as a distinctive area of study in the field of manufacturing and operations management. He suggested that research to date could be split into two separate areas; the study of the process of innovation, and the study of the diffusion and adoption of innovations. Voss identified an assumption made in both these areas of research that once successfully developed; a new process innovation will work in all subsequent uses. However, as Voss suggests:

"these assumptions break down when one considers the complex, in particular process, innovations.....there is much evidence that a process innovation can succeed in one attempt at adoption and fail in another".

From this study he proposes three relevant fields of study, in the context of the study of process innovations:

a) the development of process innovations;

b) the diffusion and rate of adoption of process innovations; and

c) the process of adoption of process innovations *(implementation).*

Voss postulated a simple life-cycle model of the process of implementation in terms of a sequential process consisting of three phases (Figure 2.13) and provided three characteristics to the implementation field of study:

1) It is the study of a process over its life-cycle. It should be concerned with developing knowledge about the process and the interaction of the process with the environment and others undergoing the same process.

2) It should be concerned with the success and failure outcome of the process, and should recognise the changing definition of success over the life-cycle.

3) It should be concerned with identifying and understanding the factors influencing the process of implementation and its success and failure. These should include (but not be restricted to) organisation, technical planning, business strategy and management.

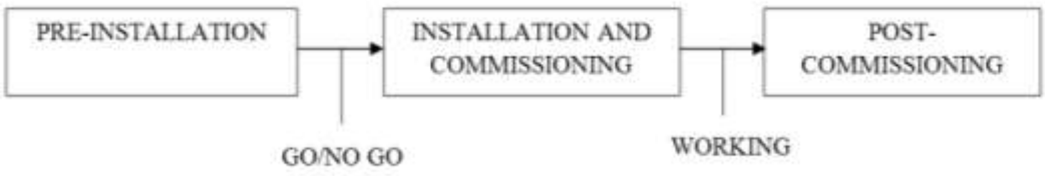

Figure 2.13 Life-cycle model of the process of implementation proposed by Voss.

2.7.1 Models of Manufacturing Technology Implementations

During the 80s and 90s the widespread adoption of advanced manufacturing technologies, and organisation failings to adopt successful, resulted in a number of authors developing models to assist project managers in their implementation practice. Voss used the case of advanced manufacturing technology to identify factors that lead to successful implementation. These factors are summarised in Figure 2.14 and are taken from three studies conducted by Voss.

Hayes and Jaikumar [82] used the term programmable automation, as a collective term for CAD, computer-aided manufacturing (CAM), computer-aided engineering (CAE), flexible manufacturing systems (FMS) and computer integrated manufacturing (CIM). The authors suggested that these technologies allow companies to make tremendous improvements; using the example of a study of 20 U.S. companies the authors suggest these FMS can reduce the amount of labour required to perform the same work by 50 to 80% and total product costs by 25% to 75%.

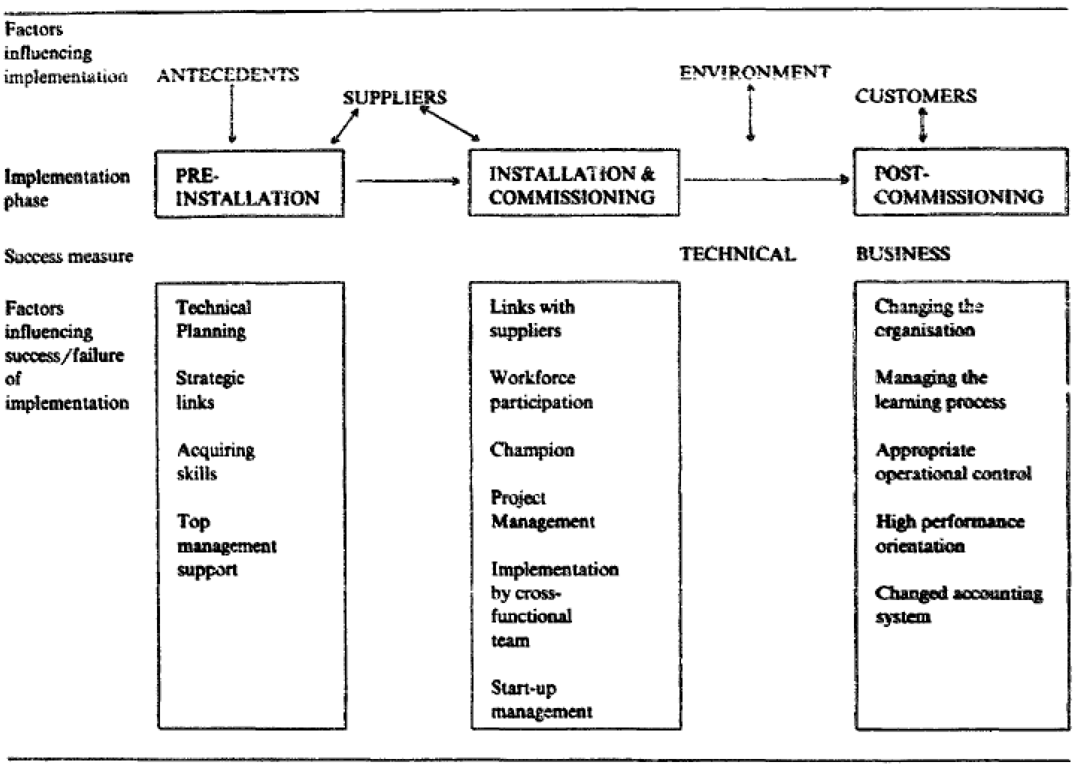

Figure 2.14 The process of implementation proposed by Voss. [24]

Hayes and Jaikumar focused on defining the requirements for successful implementation of new manufacturing technologies in response to many American companies being painfully slow to adopt, despite their potential advantages, and that only a few had been exploited to their full potential. The authors proposed that the real impediment to effective use of technology lies not in the new and unstable technology but in deeply entrenched attitudes that are incompatible with the new hardware. These barriers are infrastructural changes which if not made will result in slow adoption, high risk of failure or inability to tap into the technologies full potential. The barriers defined by Hayes and Jaikumar are set out and described below:

- *Within manufacturing* – modernisation is often approached through a series of independent projects, "islands of automation", though for the desired returns to be materialised all advances must be in place (CIM). This requires time and strategic vision. This view has been is held throughout the literature with one of the greatest advantages associated with AMT being the potential for integration, with a single integrated systems created to control all activities of a firm starting with raw materials and finishing with finished goods ready to deliver to the customer

- *Across functional boundaries* – installation should not be followed by "business as usual" as this will likely lead to disappointment. For example, FMS is not simply a faster, more flexible machine tool. It enables a company to design products differently, produce them differently, and establish different working relationships with customers.

- *With customers and suppliers* – these technologies make it possible to shift emphasis back form products to services, and to establish a direct relationship between customers and suppliers with products designed faster and more economically (CAD and CAE), and produced efficiently in small batches, essentially to order (CAM and FMS).

- *The straightjacket of financial justification* – companies reluctance to include non quantifiable, or "soft", considerations result in bias against investment in these technologies as they have significant impact in product quality, the speed and reliability of delivery, and the rapidity of new product introduction. Investment proposals for new manufacturing technologies, at the early stages of their evolution, should lie closer to R&D project proposals.

- *Command-and-control management* – many companies make the mistake of viewing a new technology as something than can perform a certain task, rather than a set of capabilities that can be developed. Therefore, companies who fully exploit a technology capabilities usually adopt early, continually experiment, keep upgrading skills and equipment as the technology evolve and strive to build close working relationships throughout the company. This point is in line with Hayes and Pisano's [83] approach to manufacturing strategy:

"…managers should think about investments more in terms of their capacity to build capabilities. Rarely, if ever, is a strategically worthwhile capability created through a one-shot investment. Capabilities that provide enduring sources of competitive advantage are usually built over time through a series of investments in facilities, human capital, and knowledge…..Investments can create opportunities for

learning. These opportunities are a lot like financial options: they have value, and that value increases as the future becomes more unpredictable."

- *Performance measurement* – The final barrier proposed by Hayes and Jaikumar is the use of unsuitable cost accounting methods, where implementation of new technologies results in costs incurred shifting from direct labour costs to essentially fixed costs, rendering traditional methods focusing on less important factors unsuitable (i.e. devoting energies to measuring costs that are likely to account for less than 25% of the total).

Chen and Small [84] focused on the pre-installation (i.e. planning) phase of Voss' life-cycle model, identifying and analysing factors that may have a positive or negative impact on the adoption of the technology. Chen and Small discuss elements of AMT implementation identified in the literature in the areas of pre-installation and justification, particularly issues in organizational and operational planning for an AMT environment. Chen and Small develop an integrated planning of the adoption of AMT based on empirical study and recorded experiences of firms that have adopted new technologies. The proposed AMT implementation activities developed by Chen and Small along with integrated planning model are shown in Figure 2.15.

Small and Yasin [85] extended this work, focusing on the planning and implementation stage of Voss' life-cycle model. They developed a framework for effective planning and implementation of AMT. Reviewing relationships supported in the literature, they further developed a number of relationships from survey analysis to present a framework for effective planning and implementation of AMT. The theoretical basis for the framework is summarised as:

1. Recognition of an increasingly complex and competitive global and international business environment.

2. Need for a strategic responses (which include adoption of advanced manufacturing technology) to meet these competitive demands, along with careful planning for the adoption of these technologies.

3. The need to establish organisational goals and performance measures during the strategy formulation and planning phases.

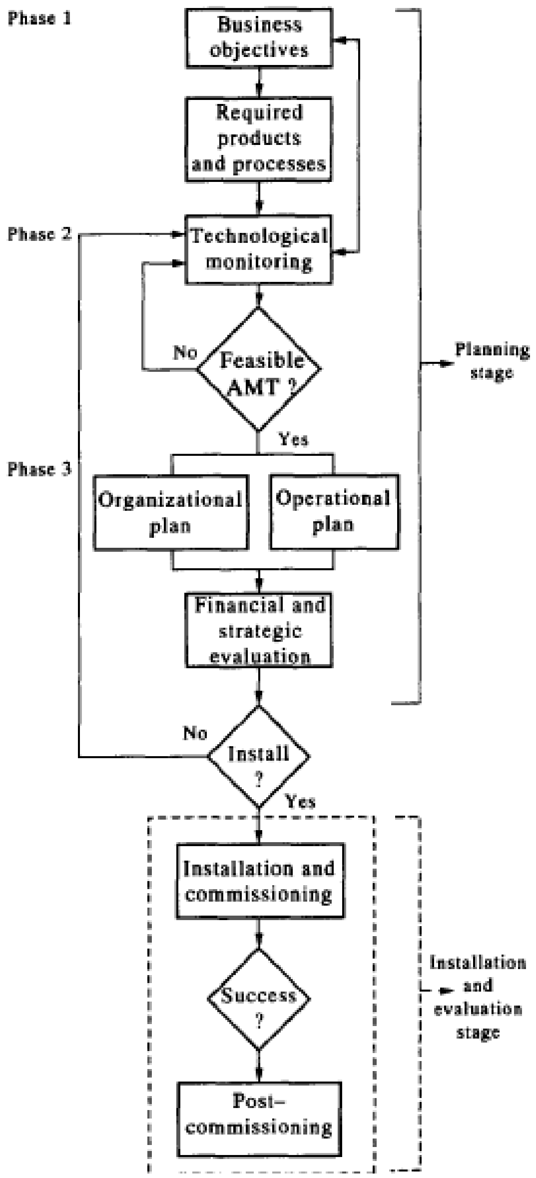

Figure 2.15 The proposed AMT implementation integrated planning model [84]

4. The need for structural changes to meet organisational goals.

5. The need for infrastructural adjustments to support the new technology structure.

6. Investment justification of advanced manufacturing technology.

7. Technology choice which reflects the expected benefits quality of organisational preparation and support for the adoption of the chosen system.

8. AMT performance evaluation.

As they concede, their analysis does not cover all technologies, all infrastructural adjustment variables or all performance variables. They also suggest an area of great potential is to focus studies on a selected technology or sub-group of technologies, focusing on only those performance variables that are known to be achievable through the chosen technology and the organisational infrastructure changes that are typically associated with implementing that technology.

The studies presented in this section of the literature review highlight the importance of planning activities in the successful adoption of new manufacturing technologies. Specifically, all of these authors draw links between the technical and organisational challenges of new process technology implementation, suggesting successful adoption requires both structural and infrastructural changes and that these changes must be planned prior to implementation.

Voss [24] suggested a number of academic areas from which the foundation of the implementation field of study could be built. One example given by Voss is Rogers study of diffusion [48], postulating that Rogers key innovation attributes could be important not only whether a technology is adopted, but how well it is implemented. Handfield and Pagell [86] employed this theory in their analysis of the diffusion of flexible manufacturing systems (FMS). At the time of writing, FMS experienced a relatively low diffusion rate in comparison to other labor-saving innovations such as robots, CAD/CAM etc. This phenomenon became a subject of many studies in management journals. Previous studies by Mansfield [86, 87] suggested that this low rate of diffusion was attributed to high costs and relatively low payback, an argument that has also been proposed in the limited uptake of AM technologies. However, although Handfield and Pagell [86] agree partially with these conclusions on FMS, they also suggested the systems offer advantages that may be difficult to measure using standard ROI (return on investment) measures. Their study explained patterns of FMS adoption and supported the finding that successful diffusion will require major infrastructural changes in adopting organizations. Finally, the authors conclude with managerial guidelines which they suggest may help FMS suppliers to improve the rate of adoption.

Belassi and Fadalla [89] returned to this subject providing an integrative framework for FMS diffusion. Their study aimed to identify diffusion factors and their measurements, and propose a framework to capture and categorize these factors, and suggests their expected impact on FMS diffusion. The authors extended existing FMS diffusion models by incorporating factors of organisational culture, organisation strategy, organisational structure and management style into the diffusion framework. This framework is illustrated in Figure 2.16. The authors develop relationships between the proposed factors and provide measures which may be used in survey questions. A criticism of the study by Bellassi and Fadlalla [89], is that the proposed framework was not tested using case study or survey analysis.

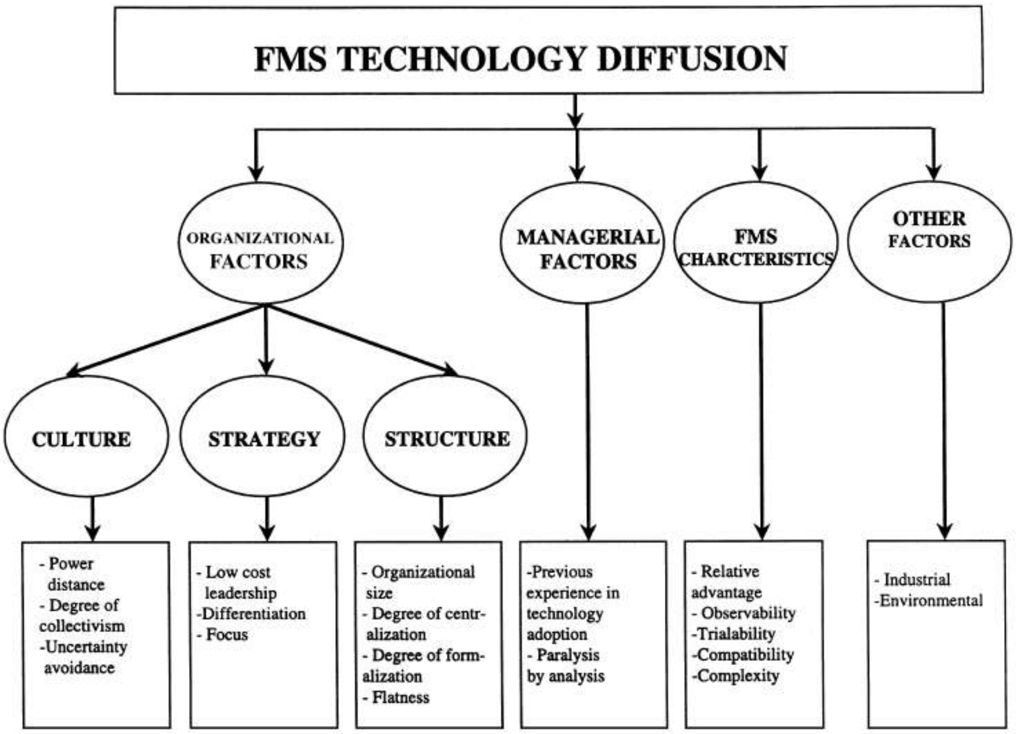

Figure 2.16 The FMS technology diffusion model proposed by Bellassi and Fadlalla.

Again on the subject of AMTs, Saberi et al [90] focused on Voss' third characteristic of implementation research, effective factors on implementation performance. The model developed by Saberi et al is presented in Figure 2.17, with factors of implementation grouped into three categories, technological, organisational and internal and external.

Finally, Voss also suggested that the plethora of information technology implementation literature could be used as a valuable source in the development of implementation research. Indeed, much of the research on manufacturing technology offers the same approaches used in IT studies, those also used to categories manufacturing strategy research, process and content (in IT research this is related to the process and factoral approaches). The researcher therefore referred to the manufacturing strategy research, along with technology implementation research, as a basis for the defining the research problem whilst developing an understanding of the approach by which a framework could be developed.

Furthermore, manufacturing strategy was identified as a key field of study as many authors suggest in order to realise the actual benefits of the technologies in the manufacturing system, classified as systemic, manufacturing strategy becomes an integrator of the whole process [93]–[95].

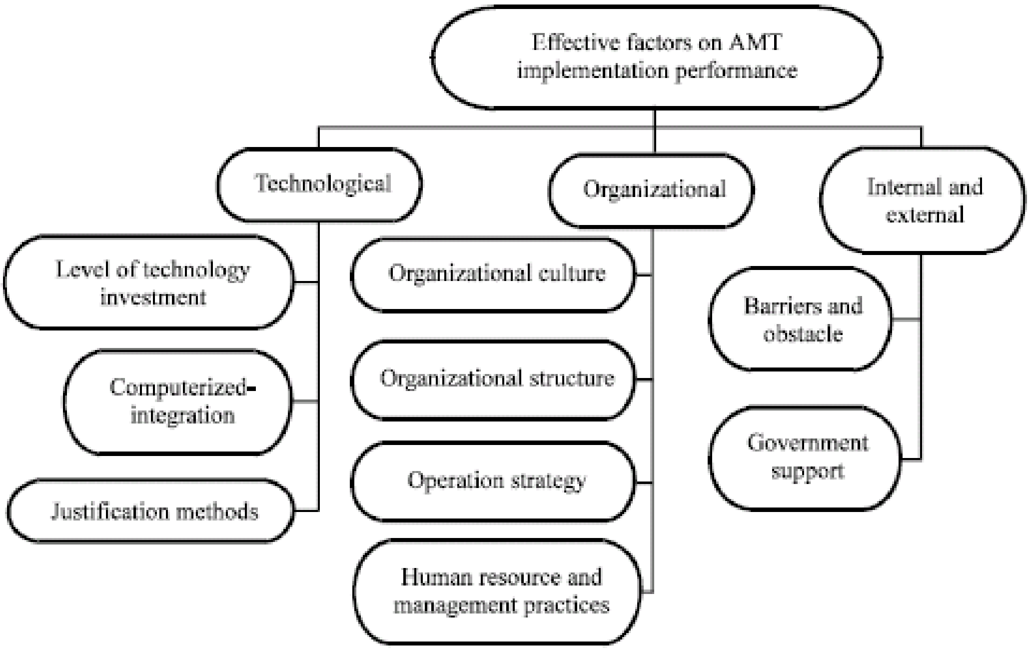

Figure 2.17 Framework of effective factors on AMT implementation performance proposed by Saberi.

2.8 Manufacturing Strategy

Different researchers have described the subject of manufacturing strategy in different terms. Initial work by Skinner [68] was among the very first in the field of manufacturing strategy and suggested that it refers to exploiting properties of the manufacturing function to develop a competitive weapon. According to Hill [91] manufacturing strategy may be defined as the manufacturing-oriented dimensions that win orders. Hayes and Wheelwright [71] defined manufacturing strategy as a consistent pattern of decision making in the manufacturing function which is linked to business strategy. The theory suggests those firms that develop congruence between their competitive and manufacturing strategies will lead to superior performance.

Although there are differing terms and concepts used to define manufacturing strategy, there is general agreement that manufacturing strategy reflects the goals and strategies of the business, and enables the manufacturing function to contribute to the long-term competitiveness and performance of the business [68, 70, 91, 92].

The research on manufacturing strategy can generally be classified into two groups: the content perspective and the process perspective. Slack suggests the content perspective contains the specific decisions that decide the manufacturing direction of the company, while the process of manufacturing strategy making consists of the methods and frameworks that are used by management to make the specific content decisions. Dangayach and Deshmukh [94] provided a comprehensive literature review on manufacturing strategy and classified 260 articles into content and process related describing these classifications as; the content approach as the strategic choices in process and infrastructure; and the process approach as the design, development and implementation of manufacturing strategy. The process perspective has received significantly less attention than the content approach.

2.8.1 Content of Manufacturing Strategy

The content of manufacturing strategy was initially considered as industrial and factory management (1950's) and evolved to operations management in the 1960's and 1970's. Operations strategy became an important subject of management study during the 1980's and the growing importance of manufacturing and operations management area has resulted in researchers integrating research with other fields of study.

	Competing through manufacturing	Strategic choices in manufacturing	Best practice
Key concepts	Order winners Key success factors Capability Generic manufacturing strategies Shared vision	Contingency approaches Internal and external consistency Choice of process Process and infrastructure Focus	World-class manufacturing Benchmarking Process re-engineering TQM Learning from the Japanese Continuous improvement
	Process		
	Measurement		

Figure 2.18 Three paradigms of manufacturing strategy proposed by Voss [94]

Voss [95] suggested, as manufacturing strategy as a concept and area of study and practice has grown the clarity of the subject has decreased as different views and different approaches have emerged. In response to this Voss provides a comprehensive study of alternative paradigms of manufacturing strategy, the three paradigms relating to content are summarised in Figure 2.18.

2.8.1.1 Competing through manufacturing

Voss suggests "at its simplest this approach to manufacturing strategy argues that the firm should compete through its manufacturing capabilities, and should align its capabilities with the key success factors, its corporate and marketing strategies and the demand of the marketplace". In his seminal papers [68,95], Skinner was the first to observe that a company's manufacturing function could be an important addition to its arsenal of competitive weapons. Skinner defined manufacturing objectives such as cost, quality, delivery and flexibility and suggested that there were trade-offs between them. In later works these objectives have become more refined and have been labelled differently; competitive priorities, key success factors and order winners.

Hayes and Wheelwright [71] provided a framework for manufacturing strategy where the initial task is to define the overall corporate/business objectives. In order to achieve these, manufacturing objectives are set which are fulfilled through various structural and infrastructural decisions.

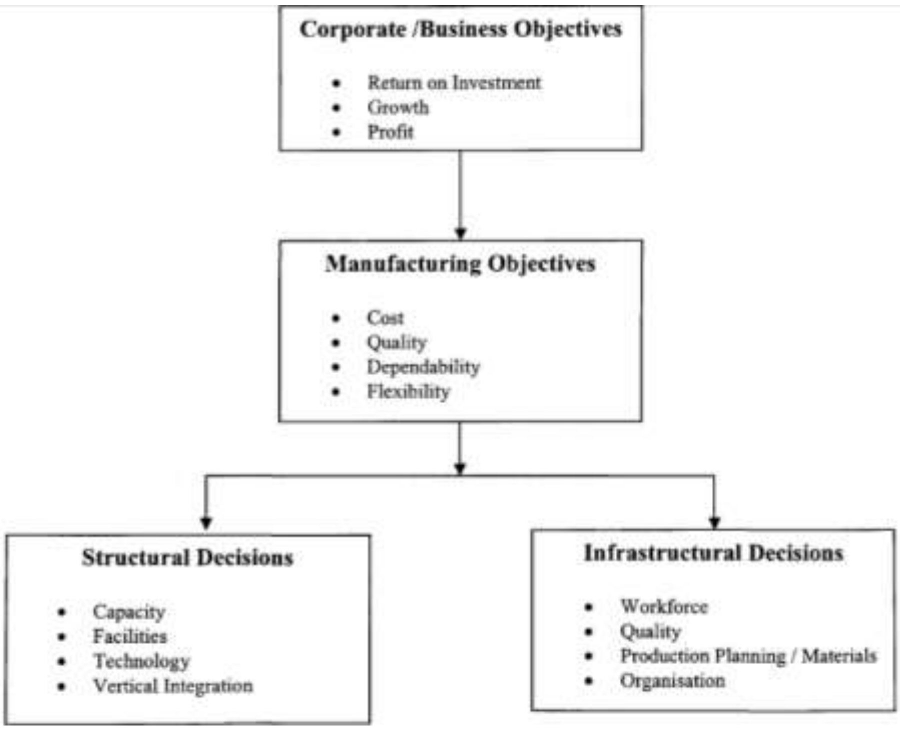

Figure 2.19 Hayes and Wheelwright Manufacturing Strategy Framework

Miller and Roth [97] conducted pioneering empirical study into manufacturing strategy, providing taxonomy of manufacturing strategies in North America. The research used cluster analysis to group manufacturing strategies in to types according to capabilities (manufacturing task); the three types of manufacturing strategy identified by Miller and Roth are described below:

- *Marketeers* – use a manufacturing strategy focused on reliability in the manufacturing process (most notably in quality and delivery).
- *Caretakers* – characterised by its focus on low price over all other potential competitive capabilities.
- *Innovators* - strategy is preoccupied with a unique emphasis on quality and the avoidance of price competition.

In later works, Frohlich and Dixon [98] revisited the subject of manufacturing strategy and found support that the groups Caretakers and Innovators still existed but that the Marketeers had been replaced by a group they called Designers. This new group of designers moved to a focus on dual emphasis on performance quality and after-sales service along with an accent on new product design. Frohlich and Dixon also found three new manufacturing strategy; idlers, servers and mass customizers. The idlers were found to be in South America and characterised by the lack of emphasis on any competitive capabilities. In Western Europe, a large group were identified with a focus on service based capabilities. Finally, a small group named mass customisers was found in the Asia Pacific, with a manufacturing strategy focused on competitive capabilities of low price and design flexibility.

2.8.1.2 Strategic choices

Voss [95] proposes the strategic choices paradigm is based on the need for internal and external consistency between choices in manufacturing strategy. Skinner [62] proposed that the key choice areas in manufacturing strategy consisted of plant and equipment, production planning and control, labour and staffing, product design and engineering, and organization and management. Hayes and Wheelwright [71] propose structural and infrastructural choices, and Hill [91] defines these into what he advocates process and infrastructural issues to be the two pillars of manufacturing strategy. Much research in the strategic choices paradigm is devoted to the choice of manufacturing process. These are in effect contingency-based approaches as they argue that choices made are contingent on context and strategy [95].

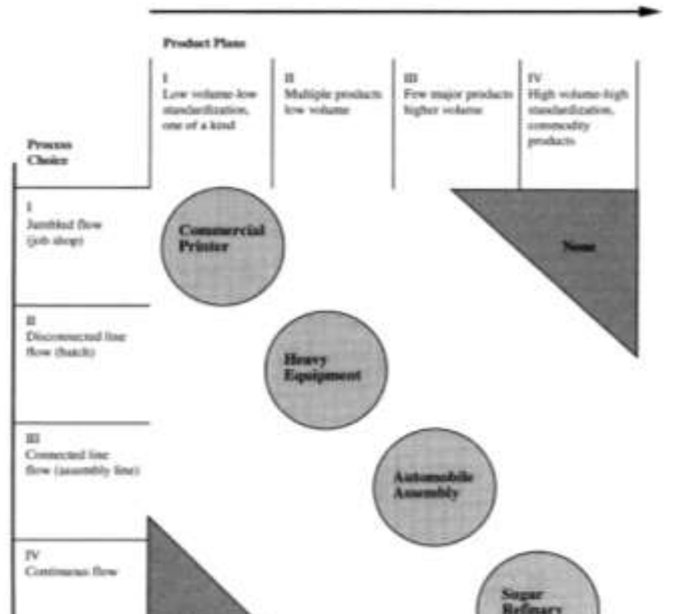

Figure 2.20. Hayes and Wheelwright Product Process Matrix [99]

This research may be traced back to the work of Woodward [100] but the first main proponents were Hayes and Wheelwright [99] in their product process matrix. Through their study, the authors showed how misalignment could lead to poor manufacturing and business performance. They also argued that as markets evolved and changed so too did the required process.

The process choice theory has been developed by many researchers. Work often cited in the literature is the taxonomy developed by Kim and Lee [93]. Kim and Lee develop a taxonomy of processes based on technical flexibility and technical complexity, relating manufacturing technologies such as FMC and FMS to the traditional process used by Hayes and Wheelwright.

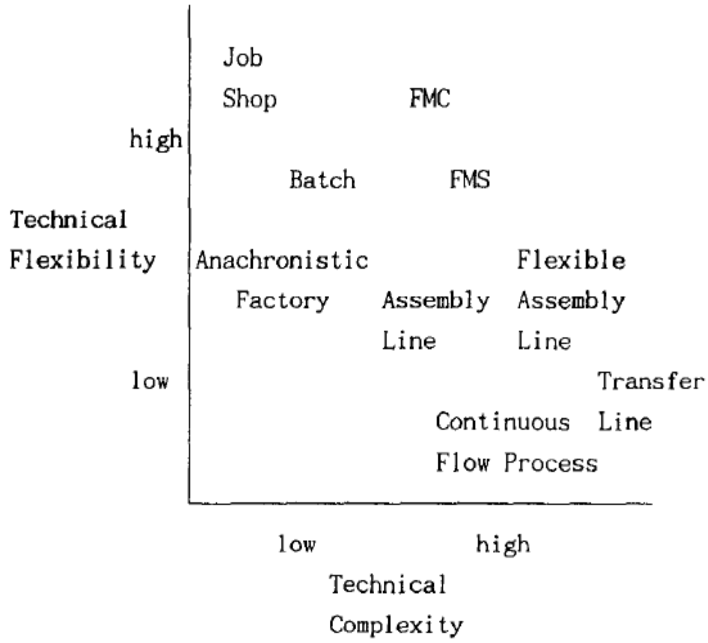

Figure 2.21. Appropriate production systems for technical complexity/technical flexibility proposed by Kim and Lee [93]

2.8.1.3 Best practice

In recent years, best practice has become the most prominent of three paradigms in manufacturing strategy, though as Voss states it may be argued best practice has been with mankind ever since the emergence of the first craft in prehistory. The literature on best practice is dominanted by the experience of the Japanese manufacturing industry. Voss [95] describes three particular stimuli which have brought best practice to greater prominence:

> *"The first has been the outstanding performance of Japanese manufacturing industry. This has led to a continuous focus in the West on identifying, adapting*

and adopting Japanese manufacturing practices. The second is the growth of business process-based approaches and benchmarking. This has led companies to identify their core practices and processes and to seek out best in class practice. Finally there has been the emergence of awards such as the Malcolm Baldrige National Quality Award and the European Quality Award. These have brought a high profile to best practice in certain areas."

Dangayach and Deshmukh [94] suggest best practice include manufacturing resource planning (MRP), optimized production technology (OPT), total quality management (TQM), flexible manufacturing system (FMS), just-in-time (JIT) lean production and concurrent engineering. An aggregation of best practice in a wide range of areas of manufacturing, which is often suggested as synonymous, is Hayes and Wheelwrights concept of "world class manufacturing" (WCM). The term world class manufacturing was widely adopted following the publication of Schonberger's book [101] with a number of authors attempting to summarise the idea in a one-line statement. Burcher and Stevens [102] provided the following:

"A world class manufacturer is one that can compete with the best anywhere in the world."

The underlying assumption of this paradigm is that best practice will lead to superior performance and capability leading to increased competitiveness.

2.8.2 The Process of Manufacturing Strategy Formulation

The process approach to manufacturing strategy has received significantly less attention in the literature compared to the content approach. However, a number of researchers have emphasized the process approach and their conclusions suggest that a formalised manufacturing strategy is characterised by explicitly expressed objectives, improvement goals and action plans. Process aspects of manufacturing strategy include design, development and implementation. Hill [91] proposed a step-by-step procedure for formulating manufacturing strategy by linking manufacturing with corporate marketing decisions, illustrated in Table 2.2.

Table 2.2. Five steps in formulating a manufacturing strategy as proposed by Hill [91]

Corporate objectives	Marketing strategy	How do products win orders?	Manufacturing Strategy	
			Process choice	Infrastructure
Growth Survival	Product markets and segments Range	Price Quality	Choice of alternative processes Trade-offs embodied in the process choice	Function support Manufacturing planning and control systems
Return on investment	Mix	Delivery speed reliability	Capacity size timing location	Quality assurance
Other financial measures	Volumes	Demand increases	Role of inventory	Manufacturing systems engineering
	Standardisation vs. customisation	Product range		Clerical procedures
	Level of innovation	Design leadership		Payment systems
	Leader vs. follower alternatives	Technical support (after sales)		Work structuring
		Meeting launch dates		Worker skill levels
		Existing supplier states		Organisational structure

2.9 Conclusions

Based on this understanding of AM technology, implementation research and manufacturing strategy, the lack of, and simultaneously, importance of, AM implementation research was identified. The literature also provided an understanding of research methods in this field of study, a subject that is explored further in the following chapter. Specifically, the combination of the above literature reviews allowed the research to define and structure the research problem in to the following central research questions.

The central research question posed from this review was: How do organisations go about implementing Additive Manufacturing as a manufacturing process either as a replacement to the conventional approach or for new business opportunities?

From this central question, the following research sub-questions are posed:

- Is there a normative framework for AM implementation to be used by decision makers at adopting organisations?
- What are the key factors in the AM implementation framework?
- How do these factors combine with technical factors to form the AM implementation framework?
- How do contextual differences influence the implementation process?

In order to answer the research questions posed in this study the following research objectives were developed:

- To develop a normative framework for the implementation of Additive Manufacturing technologies for manufacturing applications
- To capture the key technical and non-technical factors in the process of Additive Manufacturing implementation
- To identify where these key factors have been encountered and managed in different organisations.

CHAPTER 3

RESEARCH METHODS

3.0 Introduction

This chapter presents the research method and the rationale for its use in this study. The first section defines the philosophical basis of the study; the second describes the research design. Section three outlines and justifies the data collection strategy of the study and section four describes the strategy employed to analyse the data. Finally, the fifth section summarises the main points of the chapter.

3.1 Philosophical Basis of the Study

This study epistemological position, the interpretive paradigm, provides the underlying philosophy on which this study has been based. On their discussion of operations management research paradigms, Meredith [103] provides the following description of the interpretive perspective:

> "*The interpretive perspective includes the context of the phenomenon as part of the object of study. Interpretive researchers study people rather than objects, with a focus on meanings and interpretations rather than behavior. The purpose is to understand how others construe, conceptualize, and understand events and concepts. In contrast to the implicit absolutism of positivism, interpretivism is relativistic because facts are not considered independent of the theory or the observer. Interpretive researchers explain by placing behaviors in a broader context in which the behaviors make sense.*"

The motivations for choosing the interpretive paradigm over the positive paradigm is the understanding that technology implementation is a socio-technical reality, without stable and orderly social relations. The implementation of manufacturing technology involves changes to the organisation which then create conflict and instability. Adopting an interpretive paradigm enabled the researcher to interpret the socio-technical reality, which cannot be easily measured, and investigate why issues emerge during the AM implementation process and how project managers have sought ways to solve them.

The proposition on which this position is taken is the belief that the most appropriate way of collecting and analysing data on the AM implementation process, is by examining in-depth the experience of the key stakeholder in the process, i.e. the AM project manager or project champion. Critics of such an approach suggest the close attachment to the phenomenon under investigation (process of implementation) can cause the investigation to be shaped by the researcher's prior assumptions, beliefs, values and interest. However, it is proposed that the only way of understanding the complexities and intricacies of AM implementation is through taking the interpretive approach.

Taking the interpretive approach, inevitably led to the selection of a qualitative research approach, described in the following section.

3.2 Selection of Method

Under the methods associated with the qualitative research approach, the case study research approach was selected by the researcher, to enable each AM implementation to be studied in-depth and as a single case [103–105]. The definition of case studies as a research strategy has been in some debate in the literature, many have merely repeated the types of topics to which case studies have been applied. For example Schramm [107] offers the following definition:

> *"The essence of a case study, the central tendency among all types of case study, is that it tries to illuminate a decision or set of decisions: why they were taken, how they were implemented, and with what result*"

This definition suggests the major focus of case studies is the topic of decisions, whereas others have used "individuals", "processes", "organizations" etc. In response to this apparent insufficiency, Yin [104] provided a more suitable, two part definition to the case study research strategy. The first defines the scope of a case study:

- A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.

The second part of Yin's definition is rooted in the nature of real-life situations, where phenomenon and context are not always distinguishable. Therefore, the second defines other technical characteristics:

The case study inquiry;

- copes with the technically distinctive situation in which there will be many more variables of interest than data points, and
- as one result relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and
- as another result benefits from the prior development of theoretical propositions to guide data collection and analysis.

In discussing the strength of case research, Benbasat et al [108] present the following benefits of the research approach:

1. The phenomenon can be studied in its natural setting and meaningful relevant theory generated from the understanding gained through observing actual practice.
2. The case method allows the questions of why, what and how to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon.
3. The case method lends itself to early exploratory investigations, where variables are still unknown.

The uncertainties related to the central research questions, the number of variables under study, and the importance of the context of AM implementation have motivated the researcher to select the case study as a research strategy. The exploratory nature of the research, indicated by the lack of implementation studies in the field of AM research, again motivated the selection of case studies for the research strategy.

Voss [105] discussed the application of case research in operations management, suggesting that case research can have very high impact as they are unconstrained by the rigid limits of questionnaires and models therefore can lead to new and creative insights, development of new theory, and have high validity with practitioners. The "end-user" of the research is proposed to be project managers of AM implementation projects; therefore the importance of validity with practitioners is significant if the research is to achieve impact in its field of use.

However, on its own, the case study could not provide an adequate methodology for answering the central research question of this study. Purely selecting case studies as a research strategy would not provide the researcher with a guide in selecting informants or development of an appropriate research instrument to use during the case studies. For these reasons, the case study research strategy was combined with existing theory. Theis approach allows prior theory, non-technical literature, and personal as well as professional experiences to help the researcher gain insights into the data.

The use of the combined approach, case studies and background theory, enabled the researcher to use existing knowledge on process technology implementation along with knowledge of AM to develop a robust implementation framework. Achieving the goals of the research without such an approach would be difficult for a novice researcher.

3.2.1 Case studies

Despite the proposed advantages of case studies, some authors have criticised the lack of rigour in case research. Flyvbjerg [109] summarised these criticisms into five misunderstandings or oversimplifications about the nature of case research:

1. General, theoretical (context-independent) knowledge is more valuable than concrete, practical (context-dependent) knowledge.

2. One cannot generalise on the basis of an individual case; therefore, the case study cannot contribute to scientific development.

3. The case study is most useful for generating hypotheses; that is, in the first stage of a total research process, whereas other methods are more suitable for hypotheses testing and theory building.

4. The case study contains a bias toward verification, that is, a tendency to confirm the researcher's preconceived notions.

5. It is often difficult to summarise and develop general propositions and theories on the basis of specific case studies.

In response to these criticisms a number of authors [102–105] have developed methodologies and frameworks to ensure rigour in case research, which have been used in this study to ensure sufficient rigour of the research.

Nachmias [110] defined research design as a plan that...

> *"....guides the investigator in the process of collecting, analyzing, and interpreting observation. It is a logical model of proof that allows the researcher to draw inferences concerning causal relations among the variables under investigation"*

Case studies can be used for different types of research purpose, although in the past some have suggested case study research is only suitable for exploration, it is now generally accepted case studies may be applied for exploration, theory building, theory testing and theory extension/refinement [102–104,106,108]. Table 3.1 illustrates the process of matching research purpose with methodology, as presented by Yin [104], modified from original work by Flyvbjerg [86].

Table 3.1. Matching research purpose with methodology, redrawn from Yin [104]

Purpose	Research question	Research structure
Exploration Uncover areas for research and theory development	Is there something interesting enough to justify research?	In-depth case studies Unfocused, longitudinal field study
Theory building Indentify/describe key variables Identify linkages between variables Indentify "why" these relationships exist	What are the key variables? What are the patterns or linkages between variables? Why should these relationships exist?	Few focused case studies In-depth field studies Multi-site case studies Best-in-class case studies
Theory testing Test the theories developed in the previous stages Predict future outcomes	Are the theories we have generated able to survive the test of empirical data? Did we get the behaviour that was predicted by the theory or did we observe another unanticipated behaviour?	Experiment Quasi-experiment Multiple case studies Large-scale sample of population
Theory extension/refinement To better structure the theories in light of the observed results	How generalisable is the theory? Where does the theory apply?	Experiment Quasi-experiment Case studies Large-scale sample of population

Yin [104] proposes the main purpose of the design is to help avoid the situation in which the evidence does not address the initial research questions. A number of researchers have suggested processes of how to build theory from case research. Voss et al. [105] summarised the case research method into seven steps:

1. When to use case research.
2. Developing the research framework, constructs and questions.
3. Choosing cases.
4. Developing research instruments and protocols.
5. Conducting the field research.
6. Data documentation and coding.
7. Data analysis, hypothesis development and testing.

These seven steps have been widely applied in the operations and technology management research, therefore providing a suitable methodology for this research.

Using Table 3.1, this research may be characterised as theory building, however due to the immature state of AM implementation research the purpose may become exploratory in nature. Using the grounded theory approach, the supportive literature from the field of technology implementation, along with AM technical research, a proposed framework has been defined (the details of which are defined in the following chapter) represented graphically in a conceptual model. A pilot study (using the case study protocol) was used to reveal the true purpose of this research. In the early stages of research it was designed from a theory-building perspective with a few focused multi-site case studies identifying typical case studies, this was later confirmed following the pilot study.

3.3 Developing the Research Framework, Constructs and Questions.

3.3.1 Research questions

From the review of the literature, along with informal data collection, the research questions and objectives were defined. The study posses the central research question:

How do organisations go about implementing Additive Manufacturing as a manufacturing process either as a replacement to the conventional approach or for new business opportunities?

From this central question, the following research sub-questions are posed:

- Is there a normative framework for AM implementation to be used by decision makers at adopting organisations?
- What are the key factors in the AM implementation framework?
- How do these factors combine with technical factors to form the AM implementation framework?
- How do contextual differences influence the implementation process?

In order to answer the research questions posed in this study the following research objectives were developed:

- To develop a normative framework for the implementation of Additive Manufacturing technologies for manufacturing applications
- To capture the key technical and non-technical factors in the process of Additive Manufacturing implementation
- To identify where these key factors have been encountered and managed in different organisations.

3.3.2 Research framework

There is general acceptance that the researcher must develop a prior view of the general constructs or categories that are to be studied, and their relationships. This is often provided in the form a conceptual framework, Yin [104] suggests such a framework explains, either graphically or in narrative form, the main things that are to be studied. This framework graphically explains the factors influencing the success of Additive Manufacturing implementation. Factors are grouped into constructs along five areas of decision making for the implementing company; strategic, organisational, supply chain, technology and operations. The framework is of a closed loop nature, illustrating the interactions and dependencies between each construct and the individual factors within these constructs.

The following chapter details the development of the research framework based on analysis of the literature and initial informal data collection. For reference the framework is presented in Figure 3.1.

Figure 3.1. Conceptual framework of factors influencing the success of Additive Manufacturing technologies implementation

3.3.3 Defining the unit of analysis

Yin [104] suggests defining the unit of analysis is key to defining what the case is, and that it is related to the way in which the initial research questions have been defined. From Voss' [105] seminal work it is clear that implementation research, such as this, is the study of a process over its life-cycle. The unit of analysis for this study was each organisations process of implementing AM technology from the experience of the AM project manager. Emphasis is placed on the viewpoint of the people leading the AM implementation project. In most of the case studies a single person has managed the organisations AM implementation process, however, where possible the study has taken the opportunity to collect date from multiple informants. In line with Linton's [111] guidance for implementation research, this has included data collection from the organisation's AM system vendor.

The implementation cycle of AM is taken as the general definition of the unit analysis, however other clarifications are required if the unit of analysis is to be fully defined.

The immediate topic of the case study must be distinguished from those which are outside it, i.e. the context for the case study. Additionally, specific time boundaries are often needed to define the beginning and end of the case. Regarding time boundaries, the researcher has a choice of where to draw these boundaries.

Bateman [112] suggested that the users of AM technologies generally operate with 'two hats' (Figure 3.2); one side being rapid prototyping (the manufacture of conceptual or functional prototypes) and the other rapid tooling, where the same technology is used to create moulds or tooling used in other process. This characteristic of the industry represents one of the underlying challenges in this research, when to set the time boundaries of the case? Though the technology may have been implemented a number of years previously, the use of the technology for manufacturing applications (RM) is likely to be after the initial installation. This gives rise to a number of scenarios:

1. Scenario 1: the company has implemented for AM
2. Scenario 2: the company has implemented for RP and/or RT and then moved to AM

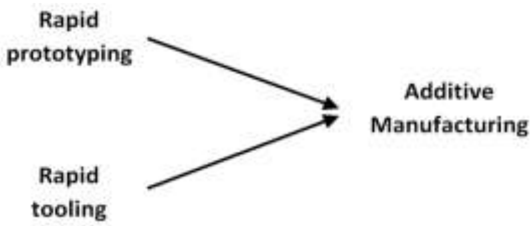

Figure 3.2. Paths to Additive Manufacturing, adapted from [112]

Figure 3.3. Scenario 1 - direct implementation of Additive Manufacturing

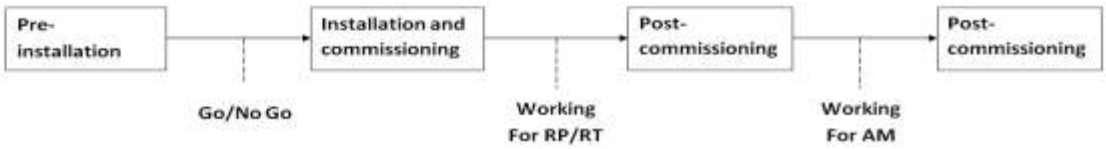

Figure 3.4. Scenario 2- Implementation of RP/RT followed by implementation for Additive Manufacturing

AM has been defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." [1]. In this definition of AM, there is no distinction between those technologies used at different stages of the product life-cycle. However, others have contended this definition and have suggested that there is a need to separate out those technologies used at pre-production stages (i.e. RP) and those used for production (i.e. RM). These technologies have also been applied in the rapid production of moulds or tools (i.e RT) and the remanufacture (of products further down the product life cycle.

This technology characteristic which is relatively unique to the field, creates a level of uncertainty around the definition of the unit of analysis. However, the central research question provides the focus and timing of the unit of analysis for this research, it is the study of implementation of AM for manufacturing applications. This may continue to by somewhat of grey area, as the definitions of RP, RM and RT can be interpreted differently by different informants. Additionally, the inclusion of RP implementation was perceived to an important aspect of the process of implementation, and the capacity for potentially running both RP and RM on the same machine, at the same time continued to add uncertainty on time boundaries. For these reasons, the specific time boundaries of the unit of analysis were not defined from the outside of research. Instead, case by case a clearer understanding of the time boundaries were developed throughout the case study analysis and provided an important insight themselves into the process of AM implementation.

3.4 Choosing Cases

There is a wide set of choices for the researcher when designing case studies, one often cited in the literature is the choice of the most ideal number of cases given the available resources. Single case research has the advantage of allowing the researcher to study the subject in more depth, for example the longitudinal study of Narasimhan and Jayaram [113] examining in service operations and Ahlstrom and Karlsson's [114] longitudinal study of just-in-time (JIT) implementation.

Yin [104] suggests single-case designs may be viewed as vulnerable as the research will have put "all of your eggs in one basket". Voss et al. [105] also suggest that single case research limits the generalisability of the conclusions, models and theory developed from one case study. Other limitations of single case research cited include the risk of misjudging a single event and of exaggerating data. Although these risks exist in multi case research, they are somewhat mitigated when events and data are compared across cases [105]. Also, the analytic benefits of having two or more cases may be substantial. For these reasons this research aimed to conduct multiple-cases in order to improve the generalisability of the conclusions and avoid the risks of misjudging the events studied.

The major issue encountered in selecting the research sample was selecting the most appropriate sample. Traditionally, sampling is conducted by identifying a population and then selecting a random or stratified sample from that population, however as Eisenhardt [106] and Yin [104] have proposed in case research a sample is built by selecting cases according to different criteria. Voss et al. [105] advocate when building theory from case studies, case selection using replication logic should be used rather than sampling logic, further suggesting that each case should be selected so that it either:

- predicts similar results (a literal replication); or
- produces contrary results for predictable reasons (a theoretical replication).

The replication approach to multiple-case studies is illustrated in Figure 3.5.

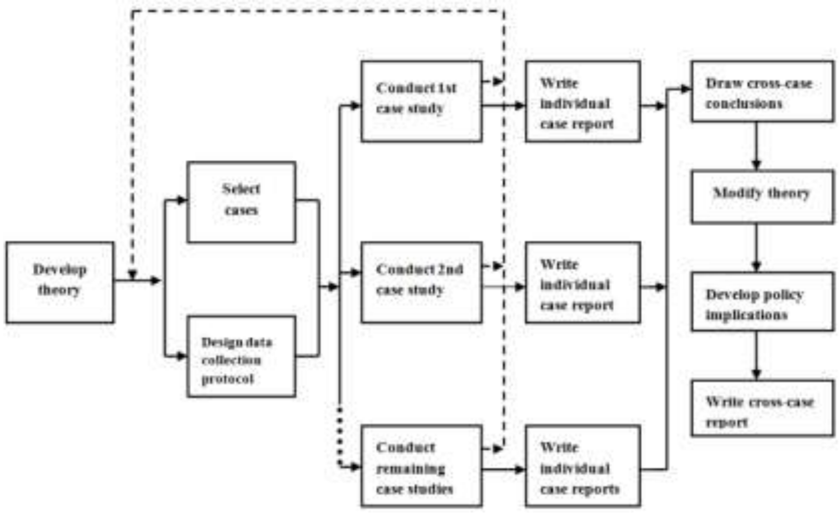

Figure 3.5. The replication approach to multiple-case studies [104]

Yin [104] identifies the “typical” case as an example of a case study approach for which even the single case study can be appropriate.

Ultimately, it is the research questions which drive the selection of the sample. The research questions of this study are focused on developing a normative framework of AM implementation, understanding how both technology factors and contextual differences influence the experience of the adopting organisation. Therefore, in choosing the sample the technology implemented and the organisational context were key determinants of characterising the potential case studies and choosing typical cases. Initially, a database of AM implementers was developed, these companies were then characterised according to the following criteria:

- ***Technology type*** – what type of technology was implemented? e.g. Direct Metal Laser Sintering. There were no priority AM technologies for the study, however there was a focus on technologies which had proven manufacturing applications, i.e. beyond prototyping.

- ***Size of the company*** – Micro, small or medium sized enterprise, or large multinational. The size of the organisation was an important contextual difference used in selecting cases. Upon analysis of the potential case studies, it became clear that the organisational antecedents (later discussed) were linked to the organisation size.

- ***Level of adoption*** - the percentage of RP to RM application was used as an indicator of level of AM adoption. A target of 70% to 30% respectively was made to focus the main study on companies who had a significant level of manufacturing applications. For the secondary study, implication of the framework, this constraint was not used; instead a clear business strategy of production application was the only requirement.

- ***Location of company*** – companies in the UK were targeted in order to control costs of travelling during the study that could affect data collection strategy.

- ***Organisational antecedents*** – Companies were grouped according to their product and service offering prior to implementation of AM for production applications. This included whether the company had a history in providing prototyping capacity and related services, or were a manufacturer using conventional process, or a new start up based on AM products.

From this analysis of the most appropriate sample, a number of typical cases were identified and used to select cases for this study with the objective of achieving theoretical replication. These are laid out in the following sub-sections. This method of sample selection is related to the research questions; specifically the understanding implementation practice is different organisational and technological contexts.

3.4.1 The typical case: The RP Convertor

Rapid Prototyping bureaus have long been the most prolific adopters of AM technologies. These companies have specialised in providing prototypes for manufacturing companies to speed product development projects. Original entry barriers to polymer systems (such as SLA and SLS) included high machine costs and high switching costs resulted in many companies being unwilling to invest in RP technologies thus the emergence of RP bureaus occurred. As machine costs decreased, machine complexity reduced, entry barriers also reduced resulting in higher competition in the RP sector, with many companies taking the RP capability in-house. There have been a number of articles profiling the demise of the service bureau, describing the need for service bureaus to adapt to these market and technological changes in order to survive. One way in which these companies may look to survive and achieve growth is through implementing AM technologies for RM application, moving up a level in the supply chain and becoming part suppliers. With experience in AM technologies, the technical knowledge is less likely to be a causal factor of implementation success; however with the lack of an established customer and experience in production, market penetration is likely to be very difficult for the RP convertor. Given the level of RP implementation in the industry, the RP convertor was used for the pilot case study to help the researcher frame the study and understand the influence of contextual differences.

3.4.2 The typical case: The Conventional Manufacturer

The second typical case taken in this study is that which groups manufacturing organisation with a history in other subtractive or formative processes, such as traditional machining. This group includes organisations that have an existing product line for production applications produced through any non-AM process. This group represented a relatively small number of the sample, with only a few available cases for the researcher to choose from. Companies in this category tended to be larger companies and were predicted to have more formalised approaches to implementation based on the literature review on technology implementation research. For this group of implementers, it was predicted that resistance to change would be a key determinant of implementation success due to the organisations history in conventional processing.

3.4.3 The typical case: The New Start-up

The final group of typical cases were those companies who had been founded based on AM products, with investment of AM technologies for production applications. Companies in this category tended to be smaller sized companies reflecting the fact that most of these companies were relatively new start-ups. For this category of implementers it was predicted that business strategy would be a key determinant of success due to the new nature of the company and lack of existing customers, systems of operations and developed supply chain.

The research then defined a suitable sample size. Considerations were given to factors including population size, time, costs and restrictions to site access. For this study the small population size, in terms of AM implementers for manufacturing applications (restricted to the companies in the EU for costs reasons), was one the key determinant of sample size. This limited the number of organisations, therefore the number of informants to be interviewed. However, this is in line with Voss' proposed research structure at the exploratory/theory building stages of research - few-focused case studies.

3.5 Developing the Research Instrument and Protocols

The research protocol and research instrument were developed based on Yin's [104] proposed guidance:

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

3.6 Conducting the Field Research

3.6.1 Sources of evidence

In case research, there are a number of sources of evidence available to the researcher as methods of data collection. Yin [104] presents six sources of evidence along with their respective strengths and weaknesses in his seminal work on case research strategy (Table 3.2).

Table 3.2. Six sources of evidence: strengths and weaknesses [104].

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

This data collection method also allowed the researcher to delve deeper into sensitive issues, such as vendor support and organisational acceptance. Through probing these issues face-to-face at the informant's work-place, a better understanding of the implementation process was formed and therefore consequently a better framework was developed.

The first interviews, face-to face, were the lengthiest as the researcher took the opportunity to uncover as much information as possible, This approach also helped to avoid the high cost of travelling to informants workplaces, and disturbing the informants frequently (potentially leading them to terminating access). Once the recordings from the first interview has been transcribed and analysed, follow up questions were conducted either by phone or email.

To enhance the quality of the interviews, this included conducting background research before the interview to obtain more information about the informants and the organisations adopting AM. Also a flexible research instrument was employed, with the interviewees own words being used to reframe the questions and re-direct the interview where necessary. This flexible research instrument was used to force the focus of the interview on the main implementation factors at the case company, whilst retaining flexibility, to allow the exploration of interesting lines of enquiry. The researcher used established tactics to make the informant feel comfortable, including dressing smartly but casually, projecting a friendly impression and holding the interviews at the informant's workplace. Also, at the end of each interview, permission was requested for follow up telephone interviews and email enquiries. These follow up interviews served to enhance the validity of the findings and confirm the interpretation made during analysis. These methods of improving the quality of the interviews have been proposed throughout the literature in qualitative research studies [103, 114, 115]

3.6.2 Gaining site access

A significant amount of time and resource was spent gaining access to the case study sites. This access was critical to the study of the AM implementation process through collecting the required data from the viewpoint of the AM project manager. The following subsections provide details of the approach taken for gaining access to the relevant sites.

3.6.2.1 Lobbying the study at conferences, exhibitions and seminars

- *11th National Conference on Rapid Design, Prototyping and Manufacturing*

The researcher attended and presented a paper in a conference devoted to research and progress in rapid design, prototyping and manufacturing at Lancaster University. The conference was attended by a large number of participants from AM community, researchers and industrialists, and as national conference the majority of the industrial delegates were from companies in the UK. The researchers' presentation of the research received a lot of attention from number of delegates; however it failed to reach the target audience of AM implementers with production applications. Following this experience the researcher decided to change strategy and attend events with a more commercial focus.

- *Attendance at TCT Live conference and exhibition, Coventry*

Along this approach to reaching the commercial audience, the time compression technology (TCT) live conference and exhibition provided the researcher with an opportunity to develop contacts with AM implementers. With a commercial focus, attendees were generally more from industry rather than academic research. Specifically, the exhibition delegates were AM system vendors, who approached and provided a number of target companies and contacts for the researcher to pursue following attendance at the conference. The conference presentations were also orientated towards industrialists rather than the research community, providing another opportunity for informal data collection.

3.6.2.2 Initial interviews with AM system Vendors

At the time of study, the University of the researcher was going through an implementation of AM systems at its Centre for Additive Layer Manufacturing (CALM). This provided an opportunity to hold some preliminary interviews with the AM system vendor, EOS. One of the main AM system suppliers, the regional manager provided guidance on which companies to contact and provided some contact details of potential informants at the adopting companies. These initial informal interviews represent not only important steps in reaching the target audience but also an informal data collection opportunity for the researcher to improve the implementation framework. At this early stage, the interviews highlighted to the researcher the challenges he would face in getting management to “air their dirty washing” regarding issues with implementation. Recommendations were given to and heeded by the researcher to target companies who had achieved success as they would likely be more willing to share their experience. This aligned with the research strategy of targeting best-in-class case study sampling.

3.6.2.3 Additive Manufacturing Network (AM Net) meetings

The additive manufacturing network, or AM net, meetings also provided an opportunity for the researcher to network with both academics and industrialists in the AM community. The AM net is a network of members from the AM community, meeting quarterly to discuss developments and roadmap activities in Additive Manufacturing. The meetings allowed the researcher to develop contacts and build rapport with implementers of Additive Manufacturing, along with gaining support and advice from academics in the area of AM. One academic, of the few that have focused on AM implementation as a research subject [18–20], provided guidance on potential applications and case studies, whilst highlighting the challenge of establishing case studies in the AM industry due based on his previous experience.

3.6.2.4 Email list of priority informants

Following success in gaining company contacts, the available contacts were then prioritised according Linton’s criteria [111]. To gain site access, each contact was then sent an email outlining the research study along with a request to meet with the relevant AM manager at the adopting organisation. Depending, on the organisation, the level of the informant within the organisation was determined mainly by company size. For smaller case companies such as 3T RPD Ltd and Reprap Ltd the lead informant targeted was the CEO or founder, for larger companies the RM manager was targeted. Response success was varied, those contacts which had been established in person, face-to-face, had a much higher success rate those who were found second hand through other contacts. Where no response was received, the researcher followed up each email with a phone call which presented further success.

In the majority of cases, the interviews were conducted with a single informant, the project manager of the AM implementation, where possible, operational staff were also interviewed to verify some of the case conclusions, activities and issues. However, the nature of industry regularly determined that the project managers or CEOs wished to control what information was divulged to the researcher. Where possible a secondary interview with the AM systems vendor was also used to support the case study, for example in the case of 3T RPD and Renishaw.

3.7 Approach to Data Analyses

The initial research questions were used to guide the approach to data analysis for this study. Two levels of data analysis were identified at the beginning of the study and were conducted at different stages of the research. These approaches are laid out in the following sub-sections.

3.7.1 Within-case analysis

The first of these approaches was conducted immediately after each of the case studies and is known as within case analysis. The objective on this analysis approach was to develop the AM implementation framework for each of the adopting organisations. The grounded theory approach was used to analyse the data and develop the implementation framework of each AM adopter. Within-case analysis followed three steps, beginning with the transcription being read line-by-line to identify initial factors of importance during the implementation process using a process known as open coding [117].

The proposed research framework, developed from AM research and technology implementation literature, was referred to in this process of identifying the factors of importance, providing a focus on relevant issues/activities. Emerging factors were also identified at this stage if they were not already captured in the research framework. Once all the factors were identified, they were then compared in order to identify any similarities and differences to identify groups of factors in a process called axial coding. For example, organisation structural, cultural and size factors were grouped together in a main category called organisational change. The other categories identified, that make up the constructs of the implementation framework, are AM strategy factors, supply chain factors, Systems of operation and AM technology factors.

Case company name	Stage of data collection	Company type	Type of AM	Typical case	Stage of implementation	Informants, position
3T RPD Ltd	Pilot	SME - RP/RM services	DMLS, SLS	RP convertor	Fully implemented DMLS systems with production applications	[1] Company CEO [2] System vendor, Regional manager
Renishaw Plc	Primary	Large multinational – Inspection and metrology	DMLS, SLS, FDM	Conventional manufacturer	Fully implemented SLS and DMLS systems for production applications	[1] RM Manager [2] System vendor, Regional manager
Materialise UK Ltd	Primary	Large multinational – RP software	SLA, SLS, FDM	RP Convertor	Fully implemented production applications	[1] UK Operations Manager
Reprap Ltd	Primary	New start up – Open source systems	FDM	New start-up	Fully implemented production applications	[1] Company Director
BAE Systems Ltd	Secondary	Large company - Aerospace sector	SLA	Conventional manufacturer	Implemented SLA prototyping	[1] AM Project Manager
HiETA Technologies Ltd	Secondary	New start up – automotive/aerospace	DMLS, SLM	New start-up	Developed applications not implemented production	[1] Company Director [2] Engineering Manager
ChocEdge Ltd	Secondary	New start up – gifts and confectionary	Extrusion-based process	New start-up	Developed technology not implemented production applications	[1] Company Director

Table 3.3. Additive manufacturing companies involved in the study

This analysis process went through several iterations until ‘saturation’ was reached, i.e. no new categories from the analysis were identified. At this stage the researcher deemed further interviews or analysis of the data added little value to the implementation framework. The first stage of analysis involved the determining the relationships between issues and activities for each case study. This was done through defining the context of each factor, defining the motivation for the activities or the causes of the issues from informant responses. Where there was no clear reason for issues from the informant, the framework was used to identify and propose potential causes. Initial logic diagrams were used to describe early relationships between categories and subcategories (Figure 3.6). The format used for these logic diagrams was based on Matsumoto and Wilson’s guidance to axial coding [118].

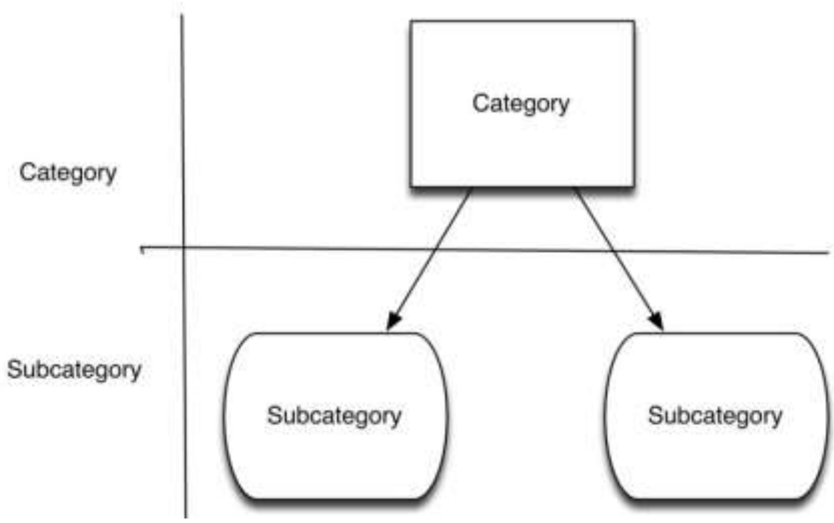

Figure 3.6. Axial coding diagram redrawn from Matsumoto and Wilson [118]

The second stage of analysis was to determine the sequence of activities and related issues. Due to the ad hoc nature of the process implementation, particularly in SMEs this sequencing of events was found to be unachievable for some cases. The process and sequence was more established in the larger companies who had followed a more formalised implementation process with clearer understanding of the environment and chain of decisions. For those case where the sequence could be established, a process model was developed, for those where this was unachievable, e.g. SMEs in a relatively turbulent environments, analysis finished at stage 1 for the within case analysis but where possible the sequence was determined logically through selective coding (Figure 3.7).

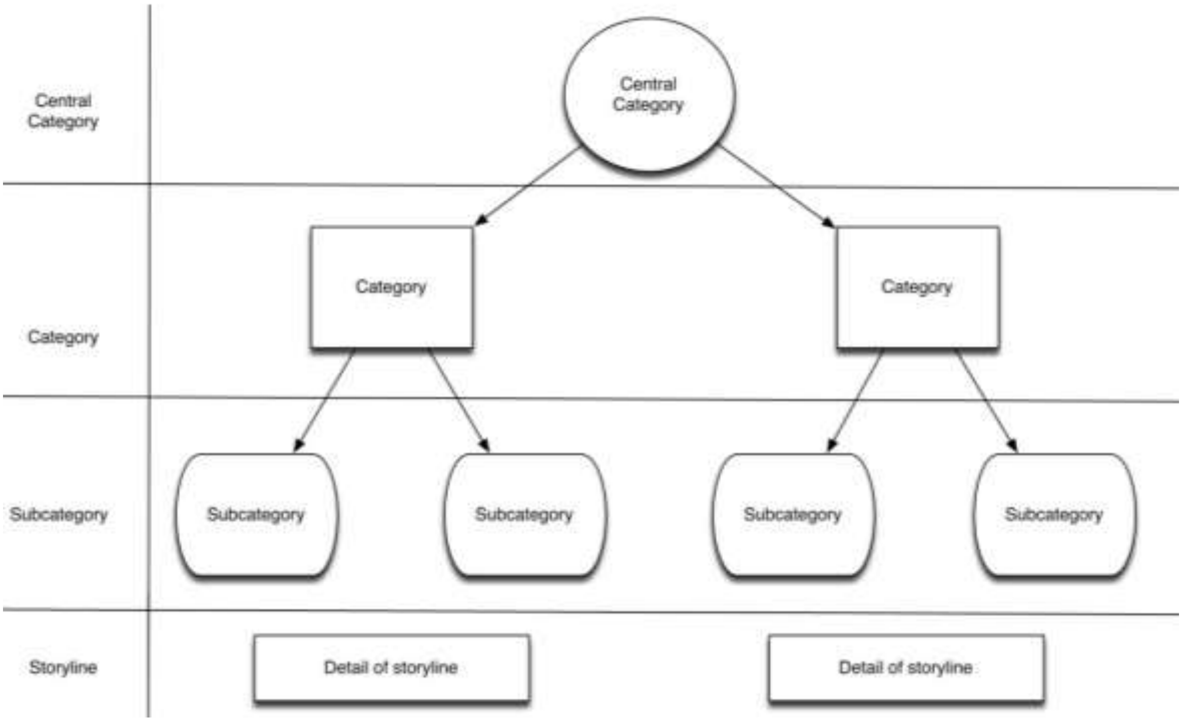

Figure 3.7. Selective coding diagram adapted from Matsumoto and Wilson [118]

3.7.2 Cross - case analysis

The cross-case analysis consisted of two main activities. Comparing the results of the case results, the objective of this analysis was to compare the implementation approaches to identify the contextual and technical similarities and differences to provide an understanding of the theoretical replication of the case studies. The key issues and activities were compared between all of the cases and grouped into the normative AM implementation framework.

The main result of this analysis was the normative framework for AM implementation, which included the differences in approach and the relationships between organisational antecedents and the factors which made up the framework. The framework describes the AM strategy and the issues and activities facing organisations with different organisational contexts. The objective of theoretical replication, producing contrary results for predictable reasons, was achieved at this stage.

Finally, the last stage of analysis took four companies who had yet to implement AM technologies and developed implementation frameworks based on the results of the cross case analysis. This was done through establishing the context into which AM would be implemented and understanding of the business strategy at the adopting organisation, using the face to face interviews with informants at the case companies. This comparison concluded the analysis for this study and provided evidence for how the framework can be applied by project managers.

3.8 Summary of the Chapter

This chapter has defined and supported the selection of the research method used in this study. The research method is based on the interpretive paradigm and designed through a combination of the case research strategy and the grounded theory approach. This combined approach has been used to developed a more robust research design and has enabled the relatively novice researcher to achieve the objectives and answer the research questions of the study. It has also enabled the nature and complexity of AM implementation in different contexts to be captured and thoroughly understood, through development of theoretical accounts that conform to the experience of the informants used in the study as described in 3.6.1.

Gaining site access represents one of the main challenges in conducting this study. The characteristics of the industry and the type of study meant that much time and resource was spent on this activity. Potential case studies were characterised prior to gaining site access to identify typical cases and achieve theoretical replication during analysis.

Once site access has been achieved, the study questions along with Yin's [104] guidance on developing the research protocol were used to develop the research instrument. The main tool for data collection was the in-depth face-to-face interview with informants who led the AM implementation projects in their organisations. Follow up telephone interviews, along with interviews with systems vendors were also used to clarify key activities and issues. Several measures were employed to enhance the quality of the interview process.

The research methodology adopted in this study is illustrated in Figure 8. Prior to the case study process, the research framework was developed using the grounded theory approach. The data analysis went through two main stages, one being a within case analysis involving the analysis of each organisation's AM implementation process. The second stages involved analysis of the implementation approaches across all organisations. At this stage each organisations issues and activities were grouped according to the research constructs and similarities and differences were identifies. The analysis produced and refined an emerging framework for AM implementation. Finally, the framework was applied in a number of pre-implementation cases, to provide guidance on its use by AM project managers (Figure 3.8). The next chapter provides a detailed description of the research framework development.

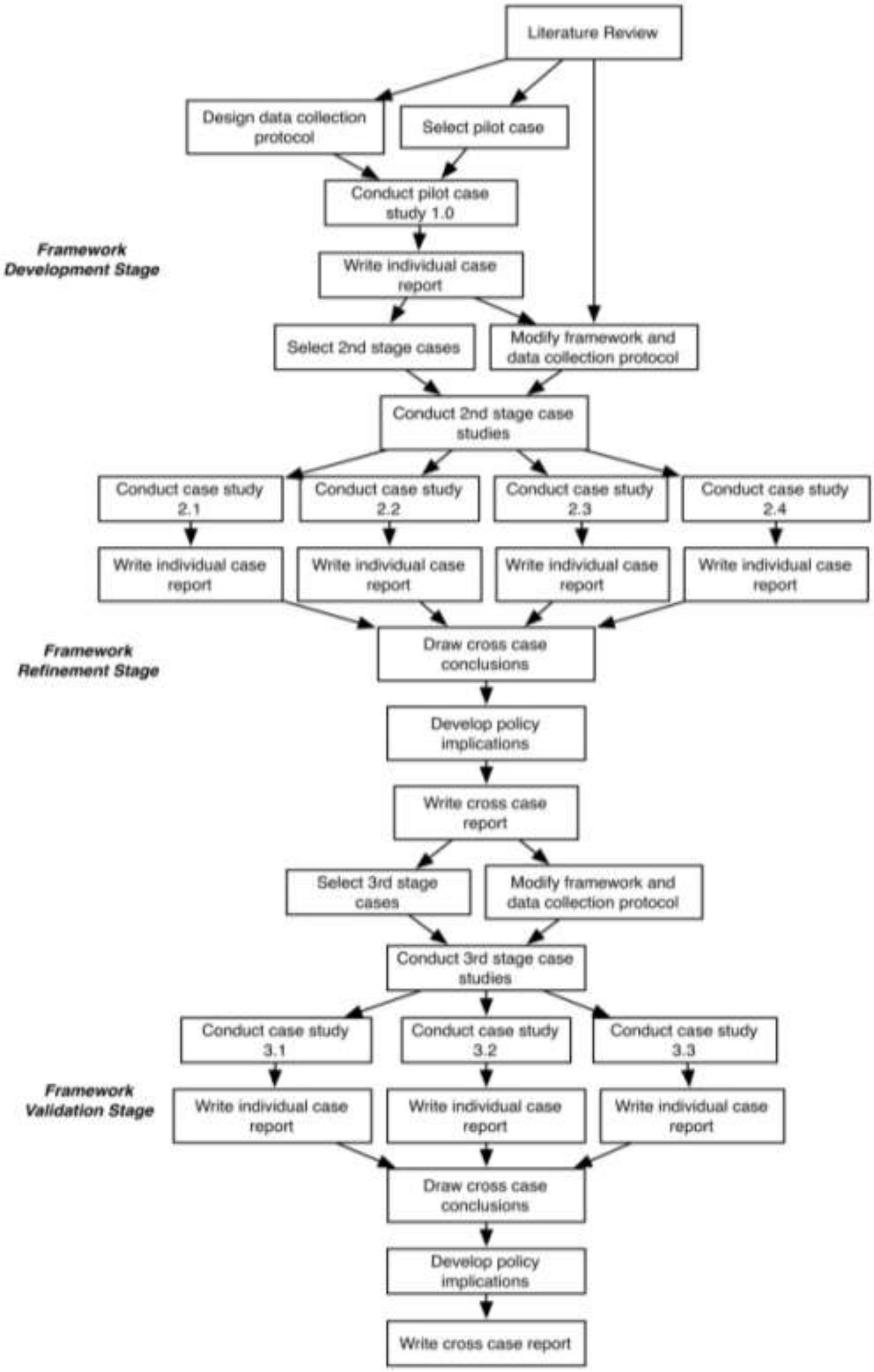

Figure 3.8. The research methodology employed in the study

CHAPTER 4

DEVELOPMENT OF THE IMPLEMENTATION FRAMEWORK

4.0 Introduction

This chapter documents the development of an initial implementation framework investigating the research questions defined in the literature review. The chapter is organised as follows; in the following section, the proposed research framework is presented explaining how the framework was determined, the next section outlines the motivations for grouping of the factors in the chosen constructs. The factors are then discussed in detail and finally the inter-relationships between factors are discussed.

4.1 The Proposed Research Framework

There is general acceptance that the researcher must develop a prior view of the general constructs or categories that are to be studied, and their relationships. This is often provided in the form a conceptual framework, Voss et al. [105] suggests such a framework explains, either graphically or in narrative form, the main things that are to be studied.

A conceptual model of factors influencing the implementation of AM technologies is presented in Figure 4.1. The model is of a closed loop nature to illustrate the interaction and dependency between the strategic, organisational, supply chain, technological and operational factors. The details of the constructs and propositions behind this framework have been developed from the literature review on manufacturing strategy, technology implementation and AM and are set out and described in the following sections.

4.2 The Research Constructs

As per the research question defined in the previous chapter, this study is interested in the key factors of AM implementation, how they combine with technical factors, and the influence of contextual differences on the implementation process. To this end, these research questions, developed from a thorough review of the literature, have guided the grouping of factors and therefore the definition of constructs. The approach to construct definition is further described in the following sub-sections.

Figure 4.1 Conceptual model of factors influencing the success of AM technologies implementation.

4.2.1 Contextual factors – Organisational and supply chain constructs

In order to capture the contextual differences between implementers, the framework contains two constructs related to the contextual characteristics of the implementer. The first being related to the internal context of the organisation: with factors including size, structure, culture and workforce experience and skill. The second construct related to contextual differences is the supply chain construct, which lie outside the immediate organisation. This construct recognises the differences in supply chains of AM implementers, and includes factors: customers, vendors, suppliers and logistics and distribution.

4.2.2 Technical factors – AM technology factors

Technical factors are captured in the AM technology factors construct, as per the second research questions this study aims to answer the following; *how do these factors combine with technical factors to form the AM implementation framework?* Therefore, those technical factors which make up the implementation process are grouped in this construct. From analysis of the literature the following factors have been selected; selection and justification, maturity, benefits and tradeoffs, and Rapid Prototyping (RP) legacy.

4.2.3 Additive manufacturing strategy and operations

The remaining factors in the research framework have been grouped in to two further constructs; strategic factors and operational factors. The motivation for this grouping is the fact that these factors are directly related to the main research question, "*How do organisations go about implementing Additive Manufacturing as a manufacturing process either as a replacement to the conventional approach or for new business opportunities?"* By grouping according to strategic and operational constructs the factors are grouped at different levels of decision making for those adopting organisation.

4.3 The Framework Factors

From the description of the framework constructs, the following sections further describes the motivations for each factors inclusion on the framework. The factors are laid out and described in the order they are appear in the framework, reading from the top downwards, not in any particular priority order. At the end of each construct group the proposed relationships within the construct are outlined.

4.3.1 Strategic Factors

4.3.1.1 Business strategy

> *"Manufacturing firms, especially in developed countries, are challenged by slow-growth home markets, increasing competition from emerging market competitors, rapid technology change, high-cost labor, rising material and energy costs, long supply chains, and poor economic conditions."* [119].

Business strategy defines the long-term plan of action a company may pursue to achieve its goals [120]**.** Small and Yasin [85] suggest the recognition of an increasingly complex and competitive global environment is the first step in considering adoption of new process technology. Companies recognise that their current processes or procedures are inadequate to provide success in the current and future business environment. Furthermore, non-price factors, such as quality, product design, innovation and delivery services are the primary determinants of product success in today's global arena [121]. These factors drive the company to develop a strategic response in order to sustain long-term competitive advantage.

4.3.1.2 Manufacturing strategy

The manufacturing strategy should then fully support the objectives of the business strategy, with manufacturing objectives set in the form of capabilities (or competitive priorities) which will enable the manufacturing unit to be a competitive weapon [68, 90, 93, 96]. The underlying factor of process choice is volume, the link between the demand for a product and the investment in processes to complete the task is fundamental to the decision [91]. Therefore the decision to invest in AM technologies must be linked to the market and product volumes. In a manufacturing context, high utilisation underpins a technology investment [91], if the process will not be highly utilised on one product it must meet the manufacturing and business needs of other products. Aspects critical to process choice in the product and markets dimension also include: type of product (customised, standardised), product range, customer order size, rate of new product introduction.

4.3.1.3 Technology strategy

Technology strategy encompasses the acquisition, management and exploitation of technological knowledge and resources by the organisation to achieve its business and technological goals [76], therefore this requires integration of the technology strategy and business strategy. Process investments can be either technology push or pull strategies. The rationale for process investments in push strategy comes from technology-based arguments, whereas pull strategies reflect investments based on defined markets needs. Hill [91] warns it is critical that companies with push strategies see arguments concerning the corporate potential to sell the spin-offs from the proposed technology investments as being only part of the evaluation and they must evaluate such investments on their own merits.

Hill [91] also suggests there are two specification needed to be taken into account when choosing processes; the technical specification and the business specification. The technical specification concerns the fundamental requirements of the product(s) and the business specification is concerned with the best way to make a product in terms of order-winners, qualifiers and order quantities. When discussing AMT Chen and Small [84] proposed the following on matching product with process:

"...management should be aware that adoption of advanced manufacturing technologies can bestow not only operational benefits such as improved quality, increased efficiency and shorter lead times, but marketing and strategic advantages as well. Benefits such as increased market share, reduced prices, improved responsiveness to changes in the marketplace, the ability to offer a continuous stream of customized products, faster production innovation and improvement of the company's image, have all been ascribed to the operation of flexible AMT".

The positive effect of founding technology adoption decisions on strategic considerations is prominent throughout literature [80, 91, 122–124].

4.3.1.4 Interrelationship between strategic factors

The authors propose that the implementation of AM must be preceded by strategic alignment of the business, manufacturing and technology strategy. The technology benefits must be linked to the capabilities required of the manufacturing unit, capabilities derived from the business strategy, this will be viewed as the market-pull strategy to AM implementation. However, it is also proposed in line with the current resource-based view of the firm that investment in AM may be seen as a structural investment which will build new manufacturing capabilities, creating new business opportunities for the enterprise, the technology-push strategy. Recent research by Sonntag [126] provides a good summary of the current view of adapting to technological change and the role of manufacturing strategy:

"A combined top-down/bottom up planning process appears to provide a better balance between strategic intent and implemented strategy (as embodied in daily operational decisions) and prevent failed implementation. This conclusion suggests that building firms' strategy development and implementation capabilities should itself be a key focus of firms' competitive strategies."

From strategic alignment of business, manufacturing and technology strategy, the company must then shift focus to ensure the structure and composition of the component parts, or functions that provide its necessary internal systems and communications are also developed in line with the manufacturing strategy requirement [123]. The structures, controls, procedures and other systems are collectively known as the manufacturing infrastructure. This internal structure also includes the attitudes, experience and skills of the people involved in the manufacturing function. The study of manufacturing infrastructure is therefore complex, but there is consensus in the literature that structural investments, such as technology adoption are more likely to be successful if pursued in conjunction with supportive infrastructural adjustments [84, 102, 126, 127]. This entails evaluating the likely impact of adopting on all units of the organisation.

4.3.2 Organizational Factors

4.3.2.1 Organisation size

The size of an organisation has been identified to be critical to the understanding of the process of implementation of new manufacturing technology. A number of scholars have suggested small business cannot be considered scaled-down larger ones, and the theories proved in large enterprises might not be suitable for small business [128–131]. The AM industry is characterised by a large number of SMEs and few large organisations. Therefore, the organisational form that the SME segment adopts is very different to the large enterprises. It is proposed the introduction of AM into SMEs cannot just duplicate the experiences of large enterprises, or vice versa. Therefore, this important characteristic of AM implementation must be taken into account during investigation of success factors in AM implementation. On their discussion of Total Quality Management (TQM) implementation in SMEs, Ghobadian and Gallear [133] provided some important characteristics of large, medium and small enterprises.

Table 4.1. A comparison between the characteristics of large, medium and small organisations [133]

Large organisations	**Small and medium organisations**
Hierarchical with several layers of management	Flat with very few layers of management
Clear and extensive functional division of activities. High degree of specialisation	Division of activities limited and unclear. Low degree of specialisation
Strong departmental/functional mind set	Absence of departmental/functional mindset. Corporate mindset
Activities and operations governed by formal rules and procedures	Activities and operations not governed by formal rules and procedures
High degree of standardisation and formalisation	Low degree of standardisation and formalisation
Mostly bureaucratic	Mostly organic
Extended decision-making chain	Short decision-making chain

Top management a long distance away from point of delivery	Top management close to the point of delivery
Top management's visibility limited	Top management's highly visible
Wide span of activities	Span of activities narrow
Multi-sited and possibly multinational	Single-sited
Cultural diversity	Unified culture
System dominated	People dominated
Cultural inertia	Fluid culture
Rigid organisation and flows	Flexible organisation and flows
Many interest groups	Very few interest groups
Incidence of fact-based decision-making more prevalent	Incidence of 'gut feeling' decision-making more prevalent
Dominated by professsionals and technocrats	Dominated by pioneers and entrepreneurs
Range of management styles: directive; participative; paternal; etc.	Range of management styles: directive; paternal
Meritocratic	Patronage
Individuals normally cannot see the results of their endeavours	Individuals normally can see the results of their endeavours
Ample human capital, financial resources and know-how	Modest human capital, financial resources and know-how
Training and staff development is more likely to be planned and large scale	Training and staff development is more likely to be ad hoc and small scale
Specified training budget	No specified training budget
Extensive external contacts	Limited external contacts
High incidence of unionization	Low incidence of unionization
Normally slow response to environmental changes	Normally rapid response to environmental changes
High degree of resistance to change	Negligible resistance to change
Potentially many internal change catalysts	Very few internal change catalysts
Low incidence of innovativeness	High incidence of innovativeness
Formal evaluation, control and reporting procedures	Informal evaluation, control and reporting procedures
Control oriented	Results oriented
Rigid corporate culture dominating operations and behaviours	Operations and behaviour of employees influenced by owners'/managers' ethos and outlook

4.3.2.2 Organisational structure

> *"No matter how well developed the systems are for defining and developing innovative products and processes they are unlikely to succeed unless the surrounding organisational context is favourable"* [134].

Technological change has been described as an incremental, cumulative process, punctuated by major discontinuities which represent major breakthroughs in product or process [135]. Tushman and Anderson further classified discontinuities as competence-destroying or competence-enhancing, because they either destroy or enhance the competence of existing firms in an industry. The former requires new skills, abilities, and knowledge in both the development and production of the product. Regardless of the extent which a new technology may be competence enhancing or destroying, it will increase the level of uncertainty as attempts are made to master new tools, devices or techniques and it has been suggested that this introduction of uncertainty is the theoretical key to hypothesised change or stability, in both structure and power [136]. A change in an organisation's technology requires adjusting the tools, devices, knowledge, or techniques that mediate between inputs and outputs and/or create new products or services [134–136].

The literature suggests that the structure of an organisation is the key factor to successfully implementing manufacturing technology [88, 89, 137–140], and that companies that adopt without first re-designing organisational structures and processes encounter high difficulties [89,141]. Organisational structure refers to an organisations internal pattern of relationships, authority, and communication [143]. A number of dimensions have been used in literature to discuss organisational structure including; centralisation, formalisation, complexity, span of control, and workforce composition [143–145]. Centralisation in the organisation refers to the delegation of power among the jobs. The less power delegated in an organisation the greater the centralisation in the organisation and vice versa [90]. Formalisation refers to the extent to which expectations regarding the aims and objectives of work are specified and written. Highly formalised organisational structures recommend what each individual should act based on rules and procedures that are obtainable. Complexity refers to the number of distinctly different job titles or occupational groupings and the number of definitely dissimilar units/departments, in a group/organisation. In the technology implementation literature, the mechanistic-organic continuum is often used to understand the organisational structure.

On the subject of AMT implementation a number of authors have suggested flatter, less complex structures with maximum administrative decentralization, are more likely toward creating a potential for improved attitudes, more effective supervision, greater individual responsibility and company performance [88, 89, 146].

Linked to organisational structure, at the operational level, manufacturing structure can similarly be measured using dimensions of job design, operator job description, operator skills, design-manufacturing integration, and so on. The respective dimensions are narrow job scope-multiple roles, formal/planned-informal/ flexible, specialized-diversified, and preplanned/sequential-on-line/ parallel [125].

4.3.2.3 Education and training

The requirement for formal education and training of the workforce is well documented throughout the operations research when implementing any new methodology or technology [22, 147, 148]. The level of education and training required for AM implementers will be dependent on the experience and skill of the workforce. This is because those with experience and skill in design for additive manufacturing, for example, will require less education and training than those with only design for conventional processes. It is proposed as the level of implementation increases, from prototyping to production, this will increase the education and training requirement.

4.3.2.4 Organisational culture

Organisational culture has long been featured in the manufacturing technology implementation research. Hopkinson et al. [5] suggest possibly the largest but unknown impact could be on company culture and how it changes to accommodate AM. Belassi and Fadlalla [89] propose culture is to the organisation what personality is to the individual, a hidden, yet unifying topic that provides meaning, direction and mobilisation. To be more specific, Schein [150] provides the following definition:

> *"a pattern of basic assumptions—invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration—that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems"*

Many authors have advocated that new technologies challenge established norms and strategic options. Organisational culture defines the complex set of knowledge structures which organisation members use to perform tasks and generate social behaviour [90]. Researchers have often used the competing value framework to understand organisational culture, which is characterised by two dimensions which reflect the different value orientations. The first dimension in this model is the flexibility-control dimension. A flexibility orientation reflects flexibility and spontaneity [151], with focus on the development of human resources and values member involvement in decision making. Conversely, at the foundation of the control-oriented culture are assumptions of stability, along with individuals respect to the organisational mandates because roles are formally announced and enforced through rules and regulations [90].

A number of case studies [89, 149] have found that a control-oriented culture may have a negative effect on implementation success of technologies, as they diminish the opportunity for organisation learning and that implementation success depends on cultural flexibility.

The second dimension is the internal-external axis, which is concerned with focus of activity occurring within an organisation (internal) and outside (external) the organisation. The internal dimension emphasises the maintenance and improvement of the existing organisation, while the external emphasises competition, adaptation, and interaction with the external environment [151].

Evidence has suggested many successful high tech SMEs (such as those in the AM industry) progress through an evolutionary process as they grow, from initial beginnings which are based on the internal technological competencies upon which the business was founded, towards an outward orientation focusing upon marketing issues as technologies mature and competition increases, this requires an increasing emphasis on the need to find new markets. Evidence has also been found that enterprises are unlikely to be successful in this evolution towards a market-led orientation unless a strategic approach to managing the business and technology is adopted.

On their analysis of CAD/CAM implementation in SMEs, Esan et al. [152] provided the following summary of the importance of culture change:

"Today companies need people to work together in development teams, sharing their hard-earned knowledge, experience and ideas and hence providing the capability of working on production and support from very early on in the design and consequentially the manufacturing phase. However, without being able to effectively use all the functional knowledge retained within the company, the team's effectiveness can be limited severely. Technology can aid this activity significantly by helping companies to look at the whole product life cycle from the start and, thus, produce manufactured products more rapidly and with greater confidence in quality. However, too often the available computer-based design and manufacturing support systems work in isolation, severely restricting the effective use of the knowledge they retain hence the need for concurrent engineering."

4.3.2.5 Interrelationship between organisational factors

Bailey [153] provided a framework linking technology (AMT), organisational structure, and product of a manufacturing firm and posits a number of relationships between the four variables (Figure 4.2).

1. The adoption of AMT would suggest that a firm's technology is evolutionary.
2. A firm's technology would influence both its operational and administrative structures to change.
3. The technological change would affect and demand changes in design and manufacturing activities
4. Consequently jobs/tasks of employees have to be redesigned.
5. To achieve superior performance a firm must try maximum fit between technology, structure and employees.

The authors propose successful implementation of AM technologies, the decision to adopt will be accompanied by a change in jobs and tasks, and thus a change in work practices and structure. This will in most cases require a change in knowledge and skill of the workforce therefore education and training of employees becomes a key factor for successful exploitation of the innovation. Resistance to technological change will create a negative impact on achieving the major benefits of the technology, Gunasekaran [154] advises training and involvement help to minimise worker resistance however it is ultimately dependent organisational culture.

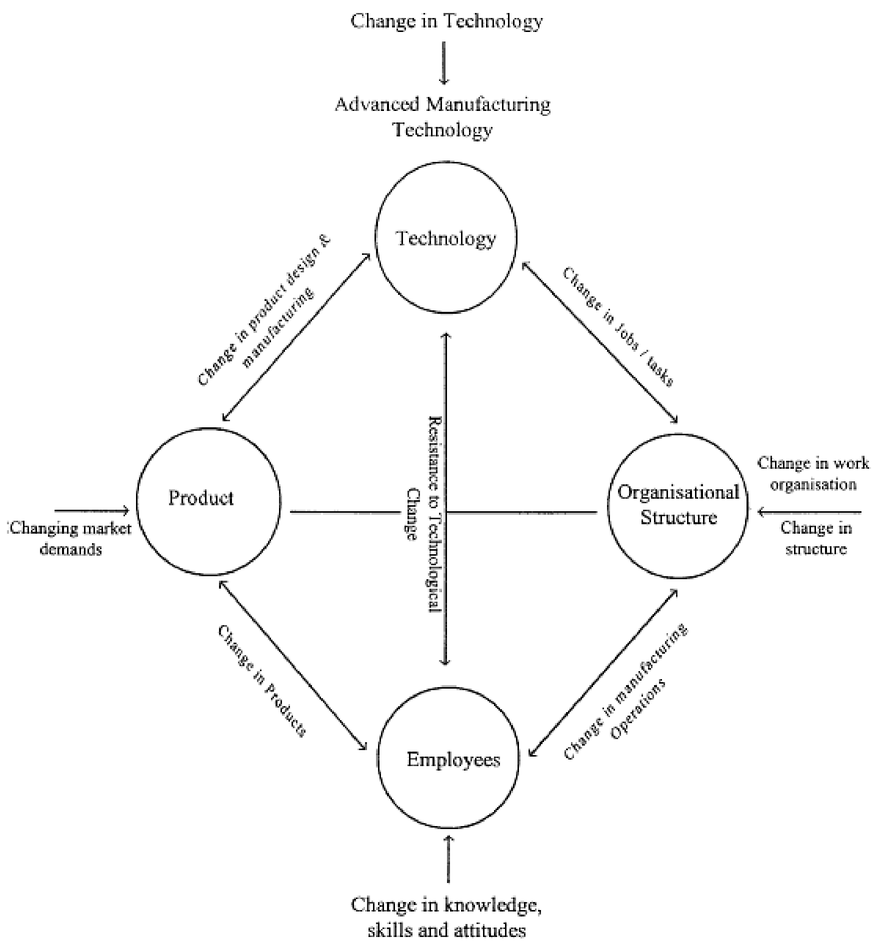

Figure 4.2. Conceptual Framework of Technological Change and Posited Relationship [153].

The orientation of the organisation culture may affect the level of success of AM technology implementation, however it is unknown which culture will provide higher level of success. From the technology implementation literature, larger studies indicate a balanced culture (high flexibility- and control- orientation) may facilitate greater success.

4.3.3 Operational Factors

As proposed by Bailey [153], a change in an organisations technology will influence both its operational and administrative structures to change. The following presents the proposed operations and administration changes required for the successful adoption of AM.

4.3.3.1 Integration of AM technology

Hayes & Jaikumar [82] suggested one of the key barriers to achieving the benefits of new process technologies is that modernisation is often approached through a series of independent projects, "islands of automation", however they suggest for the desired returns to be materialised all advances must be in place (i.e. computer integrated manufacturing). This view is held throughout the literature with one of the greatest advantages associated with AMT being the potential for integration, with a single integrated systems created to control all activities of a firm starting with raw materials and finishing with finished goods ready to deliver to the customer [89, 153, 154]. RP systems have often been viewed as an "island of automation" due to the vast number of build parameters and the variability in the models manufactured. Though there has been progress in machine development, it is generally accepted throughout the literature that no single AM process is capable of creating the quality and material properties required for truly functional use without post-processing. Therefore it is proposed that for the full benefits of the technology to be achieved, all advances within the production system must be in place.

4.3.3.2 Product design

A number of authors [61, 155, 156] have identified the impact AM will have on design operations. The design process is recognised as being one of the most important stages in product development, with the realisation that over seventy percent of the final product costs are determined at the design stage. Design for manufacture (DFM) is any aspect of the design process in which the issues involved in manufacturing the designed object are considered explicitly with a view to influencing the design. A number of authors have commented on the impact of AM on the design of products and designers themselves. The additive nature of AM processes means that this type of manufacture is unconstrained by many of the limitations of conventional (subtractive or formative) processes [6]. The unique characteristics of AM systems require new design tools and practices to be developed, contrary to early promise made by some researchers, there is not total geometric freedom and many consideration have to be taken into account when designing products for AM. It is proposed that the designers understanding of the new design for "additive" manufacturing constraints will be an influential factor in AM implementation success.

4.3.3.3 Process planning and control

The manufacturing planning and control system (MPCS) is designed to plan and control materials, labour, and equipment by developing feasible, time-phased plans and monitoring their progress [158]. One of the primary functions of the production planning task is to match market demands with supplies from manufacturing and outside suppliers to control the flow of goods and materials [159]. Vollmann et al. [158] suggested that the MPCS design must match the needs of the market, the manufacturing task, and the manufacturing process. Furthermore, they state that any of these three areas can mandate a change in the MPCS design, and that there is interdependency between MPCS option choices and process choice features. Olhager and Rudberg [159] proposed if there is alignment between market requirements and process choice, then the task of the MPCS is simpler than should there be a mismatch. A number of studies have shown that the link between market requirements and process choice heavily influences the role of the MPCS, as well as the performance of the manufacturing system [158–160].

Munguia et al. [58] investigated processing planning strategies employed at 36 AM centres in Northern Spain. They used survey analysis, supported by personal interviews with technicians, to identify the most relevant factors for AM process planning. The results found that those steps that include a certain amount of manual labour are given more importance compared to those factors which can be fully automated within the process. The researchers also identified a number of strategies commonly adopted during process planning, including:

- ***Part orientation strategies*** – aimed at minimising or controlling the affect of how different orientations might affect mechanical and aesthetic features alike for certain processes.
- ***Build volume strategy*** – this strategy was found to be imperative to controlling process costs through maximum build volume.
- ***Layering strategy*** – the study found that although it is possible to set variable layer thicknesses for different levels inside the same build with AM processes, the tendency to use a single fixed thickness value was observed in layering strategies.
- ***Support generation and minimisation*** – these strategies are aimed at generating and minimising the support structures required in AM processes. The study found that in spite of the automated support generation software, custom support design is common practice and manual correction is often required when reliable supports are need for complex critical parts.

Table 4.2. Process planning parameters in AM systems, adapted from [58]

Relevance	Parameters
1	Part orientation
2	Maximise build volume
3	Layering strategy
4	Support generation
5	Process speed
6	Laser power
7	Hatching strategies
8	Thermal control

4.3.3.4 Cost accounting system

Hayes and Jaikumar [82] suggested the use of unsuitable cost accounting methods, where implementation of new technologies results in costs incurred shifting from direct labour costs to essentially fixed costs, often renders traditional methods focusing on less important factors unsuitable (i.e. devoting energies to measuring costs that are likely to account for less than 25% of the total). A number of authors [5, 15, 16] have identified the substantial information gap regarding the true cost of AM system, implementation and operation. In previous studies on AM costing four key cost factors have been identified for additive processes: operation times, machine costs, labour costs and material costs [17, 58].

Table 4.3. The four main cost factors used in AM costing.

Operation times	Machine costs	Labour costs	Materials costs
Number per platform	Machine and ancillary equipment	Machine operator cost per hour	Material per part
Platform build time	Depreciation cost per year	Set-up time to control machine	Support material per part
Hours per year in operation	Maintenance per year	Post-processing time per build	Material cost per kg

4.3.3.5 Interrelationship between operational factors

It is proposed that the adopting organisation must have the correct design operations in place, with supporting CAD and file preparation software, in order to capture the benefits of AM technology in design for process. Design will influence downstream processes, in terms of post-processing, and the production planning and control system should match market requirements and AM technology characteristics in terms of relevant process parameters. Production planning and control should be supported by an integrated production system in order to fulfil the customer requirements in terms of quality and speed of product delivery. Design for process should also be supported by a cost accounting systems developed for the specific process and product characteristics.

4.3.4 Supply chain factors

AM implementation lies at the intersection of two supply chains; firstly it involves a supply chain from the machine vendors to the purchaser of the technology. Secondly, the purchaser will then embed the technology in their respective supply chain and hence influence their customers and suppliers. These two supply chains will be discussed separately, with an aim to understand the supply chain factors which influence the success of AM implementation. A supply chain may be defined as:

> *"...a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via a feed forward flow of materials and feedback flow of information"* [162]

4.3.4.1 Customers

The unique benefits presented by AM technologies allow new design freedom, therefore presenting not only benefits in production but potentially new product innovation allowing the adopting organisation to enter new markets. The adopting organisations ability to present benefits of AM as a manufacturing process in a clear and balanced way will determine the success of implementation [5].

Adopting firms should adopt more collaborative relationships with end users, this collaborative activity is recognised throughout the supply chain literature with general acceptance that businesses must work together to form an integrated supply chain focusing on meeting the demands of the end-user or internal customer [163]. Furthermore the goal of an integrated supply chain is to remove all boundaries to ease the flow of material, cash, resources and information [164]. With the integrated supply chain both the information and material flows are simplified, streamlined and optimised reducing waste and lead times.

Rosenzweig et al. [165] have suggested high supply chain integration directly influences the following competitive capabilities:

- Product Quality Capability
- Product Delivery Reliability
- Process Flexibility Capability
- Cost Leadership Capability

4.3.4.2 Vendors

Another characteristic of current AM industry worthy of note is the tendency for machine suppliers to be material suppliers (such as the powders used in the SLS and SLM process) following implementation. This characteristic is partly due to the immaturity of the technology (with a shortage of material suppliers) and also likely a strategy on the machine supplier's part to protect future business.

On the subject of AMT implementation, Bessant [166] has argued that for AMT to deliver its full potential significant organizational changes are required such as the restructuring of relationships with suppliers towards more collaborative forms. Chen and Small (1994) suggest that a company wanting to implement AMTs successfully should consider their likely impact on suppliers and work towards closer relationships with them. Burgess et al. [167] performed a quasi-longitudinal study on AMT implementation in the Turkish automotive industry. Their study found evidence that business success is related to the level of buyer-supplier collaboration and that as the level of AMT increases further buyer-supplier collaboration is required. Managers cited the adoption of new manufacturing practices (and hence technology implementation) as the highest rated item affecting buyer-supplier relationships and also stressed the importance of changes in product technology and therefore process innovations as they are linked directly [168].

The buyer-supplier relationship in procurement and implementation of AM capital equipment is here referred to as the vendor supply chain. Vendor support during the implementation process has long been recognised as a critical factor of implementation success. It has been proposed that the level of complexity of the technology innovation is directly related to the level of intensity of the user-supplier interaction processes [169]. The complexity, maturity and disruptive nature of AM technologies is proposed to require vendor collaboration throughout the implementation process.

Zairi [170] studied the measurement of success in AMT using customer-supplier interaction criteria, he identified the following criteria effected the level of success of AMT implementation

Criteria facilitating AMT implementation included:

- supplier ability to relate AMT products to user requirements;
- supplier competitiveness in product range, price and performance;
- supplier ability to provide a whole range of support services during the various stages of the implementation process;
- ability of users and suppliers to work closely during the implementation process;
- ability of people to relate to one another for joint problem-solving and knowledge/information sharing;
- external criteria which were specifically focused on are the ones related to the suppliers of AMT innovation and the dynamics involved in determining interaction processes between the suppliers and users of AMT;
- supplier commitment in implementation by resource allocation, determination to solve all problems;
- degree of commitment from both suppliers and users in enhancing existing relationship and in planning jointly for a long-term future.

The inhibitive vendor criteria identified by Zairi were:

- poor choice of equipment in terms of reliability;
- supplier poor technical knowledge/inability to solve problems;
- supplier inability to provide good support and back-up services;
- supplier poor communication with customer;

- supplier limited involvement during implementation;
- supplier lack of interest in users future requirements;
- suppliers lack of progressiveness.

4.3.4.3 Logistics and distribution

Walter et al. [59], Ruffo [15] and Tuck [20] have all proposed new supply chain solutions made possible by both the centralised and decentralised applications of AM. Centralised has the potential advantage of cutting high inventory costs (of slow moving parts) and reducing the need to subsidise costs with profit of fast moving parts. However, this work also suggest there will still be warehousing and delivery time cost associated with this application of AM. Previous research also suggests distributed application of AM technologies can be used to eliminate these costs; however warns there will then be the problem of having enough demand to warrant AM machines on location (i.e. machine running at capacity). Following Walters et al conclusions, it is proposed that to maximise the benefit of AM a hybrid system must be applied but that centralised application of AM will be the first to be used, due to the changes in supply chain distributed manufacture will demand on the supply chain.

4.3.4.4 Interrelationship between factors

From this review of implementation research, it is proposed that the implementation of AM technologies manufacture will require increased collaboration with suppliers and customers. Within this is the proposition that as the level of AM adoption increases (in terms of product development life-cycle, from design to production); this will require significant increases in the amount of collaboration with suppliers and customers. It is also proposed that vendor support will be critical in facilitating the successful adoption of AM technologies.

In implementing AM technologies, it is proposed that the organisation must adopt a supply chain strategy as an extension of the firm’s business strategy, where strategies should focus on improving supply chain operations which in turn helps the company attain their business objectives [171]. It is proposed for successful implementation of AM will require firms to match the process capabilities with supply chain characteristics.

4.3.5 Technological Factors

4.3.5.1 Selection and Justification

Tingling and Parent [80] suggest that technology selection and evaluation is an important area of study for the following reasons:

- Technology accounts for one third of all business capital spending
- Evaluation and selection often precede adoption and use
- Technology evaluation informs theorists, providers, consumers and policy makers.

Hayes & Jaikumar 1991 [82] suggested that the straight jacket of financial justification as one of the real impediment to effective use of technology and companies reluctance to include non quantifiable, or “soft”, considerations result in bias against investment in these technologies as they have significant impact in product quality, the speed and reliability of delivery, and the rapidity of new product introduction. They further suggest investment proposals for new manufacturing technologies, at the early stages of their evolution, should lie closer to R&D project proposals.

There has been much research in the evaluation of manufacturing technologies, and a number of tools have been developed to assist management with the decision of when to adopt a technology. Technology assessment tools are generally classified into three groups: strategic evaluation approach, economic evaluation approach and analytic evaluation approach. Economic methods justify based on the cost reduction or capacity expansion. The analytic methods frequently consider uncertainty, flexibility, risk and non-economic benefits of technologies. Strategic approaches tend to be less quantitative than either the economic or analytic techniques and typically involve subjective estimates of the key indicators. Small and Chen [172] showed that companies utilizing hybrid methods attained higher levels of success from their AMT projects than plants that used only one method. It seems that inappropriateness of one criterion might be partly balanced by the use of the other methods. It is unlikely that any single justification method will lead companies to all or even a wide range of AMT benefits and improve performance. Thus, integrated approaches (i.e. using strategic, economic and analytic methods in parallel) were recommended to quantify the tangible and intangible benefits throughout the technology investment [90].

4.3.5.2 Benefits and tradeoffs

In order for the adopting organisation to gain competitive advantage from the implementation of AM its ability to link the technology benefits to the business strategy has been emphasised. The technology benefits associated with AM include:

- Reduced lead time for new product.
- Faster response to customer requests.
- Reduced order to delivery lead times.
- Faster product modifications.
- Reduced costs.
- Higher quality products.
- Faster response to customer needs.
- Improved product functionality.
- Market changes.
- High variety at same or reduced cost.

However, as shown in previous work by [140] it is equally important that the adopting firm also understands the trade-offs in using new manufacturing technology. A review of the literature provides a number of AM characteristics which will affect the decision on investment and success of AM implementation, a number of these are outlined below:

- High capital investment
- High material and maintenance costs
- Material properties
- Support material removal, i.e. post-processing requirements
- Process costs

Hopkinson and Dickens [60] suggest that industries with high capital investment, low volumes of production and complexity in design are more suited to AM, and that in these industries the technical barriers become less significant. However, though some of the characteristics above may be inherent in the nature of the technology, others will likely be based on maturity of technology.

4.3.5.3 Technology maturity

AM technologies have found applications in a variety of industries. However, although RP has become standard practice in many industries, the use of AM for manufacture of end-use products is far from the norm [50]. Technology maturity has been highlighted as one of the key barriers to further diffusion of AM. Though some processes such as SL have been used since the 1980s, the application of these technologies for end-use part manufacture is a fairly recent development. One of the most important implications of this, for those implementing AM, is that no exclusive AM standards are yet applied to current practices. However Munguia et al. [58] identified certain uniformity among different procedures was observed showing a type of "tacit rule" for product manufacture with AM. Therefore, it is proposed that the maturity of the technology affects the implementation success of AM, with determinant factors being the adopting organisations capabilities in acquiring product certification and developing relationships with customers and suppliers.

4.3.5.4 Rapid prototyping legacy

> *"Rejection of the concept of Rapid Manufacturing usually comes in the form of in the form of comparison (for example of material properties) with existing processes. The problem at this point is that Rapid Manufacturing is seen merely as an extension of Rapid Prototyping and so parts are not seen as suitable or intended for end use. This 'baggage' of Rapid Prototyping is probably a larger hurdle to the uptake of Rapid Manufacturing than any of the technical issues we face" [5].*

The RP legacy is likely to have profound effect on the implementation of AM technologies, both internal and external to the adopting firm. Organisations implementing AM technology for end-use part manufacture must overcome this entry barrier by working more closely with customers. The adopting organisations ability to present benefits of AM as a manufacturing process in a clear and balanced way will determine the success of implementation [5]. It is also proposed that RP legacy will result in resistance to change internally for those organisations with a history as service providers. In RP applications, products are designed and produced for inspection and testing purposes, with production achieved through other manufacturing process. Using AM processes as manufacturing technologies requires designers and engineers to re-think DFM constraints, to match product with process. Employee education and training on AM technology capabilities and empowerment regarding product and process changes is proposed as key to successful implementation of AM. Therefore, it is likely that RP legacy will likely hinder the AM implementation success of adopting firms.

4.3.5.5 Inter-relationships between factors

The adopting organisations understanding of the benefits and tradeoffs of AM, as a manufacturing process, will determine the level of fit between process choice and product characteristics. The relative immaturity of many AM processes (particularly metal systems) means that the AM landscape is continuously changing and therefore these benefits and tradeoffs are also moving rapidly. Adopting organisations must undertake activities to capture knowledge on how these benefits and tradeoffs are and will change-over time, through close communication with machine and material suppliers and research institutes. Linked to the technology maturity, the legacy of prototyping will likely hinder the acceptance of AM as a production both internally and externally. Education on technology benefits will help to facilitate acceptance, however ultimately it will likely be done the culture of the adopting organisation.

4.4 Summary

This chapter has presented a research framework and its constructs in order to answer the research questions.

Organisations implement AM as a strategic choice, matching the capabilities of the technology with the environment in which they operate (the market pull approach). Alternatively, AM may be seen as a structural investment which will build new manufacturing capabilities, creating new business opportunities for the enterprise (the technology-push strategy). In order to understand the factors which will contribute to successful implementation the framework suggests that the organisations ability to match the technology capabilities with the business strategy of the firm is essential to successful implementation of AM, and that using a combined top-down, bottom-up approach may provide a better balance between strategic intent and implemented strategy (as embodied in daily operational decisions) and prevent failed implementation. Organisational factors are proposed to be critical to the successful implementation of AM and these factors include the size of the adopting organisation, the orientation of the organisation culture, the structure adopted and the education and training and empowerment of employees.

At the operational level it is proposed that AM implementation will profoundly affect the way in which products are designed and will require the adoption of suitable production planning and control systems and cost accounting systems. The integration of AM technologies into the manufacturing system is also proposed as a determinant of success. The technological factors identified as success drivers are the appropriate selection and justification of technologies, the maturity of the technology implemented, overcoming the RP legacy, and understanding the benefits and tradeoffs of AM. Finally, the supply chain factors proposed as being critical to success of implementation are the integration of customers and suppliers, the level and quality of vendor support throughout the implementation process and the decisions regarding logistics and distribution.

This chapter has provided support for the inclusion of these factors as the key constructs in the research framework from the available literature. They provide the basis for the research instrument to be taken into case studies. A summary table is presented in Table 1, detailing related references along with a supportive statement on their inclusion in the AM implementation framework.

Table 4.4. Summary of research framework constructs and factors

Construct	Factor	References	Motivation for inclusion
Strategic factors	Business strategy	[50, 82, 119, 124]	Business strategy will determine the requirements of the production system, therefore the process choice. AM process will provide business opportunities, and facilitate new business models.
	Manufactur-ing strategy	[68, 90, 93, 96, 97, 121]	AM is a structural investments which will provide new capabilities to the manufacturing system therefore influencing the manufacturing system of the adopting organisation.
	Technology strategy	[80, 83, 91, 122–124]	Either as a continuous or disruptive technology AM technology present benefits as part of a technology strategy an effective approach to technology strategy formulation and

			implementation will determine success.
Organisational factors	Business size	[129, 131, 147, 154, 172]	The framework should capture the differences in organisational context. The business size will influence the approach to AM implementation made by the adopting organisation.
	Organisational structure	[135–140, 143, 172]	AM provides a new level of automation, new design and production knowledge related to the process characteristics. It is important to understand how this change in knowledge could change the experience and skill requirements of employees and how structure changes to accommodate this.
	Organisational culture	[149, 150, 153, 154, 173]	AM technology will challenge establish norms and the ways in which manufacturing is performed by an organisation. Therefore, the framework should capture the organisational context and the cultural challenges faced by adopting organisations.
	Workforce experience and skill	[88, 89, 124, 146, 150, 174]	There will be an experience and skill gap during the implementation of AM. The organisations approach to bridge this gap will be a key determinant in implementation success.
Operational factors	Product design	[6, 60, 155, 156]	Implementation of AM as a production technology will require design for AM operations, including supporting technologies (CAD, file preparations software) and design guidelines.
	Production planning and control	[58, 157–160, 175]	As a production process, planning and control of products will be key to meeting order winners including quality, cost and speed. AM technology will determine the planning strategies which must be captured along with product design.
	Integration	[81, 89, 153, 154]	AM system should be integrated into a production system to achieve for manufacturing efficiencies.
	Cost accounting system	[15, 16, 51, 58, 60, 81]	Process innovations require new costing accounting systems as the main cost drivers switch according to the technology characteristics.
Supply chain factors	Customer and supplier relations	[5, 162, 163]	Adopting firms should move towards more collaborative relationships customers and suppliers as new processes provide new product benefits.

	Vendor relations	[83, 165–169]	High vendor involvement will be required during the implementation process to transfer the knowledge to the adopting organisation.
	Logistics and distribution	[176–178]	There is a potential to move manufacturing according to demand, with a more decentralised approach facilitated by the AM technology benefits.

CHAPTER 5

THE PILOT STUDY

5.0 Introduction

This chapter presents data and analysis from a pilot inquiry conducted as part of the first stage in data collection for this thesis. At the time of writing, the pilot case study was one of the UK's leading AM service bureaus, 3T RPD Ltd. The pilot study enabled the researcher to gain insight into the basic issues being studied and an initial understanding of the AM implementation process. This information was used in parallel with an ongoing review of the literature, so that the final research design was informed both by prevailing theories and by a fresh set of empirical observations [104]. The main factors established in this initial study have helped to form and refine the constructs and factors of the initial research framework of the AM implementation process.

This chapter is structured as follows. Section 5.1 provides a brief background on the case company and the informants interviewed during data collection. Section 5.2 presents the case study findings and followed by a discussion of the findings in Section 5.3. Finally, Section 5.4 provides conclusions regarding the refined research framework and data collection process.

5.1 Background information of the company and informants

The pilot study was conducted at a single site, 3T RPD Ltd in Newbury. 3T RPD specialises in the production of complex and functional metal rapid prototypes, aesthetic models and low volume production components to industries including aerospace, architecture, automotive, dental, medical, FMCG (fast moving consumer goods), marine, defence and pharmaceutical. The company is a capacity seller for AM processes and, at the time of investigation, the largest SLS provider in the UK and had one of the largest UK DMLS facilities, with four machines. Being purely self-funded, the company began the first steps in developing a DMLS capability in April 2007 buying their first system from machine vendor Electro Optical Systems GmbH (EOS). The company was one of the first UK companies to invest in metallic

AM processes (DMLS) in 2007 and at the time of writing held around 40% UK market share of DMLS products.

The informant at 3T RPD was the company Chief Executive Officer (CEO). The informants main career experience was in the automotive sector, as chief engineer in rapid prototyping and tooling departments and in CAD/CAM strategy development and implementation. Becoming aware of SLA (Stereo lithography) in 1987, the informant introduced the first SLA part into Rover Group in around 1988, became CEO of 3T RPD in 2005. The investigation at 3T RPD focused on the implementation process of the DMLS systems for the following reasons:

- the interviewee was directly involved in the implementation of DMLS technology and may be viewed as the project champion,
- the interviewee regarded the metals based processes as key to future success, and finally,
- when discussing production applications DMLS was the processes generally referred to as providing the major benefits.
- with a history in RP services in SLS, the focus on the DMLS implementation process provided the researcher with an insight into activities and issues of the RP convertor.

The pilot enquiry was also supported by gaining a vendor perspective of AM implementation at 3T RPD. This was through interviews with the regional manager of EOS. EOS is the world leader in laser sintering technology, selling systems in 32 countries employing around 300 people, the majority of which are based in company headquarters in Krailling, Munich. As regional manager, the informant was directly involved in the implementation process at 3T RPD.

5.2 Pilot Case Study Results

The details of this framework have been defined previously, therefore it is not the objective of the study to exhaustively list, define and provide support for this framework, rather the objective of the pilot enquiry is to perform a preliminary test of this framework using the typical case of the RP convertor.

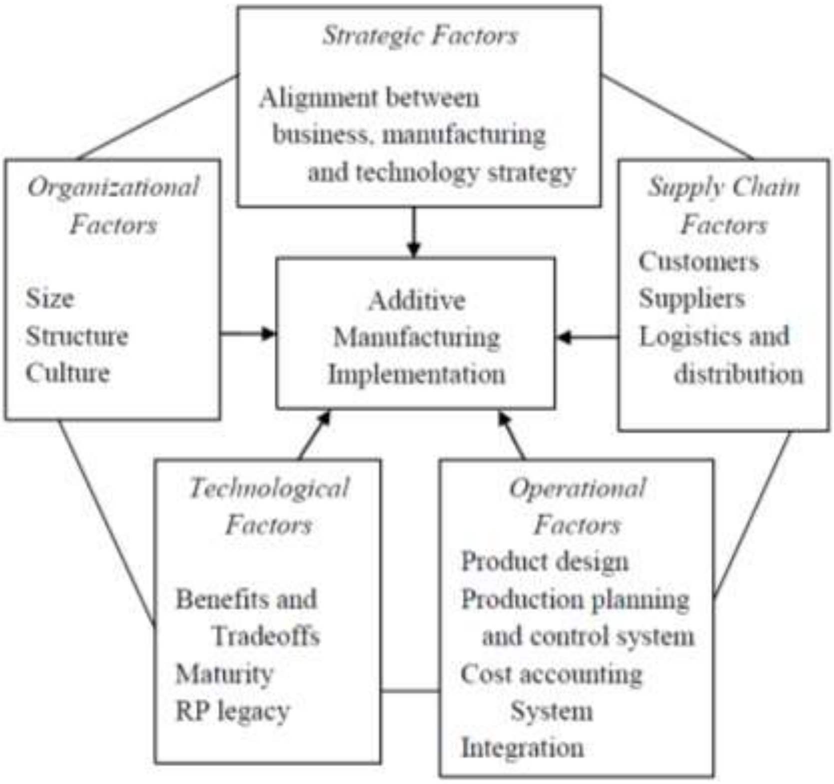

Figure 5.1. The proposed framework of AM implementation (initial)

The research framework, as illustrated in Figure 5.1, was used to develop a research instrument with open-ended questions on the project champion's experience of DMLS implementation. The constructs of the framework were used to guide the topics of discussion during the interview process; however, the research instrument remained flexible enough to discuss any important issues or activities identified in the interview process.

The results of the pilot enquiry are outlined in the following sections; the data is presented according to the related research constructs, with a summary of the findings of each provided at the end of each section.

5.2.1 Strategic factors

3T RPD was original set up as an RP service bureau supporting manufacturing companies with polymer prototypes during product development projects. The company invested significantly in AM technologies, particularly metal systems, attempting to move further towards manufacture of products rather than prototypes, with a focus on aerospace applications. A number of factors led to the implementation of DMLS systems at 3T RPD.

One of the main contributing factors to implementation was the CEOs perceived technology benefit, at a stage where the technology was very much in its infancy, the CEO recognised the potential for competitive advantage through investment:

> *"It was a belief as much as anything; there was no precedent to base it on....I could see that metals was going to be massive in the future....I wanted to make sure that I set us up ready for when it happened so that we were in a position of strength rather trying to catch up."*

Originally a specialist in purely SLS services, another factor contributing to the decision to invest in DMLS at 3T RPD were the changes in the RP sector. As the cost of RP systems reduced and the systems matured, many companies took this capability in-house which reduced the amount of services companies request from specialist suppliers, such as 3T RPD. This change had drastic effects in certain markets for the company. In motorsport, the company was primary supplier for a number of companies, who later took this capacity in house, and therefore the market completely disappeared. However, the effect in other markets was less drastic and although demand decreased it did disappear. Informant described his thoughts on the changes in the RP sector:

> *"...it's just part of the natural cycle....it may be half of the companies that take an in-house capacity continue to use us, the other half don't, it could well be a lot better than that it might be three out of four continue to use us because they know what we can do. Where it's difficult is where some companies like to go for big vertical integration"*

The company had a clear mission of becoming Europe's leading supplier of SLS and DMLS parts. The CEO outlined the stage of DMLS implementation at the time of enquiry:

> *"....were going through a very, very important phase at the moment the DMLS is just starting to make a profit, now it will make a loss next month, or the month after, or the month after, one of them its gonna go wrong. But broadly speaking it is making a profit. Wow, you know we've been losing money on that for...four years now....the key to it is gonna be how, when we get our first major production order, because as soon as we start making production.....the financial dynamic fundamentally shifts"*

Since setting up the DMLS facility the company went through periods where machine utilisation was as low as 20%. The CEO described the issue with low machine utilisation with expensive AM technology*:*

> *"...considering the machines are four or five hundred thousand Euros you wanna make that thing sweat.....the machines cost you thirty grand a month whether you do any jobs or not. That's tough....that is really tough"*.

Therefore, it may be suggested that the company was beginning to achieve technical success, with machine utilisation increasing to a point where the system was making a profit. However, business success was dependent on the company achieving the intended business benefit of the technology.

The challenge for case company was that in order to maintain the business benefits of the technology it needed to prove its production capability:

> *"....the only way we are going to make any money on this ultimately is by doing production because the overheads for production work are radically lower than they are for prototyping......so then you have the problem, you don't want to do prototyping, but that's the only business around, you want to do production, but to do production and be good at it you've got to show you're good at doing production. So you've got a real dichotomy there."*

Though it was too early to suggest 3T RPD has achieved business success, the company developed a number of production contracts, taking customers products and developing them either on their own or with them to a point where they are production viable. The biggest production contract they had to date was around two hundred units, at a quarter of a million Euros.

One informative case at 3T RPD was their experience with developing the dental application using DMLS. The ISO 13485 certification was part of a failed application development for production of dental crowns. The CEO suggested the strategy behind dental was to prove their competence in production and specifically dental production, and the business case was that "*we should make a lot of money to help us with our self-sustaining growth, because we weren't we were losing money at that time"*. However, the CEO described it as being “disastrous”, even with a very big name dental company backing them they were only producing fives and tens of units a day, needing a hundred to break even.

The CEO suggested this failure was partly due to the recession and partly because the predictions for sales were based on the DMLS dental market in Germany and the UK market structure was fundamentally different to Europe:

> *“....because the market didn’t do what it told us it would do, so many people told us it was gonna happen, and these were the people who were gonna give us the work and they were wrong.”*

This highlights one of the challenges of implementing new technologies in new markets, particularly for SMEs without the resource to fully understand the market structure. This suggests the market characteristics play a key role in the implementation of AM technologies, and the company’s ability to understand the market characteristics is key determining implementation success.

The strategy at 3T RPD was therefore significantly influenced by its organisational antecedents, coming from a RP background rather than a production background. The informant suggests that:

> *“it would have been better to be a machining company that adds it in rather than a rapid prototyping company that is trying to become a serious aerospace or whatever supplier”*

There are a number of explanations for this reasoning, influencing the approach to AM implementation at the case company. The factors contributing to this reasoning are, the culture within RP (discussed in the following section), the company not having an established customer base and lacking production capability (particularly regarding the post-processing requirements in DMLS. Their response to this apparent inefficiency was to become experts in *“design and application development in a particular way”*. Though the company built up a workshop facility to support the DMLS system, through deliberately finding and designing parts to suit the process they were able to get round this inadequacy and as the informant suggests:

> *"it is much more profitable to design the part where you don't do anything to the part after you have finished, so you design it so that it doesn't need anything doing to it and if you can do that then its far more profitable....and far quicker".*

This represents the company's main in-house capability, design for process. However, an important implication of this approach was that it required a lot more design thought, although downstream process may have be reduced, upstream process are significantly increased – further discussed in the operational factors section of this chapter.

Regarding the market for DMLS products, the informant suggested that it was difficult to know where the next job would come from and how the market for DMLS products will change over time.

> *"...a lot of the story with DMLS today is about the fact that it's a totally new market.....its changing so much....it is very, very hard to predict where the next job is going to come from.... it's a high priced product at the moment so your immediately limiting your market and my belief is that every time we can half the price of the part we will increase the size of the market available by a factor of ten. It's definitely practically exponential and the total market size in the UK alone is probably several billion. It's huge. But then you say, well what are you actually comparing against? And the problem is your comparing against a whole range of different types of things"*

It remained a particularly turbulent environment, where both the technologies and the markets were relatively new. The informant also stated that with a few exceptions, industry knowledge of the process had significantly lagged behind that of the users. One of the major challenges with implementing DMLS was the newness of the market and predicting how it would change.

Tidd et al. [134] present a simple matrix with technological maturity as one dimension, and market maturity as the other, illustrated in Figure 5.2.

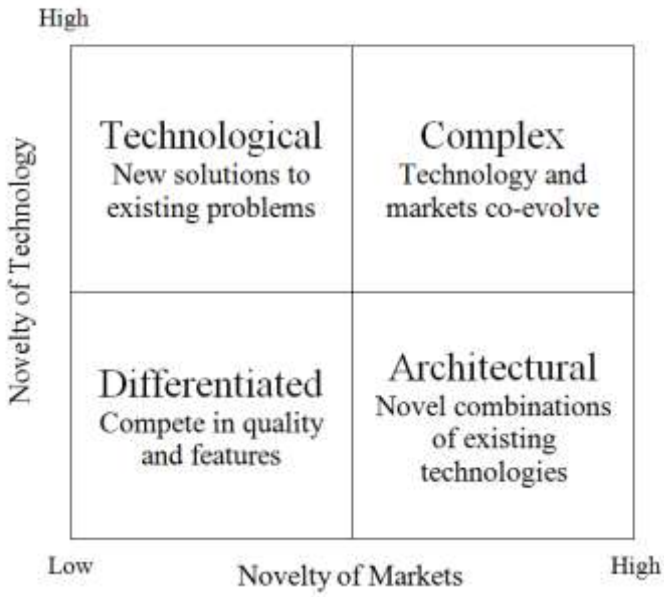

Figure 5.2. Technological and market maturity determine the marketing process [134]

From the literature and the insights from implementation of AM technologies at 3T RPD, it may be concluded that both the technology and markets for DMLS products are highly novel and sit in the complex quadrant. "In this case there is no clearly defined use of a new technology, but over time developers work with lead users to create new applications", this describes well the case at 3T RPD. Tidd et al. [134] suggests that there are many weaknesses to traditional marketing tools and techniques of novel or complex new products. One of these weaknesses particularly relevant to this case study is that "marketing techniques such as segmentation are most applicable to relatively mature well-understood products and markets, and are of limited use in emerging, ill-defined markets". This was reflected in the marketing approach at 3T RPD:

> *"the marketing and sales approach has to be much more along how we go about doing things and what types of things we do and what types of companies we look for, so that again when they've turned up, we know they've turned up....[the market] never stops changing and just the most amazing things turn up every day and we just have to decide whether we want to go with it or not and if we're consistent with our customer approach, we're consistent with our quality, if were consistent with being innovative and helpful and all the rest of it then people come to us and the reason we are where we are now, I believe very strongly that's because that's what we have done."*

5.2.1.2 Summary of strategic factors

Using the axial coding method outlined in the Research Methods, the subcategories of strategic factors were summarised. Table 5.1 provides a summary of the data presented in the case study on strategic factors in the implementation of AM:

Table 5.1. Summary of Strategic Factors at the Pilot Case Study

Factor	Issues/Activities
Business strategy	• Issues with identifying attractive markets and where to focus effort. • Competitive forces along with the CEO analysis of the technology drive implementation of DMLS system as a strategic response. • Business, manufacturing and R&D strategy are heavily influenced by the organisations history in RP • Lack of established customer base drives the marketing and sales approach
Manufacturing strategy	• Lack of established product mix and order winner characteristics drive emergent approach to manufacturing strategy
Technology strategy	• Product and materials research remains one of the key development activities. • Quality improvements required for production applications.

5.2.2 Organisational Factors

5.2.2.1 Business size

The company was an SME and purely self funded, which resulted in a lack of capital for technological investment and R&D activities, also creating a barrier to increasing capacity and developing production applications. One approach to solving these issues was using RP to fund R&D activities for production applications. Further funding was also sourced through R&D projects part funded through government competitions and innovation projects. Although, the company size was small in they experienced significant growth as they established themselves as a leading supplier of DMLS components, and services around production have grown.

5.2.2.2 Organisational culture

The company's experience in RP also affected the organisational culture, as the knowledge structures which organisation members used to perform tasks and generate social behaviour were invented, discovered or developed in an RP environment. The CEO suggests that in an RP environment the focus was "to get parts out quickly and at a decent quality", speed is likely to be an important organisational strength when dealing with change and the demand for quick turnaround is key to success. The informant added:

> *"the thing with rapid prototyping is that you have a culture which is very much you're looking to get parts out quickly and you're looking to get them out at a good quality as well and to try and increase that quality standard.....you're kind of fighting against the time all the time so you have to do it very doggedly but you tend to have very enthusiastic people who will get on, keep on working away at things...."*

For production applications of AM, the challenge for the RP convertor in this case was changing the culture within the company to a more controlled orientation, with employees training focused on quality and cost. The approach to date was through communication of these values to the employees from top-level management including the CEO and production manager.

5.2.2.3 Organisational structure

The workforce structure was composed of design engineers and engineers, with a production manager. The structure changed significantly over the implementation process, starting as a replication of the original polymer RP side of the company. The CEO suggested the organisational structure was something they "*will likely work out as they go along*", as there are no precedents work from. This lack of understanding was routed in the lack of established standard work practices:

> *"I think the organisation itself will evolve as we work it out, because there are very few precedents or virtually no precedents to go by.....there are two halves, its two separate companies, joined by a common enthusiasm for additive technology. Apart from that there's not any other commonality. Which is a surprise, this is one of the things as were going along, it's like oh no, this is very different. We knew it was going to be different, we didn't realise how different."*

The company had a centralised organic structure with the CEO being the key decision maker which has benefits in this turbulent environment for speed of response, however, as the informant confirmed they are vulnerable to individual misjudgement.

> *"So for me, being in a position where I can make quick decisions and keep things moving forward at a pace is very, very important....with that comes the burden of the*

fact that you're gonna make some mistakes, and your always trying to keep the balance between accuracy and speed as you do in most things"

At the operational level, the CEO described the difference in employee roles. Following implementation of DMLS the structure of the production team was initially setup like a "mirror image" of the polymer RP team. With design engineers and engineers and a production manager. One job role highlighted during the interview was the production manager's position. In the SLS side the production manager was initially a CAD operator, and with training from the CEO became a *"good production manager"*. However, as highlighted by the CEO, the DMLS production manager role was far more specialised, requiring expertise in metal work equipment and aerospace process flow. The CEO describes the difference:

"the production managers job in the metals is far more specialised than it is in the plastics, so the production manager in the plastics has moved from being a CAD operator to being a production manager and, from a fair bit of input from me, he's become a good production manager, would he just step straight into doing the DMLS production manager job? No. He wouldn't have the expertise. He doesn't have the background in metal work equipment and the aerospace process flow and all that kind of thing it's too much. It's a very different job."

5.2.2.4 Summary of organisational factors

The company's history, and continued activities in RP significantly affected the level of organisational change required following implementation of DMLS. The table below describes the implementation issues and activities related to the organisational change requirements for implementation of DMLS at the organisation.

Table 5.2 Summary of Organisational Factors at 3T RPD Ltd

Factor	Issues/Activities
Business size	• As an SME, the company had scarce resource available for increasing capacity and R&D activities. (linked to high cost of AM processes and technology maturity)
Organisational Culture	• RP culture creates resistance to change in terms of production working practices and knowledge gap (linked to RP legacy)

Organisational structure	• Workforce experience skill gap mainly in production management role as the skill requirement is significantly different to that required in a prototyping environment. (linked to the business strategy) • Structure of the workforce original set-up as a mirror of plastic RP, had yet to be fully established and therefore suggested it will continue to change (linked to company business strategy)

5.2.3 Supply Chain Factors

5.2.3.1 Customers

The case company's background in RP created a lack of an established customer base for production metallic components. Compared to a machining company, trusted as a parts supplier, the company spent significant amounts of resource on attracting new customers (related to operational factors), and R&D time on developing new products. This was reflected in the company's marketing and sales approach. The target customer base for the case company was aerospace suppliers, with high quality requirements, high risk of product failure, high product value and one heavily influenced by environmental factors including legislation and fuel prices.

5.2.3.2 Suppliers

On the subject of machine suppliers, vendor restrictive practices were highlighted as a key issue in DMLS implementation. These restrictive practices include machine suppliers controlling what materials can be processed (through trade agreements) and locking down machine parameters. These practices reduced the material range available to the organisation, reducing the potential products and therefore markets the company can serve. Locking down process parameters also created a dependency on supplier R&D practices. With a strategy based on new product development, the flexibility of the DMLS systems was important to establishing new product innovations and attracting new customers. The CEO also suggested it was surprising how little the machine vendors looked to learn from the experience of the company regarding machine development. In particular, the informant highlighted out how some vendors were more responsive to making them production capable than others.

Powder control by the supplier resulted in material cost remaining high, due to the lack of competition. This lack of competition and relatively high cost of raw materials (when compared to conventionally processed materials) reduced opportunities for DMLS applications, as product cost were high, price competitive markets (such as automotive) remained unattractive for the adopting organisation. The "locking down" of process parameters also created "annoyance" for high end users such as 3T RPD as it hindered the R&D practices of the company as they were unable to experiment with process parameters optimisation tasks. This issue also created a reliance on the machine suppliers R&D activity, as the systems become closed to operator adjustment.

5.2.3.3 Logistics and distribution

In this case, the location of manufacture remained one of centralised production, as the option of locating production according to demand is reliant on an established customer base, or at least an understanding of the demand for products according to location. Also, the requirements for post-processing and supporting equipment (CNC etc.) required for DMLS production restrict location flexibility, until further machine improvements are in place which reduces these requirements and DMLS moves closer to net-shape manufacture, this was unlikely to change.

5.2.3.4 Summary of supply chain factors

With a history in RP, the supply chain under consideration in this case, remained relatively un-established and fragmented. The goal of the RP convertor was to effectively move up a tier of the supply chain and become an aerospace component supplier. The supply chain related issues faced by the case company are summarised in Table 5.3.

Table 5.3 Summary of Supply Chain Factors at 3T RPD Ltd

Factors	Issues/Activities
Customers	• Lack of established customer base for production applications of DMLS resulted in high level of operations and resource spent on attracting customer (operational factors) • Quality and traceability demands of the customers and supply chain

Suppliers	• Lack of vendor responsiveness to production requirements of AM systems • Machine vendor restrictive practice hindered R&D approach at adopting organisations as processes become less flexibility to experimentation (linked to R&D strategy) • Powder control by machine supplier holds a high price for metallic AM powders • Lack of volume in powder supply chain restricting cost savings
Logistics and distribution	• Centralised production of DMLS systems due to post-processing requirements of current DMLS components (technology benefits and tradeoffs) and lack of established customer base (business strategy)

5.2.4 System of Operations

5.2.4.1 Product design

The move to production AM, where design for process was established, combined with the move to metal materials, which have significantly more design constraints, required the adopter to capture a new set of design knowledge. As the company was one of the pioneering companies, being one of the early adopters, they also pioneered many of these new design rules with relatively little previous work to gain this knowledge from. Though this presented many challenges it became the company's main in-house capability and this reputation of experts in design for process attracted new business. As the company did not have an established customer base, the company spent a large percentage of customer facing time educating customers. This education was around processes capabilities and constraints, particularly on the design side.

5.2.4.2 Production planning and control

The process chain in RP and AM applications was highlighted as a significant issue during the case study. The length and complexity of the process chain in AM applications was drastically increased with the requirements for heat treatment, finishing and measuring of AM parts not present in RP. In this environment the CEO suggested it becomes "*a whole workshop coordination*". This increase in complexity was partly due to the characteristics of the DMLS process, requiring support removal and other post processing activities. Secondly, this was partly due to the quality control requirements for production parts, compared to prototypes. One strategy employed by the adopter was reducing downstream process through quality design for process and optimised process planning strategies.

The quality control changes required for DMLS production were also highlighted as a significant operational challenge. For production (contrary to prototyping) the products produced must meet the functional requirements of the product application, for aerospace (one of the company's target markets) these requirements were difficult to achieve with the DMLS process at the time of implementation. This was also related to the level of technology maturity, as the processes were not fully understood, the inspection and quality management tools and techniques required for customer requirements to be met were not established. In an effort to build confidence in both the technology, and their in-house quality, the company pursued and successful gained a number of recognised certifications, including; ISO 9001:2000 certification for continuous commitment to quality and ISO 13485. international quality management standard for designers and manufacturers of medical devices.

5.2.4.3 Cost accounting system

From this case study the quoting process was identified to be a time and resource consuming operation. In RP, quoting was a much less onerous task for the implementer for a number of reasons, including; the process chain was significantly less complex (discussed below), there was no need for part re-design, and finally, cost was not necessarily an order winner (speed may be more important). However, this was not the case in production AM. The details of the cost accounting system used at the case company were not discussed or provided by informants due to the sensitive nature of this data.

5.2.4.4 Integration

The level of complexity in operations was highlighted by the informant as a significant change during the DMLS implementation process. A comparison was made to the company's previous process flow, in polymer RP, to that required for DMLS production. The two process chains are presented in Figure 5.3. This new requirement for workshop co-ordination and integration of processes presented one of the significant implementation issues for the RP convertor. The company's operations remain a "piecemeal" approach, with the DMLS process being a standalone system, or "island of automation". With low levels of integration the company lacked sufficient tools to integrate a DMLS production with the customer requirements.

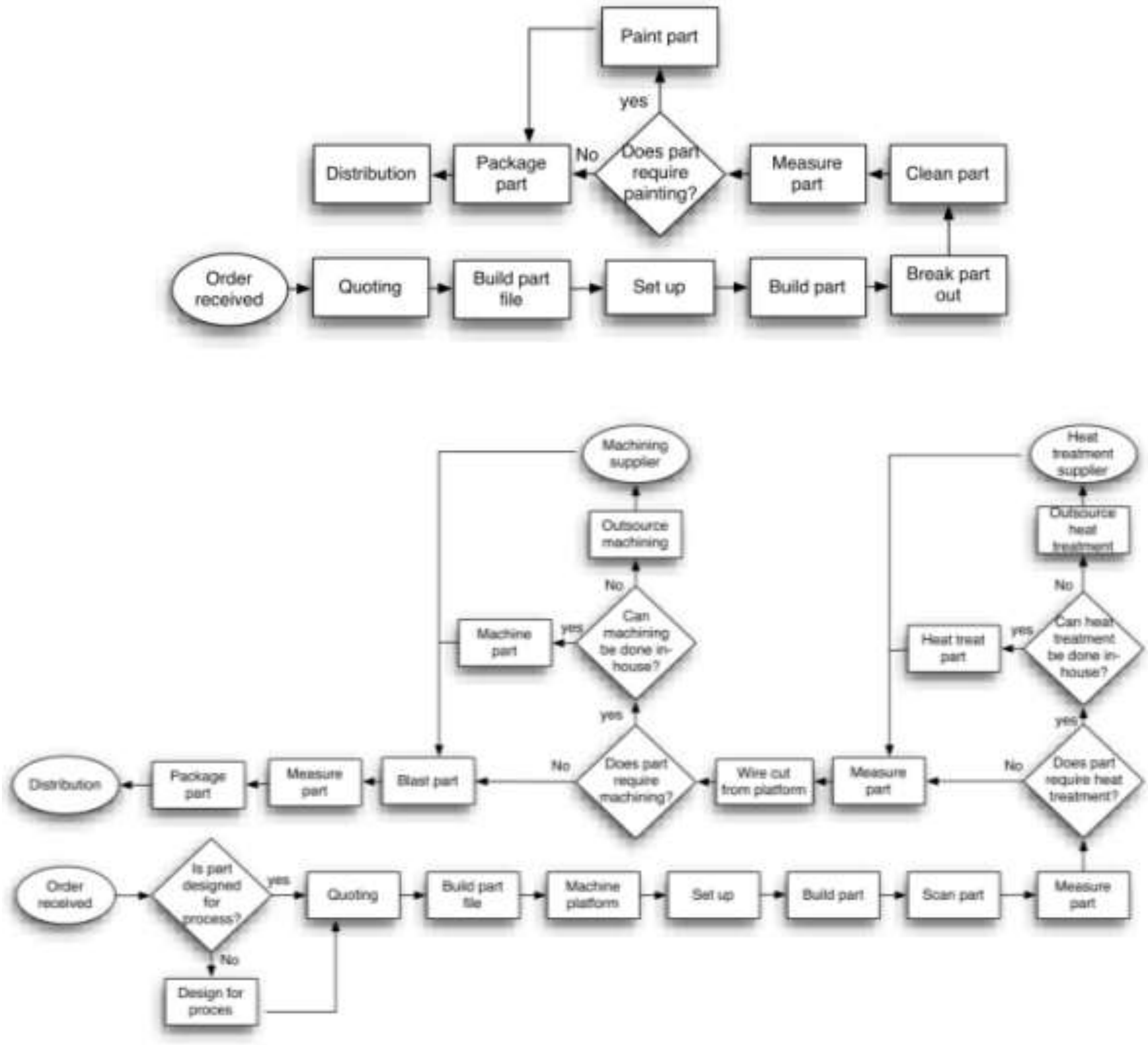

Figure 5.3. RP process chain (top). AM process chain (bottom)

5.2.4.5 Summary of operational factors

Table 5.4 provides a summary of the key issues/activities highlighted through this case study along the operational factors identified in the research framework. This data highlights that for this case study, the implementation of DMLS resulted in a significant increase in the scope and complexity of operational decisions faced by the adopting company. These decisions ultimately determined the systems of operations, and it is these systems that will either build or reduce customer confidence in DMLS as a manufacturing process. Without an existing customer base, and the legacy of RP, it is this confidence that would ultimately lead to the company achieving production applications, high machine utilisation and business success.

Table 5.4 Summary of the Operational Factors at 3T RPD Ltd

Factor	Issues/Activities
Product design	• Product design operations take a significant amount of resource • Quality design for process operations can reduce downstream operations
Production planning and control	• Planning and control activities align with the business strategy • Process unknowns create quality uncertainties and result in expensive inspection and QA techniques • Represents one of the key challenges/opportunities for the RP convertor – to build customer confidence in process and supply
Cost accounting system	• Quotation process highlighted as a time and resource consuming activity due to product re-design requirement and level of post-processing
Integration	• The requirements for integration of the DMLS process into a production system are highlighted but it remains an "island of automation"

5.2.5 AM Technology

5.2.5.1 Benefits and tradeoffs

The CEOs perception of the major benefits of DMLS technology were the whole life cycle benefits, communicating this benefit was one of key challenges faced when educating customers of the real technology benefit. This was reflected in the company's focus on aerospace products where there is the potential to reduce part weight through the design freedom unlocked when using DMLS processes, creating mass savings over the product life cycle. This was also reflected in the company's main in-house capability, design and application development for AM process. The CEO suggests:

> *"....in terms of material usage....particularly with the metals it's very good but you have to go through a high energy process of turning it into powder in the first place, do you really gain a benefit there? It's marginal to be fair. The actual machines are they really efficient at building stuff now? No...In terms of efficiency of use of energy they are not very good at all.....but the real benefit is when you look at the fact that you can produce lighter parts ....That is really where it comes into its own and the fact you can then turn things round faster, you can design things that are closer to doing the job that you wanted to do in the first place but you had to compromise."*

The most significant trade-off for the case company was identified as the machine cost, hindering increasing in-house DMLS capacity. Other tradeoffs identified by the CEO included process cost resulting in high product costs reducing the potential market size of DMLS. Though as the informant stated these are likely to change as the technology matures:

> *"The tradeoffs are constraints in terms of design for the metal parts because of the need for supports....currently limited range of materials but that will change....it's expensive, that will change a fair bit. In fact it will probably become an irrelevance at some point in twenty, forty years time or whatever.....one massive trade-off is the machines are so ridiculously expensive, to buy a half million pound or third million pound machine, that's a big barrier to entry and a company this size to have that, to buy one more machine...that's a nightmare"*

5.2.5.2 Maturity

At the time of investigation, DMLS technology was still in early stages of exploitation, as a production technology and there remained very few examples of production applications. The maturity of the technology presented significant challenges in its acceptance in the target market of aerospace components. Though the informant's view of the true benefit of AM processes is linked to its main R&D focus, developing aerospace applications, the certification periods for this sector meant the company were forced to search for other suitable products in other sectors. This was partly due to lack of technical standards for AM, therefore certification for safety critical parts in aerospace commercial applications will take some time. The maturity of the technology also affected the price of DMLS products and therefore the market size. The lack of industry knowledge, outside of aerospace, also created a challenge in marketing for the case company.

5.2.5.3 Legacy in RP

The legacies of RP system created a number of issues for the case company during implementation. The technology legacy has created a perception of "only good for prototyping" in certain industries, thus creating a barrier to entry for the case company in certain markets. The RP legacy of AM systems also affected the development of DMLS systems themselves, the emerging supply chains, and internally, the organisational culture of the case company. System architectures tended to be flexible, but lacking in process control. This was recognised by system vendors and is highlighted in the "locking down" of process parameters, which although may hinder R&D of the adopting company, may improve process repeatability. However, the effectiveness of this approach may be questioned due to the supply chain issues resulting from the RP legacy. These included the relative decoupling of customers, capacity sellers and machine vendors thus lack of integration, in a prototyping environment this may not have significant effect. However, for manufacturing this lack of integration may result in misalignment between user requirements and technology developments.

Finally, the organisations history in RP, and use of RP systems, has created a culture focused on speed of response and lacking in quality control and understanding of production engineering principles.

5.2.5.5 Summary of technology factors

The technology factors highlighted through the pilot case are summarised in Table 5.5.

Table 5.5. Summary of Technology Factors at 3T RPD Ltd

Factor	Issues/Activities
Benefits and tradeoffs	• Key benefits: - design freedom facilitating weight reduction of component, and related integration of components - Benefit in lack of tooling – turnaround from CAD to part • Key tradeoffs: - Cost of machines (500K Euros) - Cost of production (linked to cost of machine and process speed) - Material range
Technology Maturity	• Production costs remain high • Industry knowledge of the process and capabilities (linked to operations and supply chain) • Market volatility
RP legacy	• Restricting its acceptance as a manufacturing process • Fundamental machine design is not optimised for production • Resulting supply chain fragmentation

5.3 Discussion

In order to assess the framework performance in answering the proposed research questions, the results of the case study are now discussed in view of each of primary research questions on which the framework was based. The key issues along with implementation activities are presented in Figure .

- *What are the key factors in the AM implementation framework?*

From the analysis of the data, based on the number of interactions highlighted, the *lack of an established customer* base for DMLS products presented the key issues for the case company. This characteristic had an impact on all strategic and operational decisions along the implementation life cycle. Without an established customer base for production applications, there were no established product mixes and order winners for products. This resulted in an *emergent approach to manufacturing strategy* being taken, with *R&D activities focused on new product and materials development along with quality improvements* for target applications in the aerospace market.

The lack of established *technology standards* created a significant barrier to entry into the target market; therefore the company looks to other markets. However, *industry awareness* outside of the aerospace markets was low, a market characteristic which heavily influenced the operational activities associated with DMLS implementation at 3T RPD. The competitive knowledge on which the vale offering was based included the technical knowledge on *design for process*; this was related to one of the key *technology tradeoffs*, design constraints.

The company's history in RP dictated the *operational changes* required during the DMLS implementation process. These included the implementation of supporting systems of operation for production. New *production planning* practices were adopted as a result of the increase in complexity of the process chain along with *quality control* activities to achieve the revised product requirements for end-use components. The lack of established customers and therefore product mix was reflected in the level of operational activities around *product design* and applications development. This were targeted at communicating the *technology benefits* and improving DMLS *market acceptance*. The company's lack of *experience* in conventional machining, but experience in design, dictated the approach to product development. Upstream processes were significantly increased, as applications engineers worked with customer to redesign products for process, whereas downstream process were decreased as net shape production through DMLS was considered the target during design.

Along the *supply chain***,** the lack of an established *customer* base, and product mix, restricted the level of *supplier-customer* integration achievable during implementation. Furthermore, machine supplier restrictive practices put a dependency on vendor R&D practices that when combined with the lack of integration of the supply chain; restricted technology development in terms of production readiness levels and market penetration. The lack of competition and volume demand in the powder *supply* chain also restricted machine utilisation due to the relative high cost of materials. *Logistics and distribution* were discussed at some length but the opportunities for distributing DMLS capacity according to demand were soon dismissed due to the lack of an established customer base and the requirements for supportive processes.

- *How do these factors combine with technical factors to form the AM implementation framework?*

One of the fundamental technology characteristics determining the implementation approach at 3T RPD was the perceived unsuitability for prototyping. Unlike other AM technologies, the high equipment costs associated with implementation (including the required finishing tools); along with the relative *immaturity* (short depreciation time), and *technology tradeoffs* (including support requirements) resulted in a less attractive offering to end users in terms of prototype price and performance. In addition, the market for metal prototypes was significantly different to that of polymer prototypes, including the relative high level of *competing technologies* with high speed CNC etc. Therefore, in order to achieve business success *technology factors* have driven the strategic decision to move from prototyping services to production services and ultimately determined the operational activities that the company engages in.

The *benefits* in design, but *tradeoffs* in speed and cost, influenced the decision to target customers with requirements for low volume, high value parts with the potential for life cycle product benefits outside the manufacturing process, i.e. the aerospace market. However, the lack of established technology *standards* created a barrier to entry in markets with high risk of failure.

Customer acceptance of DMLS products, and therefore implementation success, was heavily influenced by the *maturity* of the technology and the case company showed the challenges faced by the RP bureaus with attracting customers with the current technology gaps and supply chain maturity. High production costs, market volatility and low customer awareness influenced the operational activities of the adopting organisation. Interestingly, without its own product line, the implementation of DMLS was based on its leading capability in design for process. As technology matures, and machines become better understood this knowledge gap will undoubtedly decrease, therefore the sustainability of the company RP convertor *business strategy* and therefore its justification for implementation, without in-house product development, may be questionable in the long term. From an industry growth perspective, this is also likely to result in competing interest throughout the supply chain, as companies look to protect the knowledge hard fought in the pioneering years of DMLS implementation, this will likely impact the success of development projects and ultimately technology take up.

The *RP legacy* associated with AM processes (industrial applications) presented one of the key challenges with DMLS implementation, as it resulted in not only gaps in technology development but also increased market inertia of related products. Furthermore, the case highlighted this factor not only affects the downstream supply chain in terms of market acceptance, but also the upstream supply chain which has emerged from its roots in prototyping. Relationships between customers, DMLS users, and DMLS suppliers remain fragmented with a low level of communication and information flow between stakeholders. As identified in the framework, without such integration, alignment between technology benefits and market requirements are likely to be restricted in implementation of DMLS.

- *How do contextual differences influence the implementation process?*

The case company was an SME, with the business *size* restricting the increase in DMLS capacity, and short term financial goals of machine utilisation restricting R&D activities around product development. With equipment cost so high, machine utilisation became a key determinant of implementation success for the SME, one that was only exacerbated by the immaturity and therefore short depreciation times of DMLS equipment.

The organisational context, in which DMLS was been implemented, in terms of structure and culture, was set by the organisations history in RP. The case has shown the conflicting orientation of the organisational culture and the strategic choice of DMLS investment for production applications, due to the workforce experience in an RP environment. Key activities included the CEOs continued communication with employees in re-establishing the values of the company, moving away from purely speed, to awareness of quality and cost control. These cultural challenges and re-working of values and working practices, were accompanied by a high level of operational change, as new production planning, quality control systems were adopted. Being an SME presented benefits in this challenge, as the CEO could directly make changes quickly, and the flexibility of the organisational structure created less resistance to change, but also created difficulties in attracting the relevant skills to the organisation.

The main *skills and experience gap* for the case company identified through this study was in production management, specifically the production experience in metal working processes and aerospace process flow. Originally set up as mirror of the plastics system, the structures continued to change. The company attempted to fill this gap through the sourcing of core staff in the production management role and establishing suppliers for supporting processes outside of internal capacity (vacuum heat treatment etc.).

These activities have helped to capture the required knowledge and experience during implementation. The challenge of changing the customers' opinion of the company's production capability is one which significantly influenced the success of DMLS at 3T RPD. Structural changes have been used to fill the organisations skill and experience gap, but lack of established customer base, failed production applications attempts, indicate that *market perception* remain unconvinced that the technology and/or the adopting organisation were capable of achieving production requirements.

5.4 Conclusions

The pilot case study has presented an account of the experience of a rapid prototyping service bureau implementing DMLS for production AM, firstly, in response to competitive forces, and secondly from the CEO perception of the technology value. From in-depth analysis of the data obtained through this pilot case study, the technology characteristics have resulted in a shift in focus for the organisation from prototyping to production, and it is this strategic response that presented the key issues for the RP convertor and has determined the implementation approach. This analysis has developed further understanding of the relationships between the organisational and supply chain context of the RP convertor, the related strategic and operations decision and DMLS technology. The case study shows that the business, manufacturing and R&D strategy are heavily influenced by the organisations history in the supply of prototypes, and the technology legacy. The findings may provide a decision model for the RP convertor.

The pilot case company has shown to provide some support for the research framework, its constructs and provided insights into the relationships between the variables. During the analysis stage care was taken to identify the reasons for the factors identified; to identify those that may be common characteristic to AM implementation in a certain environment and therefore a source of a potentially more generic solution (improving external validity). Some of the management and implementation challenges for the RP convertor have been discussed along with potential solutions and opportunities.

The scenario investigated in this chapter was that of a company coming from a background in prototyping and implementing AM as a new manufacturing process for production of new products. It is expected that the influence and importance of the framework factors will be determined by the scenario under study. For example, the challenge of changing an RP culture and building a reputation as a production company are likely to be less influential in a company coming from a background in traditional machining and established in an aerospace supply chain. In such a case, the challenges with understanding new design for AM constraints and changing a traditional production culture would likely have greater influence on implementation success.

Limitations of the study include the fact the framework was tested using a single case study. Yin [113] suggests single-case designs may be viewed as vulnerable and Voss et al. [114] also advise that single case research limits the generalisability of the conclusions, models and theory developed. Although these risks exist in multi case research, they are somewhat mitigated and therefore to improve the generalisability of the framework future work is focused on further case studies of AM implementation in different organisational contexts and supply chain scenarios. This is reflected in the research methodology adopted in the primary data collection of this research.

5.4.1. Framework refinement based on pilot study

Based on the pilot study a number of factors have been adjusted, removed and added to the research framework. The refined framework is shown in Figure 5.5. and the motivations for these changes are outlined in the following text.

5.4.1.1 External forces

Based on the analysis of the pilot company, a group of elements which was not highlighted in the research framework was the effect or environmental forces which influence the implementation process of AM. Specifically, these external forces were factors which lie outside the company's control. Therefore, it is proposed they must be considered throughout implementation to determine the strategic or operational response required from the organisation. The external forces drawn from this case study included the following:

- *Competitive pressures:* This case outlined the drivers for implementation came partly from the changes in the RP sector, as RP technologies matured, competition for RP service increased as service bureaus competed with customers internal design houses. A strategic response by the case company was to move to metal systems and focus on production applications. An ongoing task, the analysis of competitive forces also includes an understanding competition from conventional processes. This case has shown that this analysis is not a simple task as the competition for DMLS production include a large array of conventional metal working processes, including high speed machining, casting, moulding and a combination of these processes.

- *Environmental legislation*: the case has shown that one of the key benefits identified for DMLS is the potential life cycle benefits from the new design freedom. Product life cycle benefits are highly related to governmental policy on environmental legislation; new legislation creates further importance on the product life cycle impact of products on the environment, thus the arguments for process innovations which can improve this become more desirable to technology managers.

5.4.1.2 Systems of operations - Quality control

The case study highlighted the quality control challenges with DMLS implementation for production applications. Quality control was shown to be one of the key R&D strategies of the pilot case study. In order to better understand the relationships between quality control with technology and contextual factors, it was proposed as an operational factor in the research framework.

5.4.1.3 Supply chain factors - Location of manufacture

Interestingly, this case showed that the combined impact of technology tradeoffs and lack of an established customer base has resulted in a centralised production facility at a single site. In order to establish whether this factor was purely related to the characteristics of this case study, logistics and distribution was replaced by locations of manufacture. This approach was proposed to focus on answering the question of distributing manufacturing and understand what other factors may facilitate supply chain scenario.

5.4.1.4 Technology factors – AM standards

Along the technology dimension, the importance of technology standards was highlighted throughout this case study, as it was a key determinant of market acceptance of the DMLS products and ultimately implementation success. In order to capture the effect the presence of technology standards or lack of, AM standards was been included in the technology factors as a key characteristic of the framework, determining the operational activities of the adopting organisation and the success of implementation in the supply chain. It was also important to understand at a policy level what standards should be produced and further investigate the key processes in overcoming the lack of technology standards for early adopters.

5.4.1.5 The proposed implementation framework (refined)

Based on this pilot study, the research framework was tested and refined. The refined AM implementation framework is presented in Figure 5.5. The next stage in this research was organising the collection of the primary data to further refine the research framework through a wider study of AM implementers.

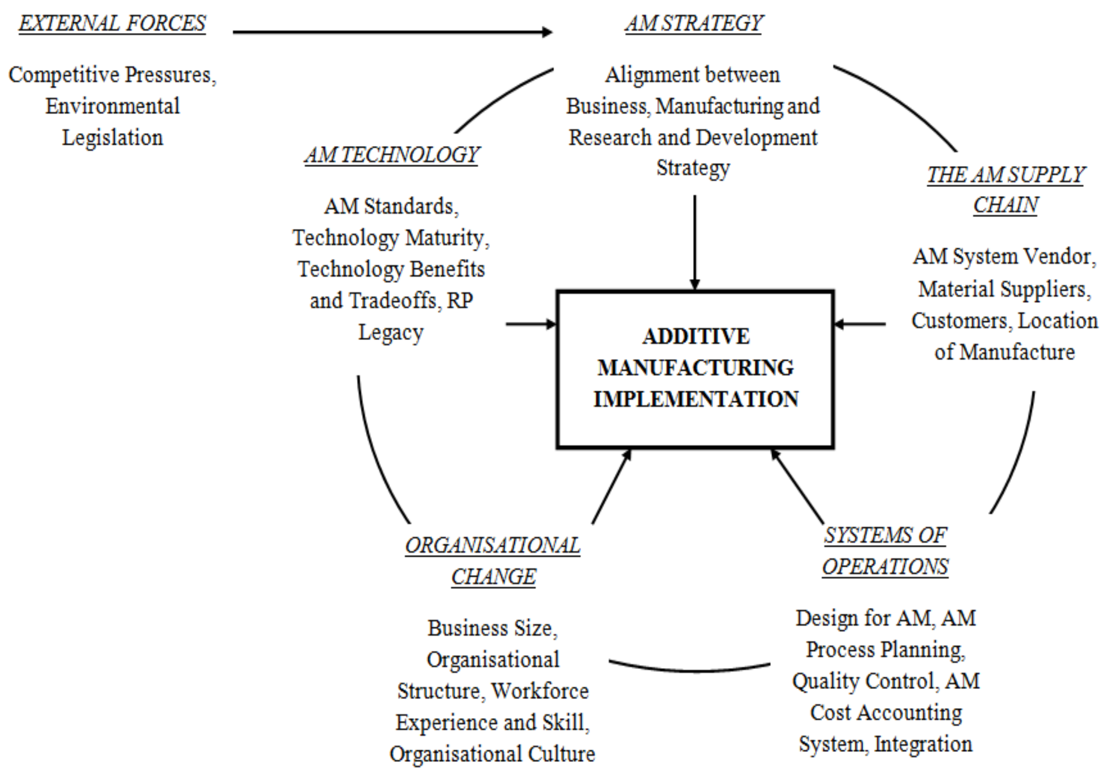

Figure 5.4 The refined AM implementation framework

5.4.2 Research methodology implications

There were a number of lessons learnt during the pilot case study that contributed towards the refinement of the data collection approach, particularly the interviewing method. Firstly, precautions must be taken when discussing sensitive issues. During this case study these included costs accounting, resistance to change and problems in DMLS implementation. Although probing the informants was required to delve deeper into these issues, it was important not to proceed along these paths of questioning in the early stages of the interview, but wait until the informants look comfortable in discussing them. Should the informant suggest verbally, or physically, that they were uncomfortable with the subject of the discussion; the interview must proceed to less sensitive issues. Indeed for this case, the interviewer had much success in probing issues with suppliers and production failures (dental applications); however one area which was not discussed at length was the company cost accounting system. The sensitive with this issue is likely due to commercial sensitivity of this information and the company did not wish to divulge specifics. The approach therefore was adjusted, where questions around the cost drivers and quotation processes were asked, rather than specific questions on cost accounting. This challenge during the interview process was embedded in another lesson learned during the pilot case study, the need for a flexible interview guide. This will ensure that the interview will cover the implementation issues and activities, whilst allowing the interviewer to probe into any emerging issues. Finally, the decision to hold interviews in the informants' place of work was justified, as they seemed more relaxed and comfortable in familiar surroundings, therefore more likely to talk freely about the implementation of AM.

5.5 Summary

The pilot study has enabled an initial understanding to be formed of the AM implementation process in the manufacturing sector using a typical case of the RP convertor. It has led to the refinement of both the AM implementation research framework, and the research data collection prior to the primary research investigation. For the researcher, the experience provided confidence in his approach to interviewing AM project managers prior to primary data collection and has provided an opportunity for his interviewing skills to be enhanced.

The next step in this research is organising the collection of the primary data. The primary data collection took place in four companies. Analysing these organisations will provide a number of emerging AM implementation issues leading to a new framework. These case studies will be presented in the following chapter.

CHAPTER 6

THE MULTI-CASE STUDY: AM IMPLEMENTATION FOR PRODUCTION APPLICATIONS

6.0 Introduction

The multi-case study analysis is presented in this chapter in order to gain a detailed insight into the impact and process of AM implementation in manufacturing organisations. The objective was to identify and refine the framework propositions for the manufacturing organisations who have implemented AM technologies to a stage where production applications have been achieved. Three case studies were investigated, presenting an overview of the AM implementation process in the three typical case classification identified in the research methods chapter. These included the RP convertor, the conventional manufacturer and the new start up. The cases are classified in Table 6.1 below.

Table 6.1. The three typical cases classifications

Company name	Company Size	Technology	Stage of implementation	Informants/ position	Typical case
Renishaw Plc	Large multinational	DMLS, SLS, FDM	Fully implemented SLS and DMLS production applications	[1] RM Manager [2] System vendor, Regional manager	Conventional Manufacturer
Materialise UK Ltd	Large multinational	SLA, SLS, FDM	Fully implemented SLA and SLS production applications	[1] UK Operations Manager	RP Convertor
Reprap Ltd	Micro SME	FDM	Fully implemented FDM production applications	[1] Company Director	New start-up

These three typical cases provide a comprehensive investigation on how AM was implemented in different contexts, and provided the data for identifying similarities and differences in factors influencing the AM implementation. The case study analysis presented in this chapter is the within-case analysis of the three case studies and the chapter is structured as follows; each case study is presented sequentially, following the order of investigation. Each case section provides a brief background to each case company, followed by the data presentation, analysis, summary of the findings and a discussion on the framework propositions. Finally, a summary of the chapter is presented.

6.1 AM Implementation at Renishaw Plc, Gloucestershire

The case company was a large multinational with core skills in measurement, motion control, spectroscopy and precision machining. With offices worldwide its production facility in Gloucestershire carried out all manufacturing operations. It is at this site the interviews for this case study were held. The main informant for the case study was the Rapid Manufacturing (RM) Manager, leading the RM department, whom has also been a key figure in the AM industry often speaking at conferences and trade shows.

The RM department supported all streams of the company’s manufacturing operations and product development also running a production facility for dental products using DMLS. It is this DMLS production application and implementation project on which the data collection focused for two reasons. Firstly, the informant was defined as the project champion. Secondly, it represented the most significant AM production activity at the company when considering production volumes.

However, the company had a number of production applications in SLS and this investment was identified as being a key activity during the implementation process. Therefore, this technology implementation was also used to support the case definition and understand the process of AM implementation. The case company may also be described as a system vendor, following its acquisition of SLM system vendor, MTT Ltd. Again, this was identified as one of the key activities in the AM implementation process for the large multinational during the investigation and was therefore included in the data collection.

6.1.1 AM Strategy

6.1.1.1 Business Strategy

The company’s main business in terms of percentage of activity was the development of CNC and CMM (co-ordinate measuring machine) machine tools. The antecedents to implementation were identified in the design and production of scanning machines and probes. Due to its expertise in metrology and inspection, the company was approached by a customer requesting a single tooth scanner for digitising a single dental coping. The development of these products provided an entry point into the dental market. Eventually, the company developed their own scanning technologies, including a system to scan whole bridges and maxillofacial bones.

With a presence in the dental market the strategic decision was taken to manufacture zirconia crowns and bridges, turning the scanning platform into a manufacturing platform, replacing the scanner with a cutter thus providing a CAD/CAM solution to the production of dental copings. This approach resulted in the company becoming established as suppliers of ceramic copings to the dental labs.

The strategic decision to move into metal copings production was driven by market demand. In the UK the ratio of metal to ceramics copings is around 9:1 (including other non-precious metals not only cobalt chrome). The informant suggested this market characteristic being highly dependent on the country; in the US for example, people are prepared to pay premium price for ceramics. Considering these market demands, the company then assessed the available technologies, evaluating a number of alternative, and finally selected DMLS as the process choice.

The DMLS dental production process chain was defined by the informant:

- Dental labs create 3D model of dental implant using digital scanners and specialised software (may choose to use Renishaw scanners and software).
- Model is sent to Renishaw facility with patient identification number
- Specialised software is then used to generate supports and include patient specific identification
- File is prepared on the DMLS system software
- DMLS processing and part removal
- Short stress relieving cycle and removal from built plate
- Removal support structures and grinding of surface by hand
- Packaging and sent to dental labs for finish machining.

Figure 6.1 Dental copings produced at Renishaw on DMLS M270 (courtesy of Renishaw)

6.1.1.2 Manufacturing strategy

The rapid manufacturing department at the case company had existed for seven years, primarily supplying electronics prototyping. The first steps in AM began with the investment of FDM machine. This provided a low cost entry point for the company to enter AM. The next for the case company was investment in SLS, this was at a much higher costs, but the justification for investment was the opportunity for running production of small polymer components i.e. applications beyond prototyping.

Finally, the company invested in a DMLS machine, as general use machine with the intention of eventually producing dental copings. The motivations for investing in DMLS rather than casting included:

- DMLS facilitates the production of many different parts on a single machine at any one time so the potential throughputs are higher than casting.
- DMLS is highly automated reducing the potential for human error.

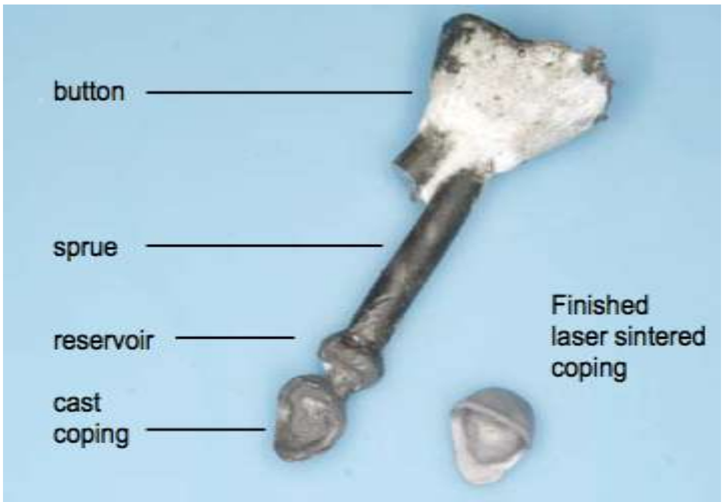

Figure 6.2 Comparison of dental copings produced via casting and DMLS (courtesy of Renishaw)

In April 2010, DMLS was commissioned for production of dental products, cobalt-chrome copings and bridges. With one DMLS machine running each evening the production volumes for average around 120 units a day (a 12 unit bridge defined as 12 units, a single coping as 1 unit).

It took 3 months for quantities to reach break-even point and although the growth began to slow, volumes did not drop below the break-even and it is considered a financial success. Such a success has demonstrated that the company has implemented appropriate AM strategy to align its business strategy. Although their in-house core-capability remained in CNC/CMM technologies, their experience in dental production and market know-how led to a successful implementation.

6.1.1.3 R&D Strategy

The case company’s business model relies on new product innovation and the creation of new patents. As market leader in these high technology markets, the business drive the technologies forward protected by patents.

The RM department provided open access equipment to the organisations various design teams, allowing designers to produce prototyping on demand using AM processes such as FDM and Inkjet. Workstations such as SLS were perceived to be too highly skilled for designers, so the RM team ran them once or twice a week depending on demand.

The SLS machines were used for both prototyping and production, around 80% to 20% respectively (with 50 or 60 parts a week in total). The percentage of production to prototyping was steadily increasing. For the case company, the SLS process lends itself to running both production and prototyping together (see technology factors). With smaller production parts packed around larger components, production components were made available on Kanban supply and shipped on request. The mix of parts for SLS varied week-by-week such that scheduling was not performed weeks in advance, instead capacity was made flexible to prototyping needs.

Table 6.2. Summary of AM strategic issues and activities at Renishaw

Factor	Issues/Activities
Business strategy	• Business strategy based on protecting novel products and processes • Established in dental market with scanning and milling processes • Decision to enter metal dental market due to market demand
Manufacturing strategy	• Introduction of AM through a step-by-step approach. Low cost entry of prototype system to high cost dedicated metal production machine. • Dedicated production of dental copings justified through productivity and quality improvements. • Flexible supply of production/prototyping in SLS facilitated through process characteristics
R&D strategy	• New product development facilitated by open access to designers and ease of use of FDM and Inkjet machines. • Development teams focusing on applications development

The findings in the case show the experience of a large company with a formalised R&D strategy based on the protection of new product innovations. The case supports the framework proposition that successful implementation is preceded by identification of the market needs and matching of technology benefits with this need.

The fact the machine was purchased as a general use machine and then dedicated to dental production supports the combined market-pull and technology push strategy as identified in the framework [126]. The implementation of DMLS enabled the company to capture new market opportunity, and the investment was matched to the demand ensuring high utilisation of DMLS in line with the framework proposition [180].

The case also showed how higher utilisation and manufacturing agility can be achieved through combined SLS manufacture of Kanban supply production components and one-off prototypes. A strategy not originally identified in the framework, this finding supports the prediction that AM may be identified as both a lean and agile manufacturing technology. This has been identified in part by Tuck et al [20], though they did not consider how this could be supported through prototyping and production. This case has shown how in practice how and which AM technologies can support this strategy. The case also shows the successful implementation for production of customised products, supporting propositions made in previous works by Tuck and Hague [18, 19].

6.1.2 Organisational change

6.1.2.1 Size & Structure

The rapid manufacturing development team at Renishaw was composed of ten team members with experience in manufacturing engineering. The informant had been at the company for over twenty-five years and had led the department for seven years. With a background in CNC machining; he described himself as a manufacturing engineer. The team had been set up as follows:

1. Model maker and engineer
2. CNC machinists
3. Injection moulding designer
4. Development engineers
5. Laser expert and electronics
6. Manufacturing engineer

This structure showed the team members experience and skill was in conventional processes.

The department had a vast number of AM equipment in-house. Low cost systems, such as FDM, were used by designers with minimal training. The SLS and DMLS systems required higher skill requirements and were therefore used by trained staff in the development team.

The use of DMLS and SLS as general use machines allowed the company to capture knowledge of best practices throughout the implementation process with vendor training used where necessary. The informant stated that vendor training was required most during the certification of the DMLS dental system, as it was dedicated to dental production.

6.1.2.2 Culture

Described by the informant as a cultural clash, the company were still going through cultural challenges of AM implementation during the case investigation. It was defined as a clash between technology enthusiasts, those at the company who believed everything should be made through AM as you *"can make whatever you want"*, and those that believed it is only suitable for prototyping, the *"only good for prototyping"* group. This cultural clash was made worse by the hype surrounding the process (described in technology factors).

The informant emphasised the need for a culture of understanding:

> *"AM is another alternative, which fills in the gaps that conventional manufacturing leaves behind, so things like medical parts where every part is different or in aerospace where there is a need for highly complex or lightweight structures and value is added through the reduction in fuel costs."*

It was the informants view that if there were to be factories of AM machines in the future, they would likely only be service bureaus specialising in AM; they would not make other technologies obsolete. A key challenge highlighted by the informant was the challenge of technology mapping, as the business case for AM was continuously changing over time as process tradeoffs reduced (linked to the technology maturity).

The informant stated the cultural clash came partly from the lack of technology understanding and partly from the legacy of the way engineering has developed around the processes that are available. The example was given of injection moulding compared to AM, where injection moulding parts could be produced at very low cost at high volumes after high initial investment. These models did not apply in AM where the initial investment was not there but the high cost is, and as volumes increase costs do not necessarily reduce. This is in line with the conclusion of Ruffo et al [17]. This had implications in AM part suitability, as the case for AM was not solely based on the cost per part, but also considered the value added of the operational quantities.

Table 6.3. Summary of organisational issues and activities at Renishaw

Factor	Issues/Activities
Size	• The company was a large multinational with experience in CNC and an established customer based in machine tool and dental markets.
Structure	• The structure of the team largely remained the same with supplier training used to fill workforce experience and skill gap in DMLS. • Dedicated dental production with product design automated through supportive software reduced the requirement for education of design for process. • Experienced in conventional processes and dental production
Culture	• Cultural clash between AM evangelists and cynics. • Education used to change culture based on educating employees as to where AM “fits in” with other processes.

The size of the organisation was identified in the research framework as a key organisational characteristic, with the proposition that it would result in a more formalised approach to implementation [154, 172]. The staged approach to technology introduction, and the business needs assessment at each stage, supports this proposition.

The structure of the company largely stayed the same through the implementation process with vendor training used at the certification stage. Importantly, the development of tailored software tools reduced the training needs in design-for-process. This finding identified the details of the relationship between structural investment in software and the requirements for organisation change, identified in the implementation framework.

Finally, the framework proposed organisational culture as a key determinant of implementation success [149, 150, 173]. Organisational culture was identified as one of the critical issue faced by the project manager, suggesting education and training on technology benefits and tradeoffs as the key activity.

6.1.3 AM Technology

6.1.3.1 Standards compliance activities

Standards compliance in the case study was most relevant to the DMLS system implementation when it was converted to a dedicated dental coping production machine from a general use machine. The cost for training and software was estimated at €20,000, followed by a cost of €40,000 for decontamination of the machine hardware including filtration system. The company then went through the design plans and certification for ISO13485 compliance. As the company already had ISO13485 compliance for zirconia implants, it was effectively a repeat exercise making the process easier.

6.1.3.2 Benefits and Tradeoffs

The case company identified the benefits of SLS, maximising the build envelope by building parts on-top of parts, as supports are not required (see operations). For production work in DMLS, the machine was confined to a single material to avoid cross–contamination of materials, restricting the capability to produce parts from other non-precious metals for dental.

The informant identified one of the key issues with most AM process; tolerances being a function of the size of the part due to the thermal cycle. Components were therefore stack in build chambers according to defined tolerances, with best practices identified to reduce the distortion of components and therefore quality issues.

The case highlighted the design issues for larger parts in SLS and DMLS, fundamentally different from CNC and injection moulding. The informant described the issue during implementation when designers request tolerances of a machine. Traditionally, production staff would provide an answer such as *"plus or minus twenty microns"*; instead the answer in AM production is, *"it depends on the part*". Renishaw's focus on dental DMLS mitigated this trade-off to some degree, as the process lends itself to dental due to the small component size.

The success of dental DMLS was driven by the cost savings of removing people from the process, when compared to traditional processes. For dental coping production, DMLS was competing with casting and as many dental labs had investment casting in-house, they were used to very short lead times. These lead times could only be replicated through DMLS. The benefit of using DMLS was removing people from the preparation process and that was where the cost advantage was made. There was also a quality improvement, improving consistency through removing potential for human error.

6.1.2.3 Rapid prototyping legacy

Through the process of DMLS implementation the informant discovered one of the major technology related issues; the fact that the platforms were basically prototyping platforms and not designed for production applications. This was has one of the key motivations for the company to vertically integrate and become a machine vendor (see supply chain factors).

The company had to overcome the perception of being seen as a prototyping team following implementation of DMLS. Changing this perception and building credibility as a production team took time and influenced the operational activities required post investment (linked to operations).

6.1.2.4 Technology maturity – hype vs reality, managing expectation

In this production environment the informant suggested the claims of *"one off production with AM"* fall down. In reality, although the production team could use their knowledge of design for process and get a sensible guess of part quality, the technology characteristics resulted in the requirement to build a sample component for measurement and inspection. The team would then compensate with build parameters or, more desirably, the design file (STL) so that build parameters were not continuously changing.

Beliefs such as *"manufacture-for-design instead of design-for-manufacture"* and *"complexity for free"* also existed amongst designers at the company and beyond. The informant suggests these beliefs ignore post-processing and material properties, consideration particularly important in metal AM. Also cost, manufacturability, yield rate and other production engineering considerations are still implied at the design stage. Education was key to managing expectation during implementation.

Table 6.4 Summary of technology issues and activities at Renishaw

Factor	Issues/Activities	
Standards	• Standards compliance for dental DMLS came at a very high cost • Requirement for the machine to be dedicated to a single material and product	
Benefits and Tradeoffs	• Key benefits – DMLS: - Cost (removal of people) - Quality improvement - Speed of delivery • Key tradeoffs – DMLS: - Tolerances are a function of part size - Material inflexibility - Requirements for supports (unable to stack parts) - Requirements for dedicated production system	• Key benefits – SLS: - Ability to run production and prototyping on the same machine - Process flexibility • Key tradeoffs – SLS: - Tolerances function of part size
Maturity	• Maturity of the technology resulted in unknowns on process results • Managing expectation was a significant challenge	
RP Legacy	• Operational and supply chain activities influenced by prototyping legacy • Industry hype and technology perception hindered organisational change	

The case showed the importance of technology standards and thus supports its inclusion in the implementation framework. Furthermore, the case identified the relationship between technology standards and operational systems. In this case, for dental application, not only the AM technology and material but the whole process chain was assessed.

In this case the project manager clearly understood the technical benefits and tradeoffs of the various AM processes and linked them to defined application requirements and business opportunities [126]. The high level of fit between DMLS and dental production was a significant factor in the success of implementation. As identified in the research framework, and supporting the claims by Munguia et al. [58], technology maturity results in a lack of standard working practices. However, the case also confirms Munguia et al.'s findings that best practices can be adopted to predict part performance and process results. Furthermore, the case added to the understanding of best practice for DMLS and SLS technologies.

The case supports the framework proposition that the prototyping legacy hinders acceptance of the technology as a manufacturing process. The case shows evidence that production engineers and designers will likely sit in two separate camps and require different approaches to education and training.

6.1.4 Systems of Operations

6.1.4.1 Design for process

The informant highlighted in order to utilise the possible advantages of additive over subtractive manufacturing, all of the production engineering consideration were included at the design stage. For dental DMLS, implementation was preceded by the development of design tools to automate the design of the customised copings.

For other product lines, the organisation developed best practices for the initial design stages of AM production. This began with the initial assessment of whether a part was suitable for AM with component size used as an initial indicator of whether the component was suitable. Following this initial review two questions were posed to the designers:

- *What is the part for?* This would dictate the material requirements, surface finish and therefore the amount of post-processing.

- *How many are required?* If quantities were high then it is likely that traditional processes may be more cost effective.

This approach reflects the cultural change occurring at the organisation, the education of staff of when AM is the correct process choice.

6.1.4.2 Production planning and quality control

In the case of DMLS production the case company employed the same production controls as used in their manufacturing service division. For example, they used the same ERP system, quality controls and quality recording systems as their manufacturing services division. The company also had in-house software, tailored CAD packages, and automated planning and costing.

The informant also stated that when moving from prototyping to production, the design guidelines became key to the productionisation process. The example of build orientation was given. If a component was built mostly in an x, y orientation during prototyping, then production was changed to a z orientation for cost savings, designer must be aware that the component properties would change.

The issues of quality control were tackled in dental production though a number of activities. Related to the technology factors, the company achieved a number of quality control standards. As the parts were relatively small, thermal distortion was also less of an issue and for larger parts (bridges) stress relieving was used.

6.1.4.3 Integration – the standalone DMLS system

The company supplied their own software and scanning equipment to the dental labs and this integrated solution automated the part design. However, post processing remained a relatively piecemeal and antiquated process. Supports were broken off with pliers, with component then hand ground, bead blasted and sent to customer. The informant highlighted that for what is supposedly a "*high tech and very expensive system*", post-processing remained an issue.

Table 6.5 Summary of operational issues and activities at Renishaw

Factor	Issues/Activities
Design	• Software and scanning tools automate the design process. • The advantages of low cost AM systems facilitated open access to designers and speed up product development. • For production applications, design for process was highlighted as key to understanding suitability for AM (linked to technology factors) • New production engineering rules must be understood at the design stage (cultural changes) • Best practice was to change design not the process parameters.
Production planning	• Production planning and control systems transferred from manufacturing service division.

Quality control	• Design for manufacturing guidelines identified as key to quality control • Matching product and process reduced quality issues i.e. small parts for DMLS • Software tools with design for process guidelines coded used to automate process of file preparation
Integration	• Highly integrated downstream processes • DMLS system itself remained standalone • Antiquated support removal process

The case has shown support for the inclusion of all of the operational factors identified in the framework. The prior development of AM design software and scanning technologies to automate designers process was key to success. Matching product and process has significantly reduced quality issues for the case company supporting their inclusion in the framework and providing an understanding of their relationship.

The case shows that production planning and control was transferred directly from the manufacturing service division. This suggest that once the process chain is relatively well defined, and if the product characteristics are similar to the conventional design (in this case the similarities with zirconia copings), operational change is reduced.

The proposition that integration would be a key factor in successful implementation was supported by the efforts the project manager placed on integrating downstream design processes. The case findings suggest further developments on integration should be the focus of future machine and production developments, integrating post-processing and materials handling.

6.1.5 AM Supply Chain

6.1.5.1 AM system vendor – vertical integration

With a history in metrology and inspection tools, the company had the ambition to become a machine manufacturer for a number of years. However, the company had no desire to be a "conventional" machine tool producer for two reasons:

- The market is flooded with machine tools and not suited to a business model based on patents and protecting new products.

- The company's major customers are machine tool suppliers, for probing and accessories for CMM. Therefore, to become competitors of their customers would likely affect future business for these products.

In terms of AM, none of the big AM companies were customers; indeed they were suppliers. Further, the company also believed there was significant potential in developing a production AM machine, rather than prototyping system and in doing so develop valuable patents. These factors combined as the motivations for the acquisition of MTT and justification for vertical integration.

At the time of enquiry the acquisition of MTT had only recently occurred, as such the informant provided the proposed relationship between the two sites and the opportunity for machine development. Renishaw would work towards process development and MTT would maintain hardware and materials development. Through building benchmark tests for customers, the company would take order request from customers, inspect parts and decide whether the customer should buy the machine or not. Renishaw would also develop the process and design guidelines for the customers, in terms of orientation and establish the costs, build parameters, repeatability etc and assist the company in the make-or-buy decision. The feedback of customer requirements and process improvements into MTT hardware, materials and machine development programs was seen to be the key opportunity for competitive advantage.

6.1.5.2 Powder suppliers

With sympathy for the material suppliers, the informant proposed development costs combined with low volumes as the reasoning for restrictive practices. The informant suggested powder suppliers must recoup development cost at low volumes resulting in high costs per kilogram.

> *"As machines become more and more common, then the volumes go up so the rate at which they recoup their development cost come down so they can then lower the R&D return per kilo."*

The informant also suggested that restrictive practices by suppliers were slowly disappearing and gave the example of SLS, where there were a number of companies supplying SLS powders that were not SLS machine manufacturers. As this continues the costs will reduce, but as the informant suggested it needs those quantities of machines and quantities of uses to drive this effect, in line with theories of economies of scale and propositions made by Hopkinson et al. [60].

6.1.5.3 Location of manufacture

The company distributed products to customers in Europe though most were in the UK. As their DMLS machine was not running at full capacity, they could serve their European and UK customers from their current facility, and therefore did not see the need to distribute production. Should demand grow to sufficient levels, the informant suggested they would consider locating other plants to serve local markets.

Table 6.6 Summary of supply chain issues and activities at Renishaw

Factor	Issues/Activities
Customers	• The company was already established in the dental supply chain, with a customer base for zirconia copings. • Internal customers were given open access to non SLS and DMLS systems
Suppliers	• Supplier practices were understood by the informant • Restrictive practice were slowly disappearing • Higher level of communication with machine supplier at the production certification stage • Vertical integration through acquisition of machine tool suppliers
Location of manufacture	• Centralised production facility as demand for DMLS dental did not justify distributing production. • SLS centralised to allow trained personnel to run both production and prototyping for both internal and external customers.

The case shows the experience of a company established in the dental supply chain with the capacity to develop integrated software solutions to capture user requirements and exploit AM benefits. Education of internal customers of technology benefits was assisted by the open access approach. These findings support the framework propositions and identify relationships between the technology and supply chain constructs. The case highlights the changes in the AM supply occurring as technologies mature and supplier restrictive practices begin to disappear.

The vendor involvement at the certification stage supports its inclusion in the research framework and provides an understanding of the level and timing of vendor involvement [167, 169]. Furthermore, the case shows the potential for the implementer to improve vendor integration through acquisition of machine vendors and vertical integration.

The case supports Walter et al.'s [59] conclusion that centralised AM will likely be the first to be used due to the level of demand and capacity utilisation (made more relevant for relatively expensive AM processes such as DMLS). One of the key findings of the case is the SLS process supporting a centralised production/prototyping serving both internal and external customers. This finding adds to the understanding of the framework constructs and relationships between the technology benefits and supply chain practices.

6.1.6 Summary of case study

The case study has shown the implementation approach at a large multinational, with an established customer base and expertise in conventional CAM and CMM processes. These characteristics of the case company are used to define the case as the typical case of "The Conventional Manufacturer". The case also shows the successful implementation of a metal powder process combined with scanning and software tools to provide a mass customisation alternative to conventional casting and machining processes. The case is now summarised according to the main research questions.

What are the key factors in the AM implementation framework?

The key factors of AM implementation at Renishaw, include the company already having a presence in the dental market and therefore the presence of an *established customer base* in the dental supply chain. The *history in CNC and CMM* also significantly influenced the approach to AM implementation. The *size* of the organisation resulted in a more *formalised stage approach to implementation,* driven by the technology *benefits and tradeoffs* of the various AM processes. The stage approach shows changes along each of the constructs as implementation moves from pure *prototyping in FDM*, to *dedicated production in DMLS*. Key activities included *education and formal training of staff* for production processes including SLS and DMLS with a higher skill requirement. Dental DMLS required *expensive certification* activities and a *dedicated machine* and *high quality control* requirements.

Termed by the informant as a "*cultural clash*", the presence of a clash of beliefs affected the process of implementation negatively. The cultural clash was between those who held the belief that AM was only good for prototyping and those who believed AM should be used for everything. *Education and training* of where AM could "fill the gaps" other processes left defined the cultural change strategy during implementation.

Other cultural challenges affected the *operational* activities during the implementation process. These included the definition of *new design guidelines* and *best practices,* fundamental rules which contrary to conventional understanding. These operational activities included the development and use of software tools to automate the *design and fixturing (i.e. support generation)* processes.

Key activities along the supply chain included the acquisition of a machine vendor, therefore *vertical integration* activities. *Restrictive material supply practices* were slowly disappearing but still caused some issues in implementation. The increased vendor support at the "productionisation" stage of dental DMLS was used to *transfer knowledge and certify the process*.

How do these factors combine with technical factors to form the AM implementation framework?

The stage process of implementation was largely driven by the benefits and tradeoffs of the individual systems. Low cost FDM machines provided a *low cost* introduction to AM but *mechanical properties* and *surface finish* restricted their use beyond prototyping. SLS presented opportunities in running both production and prototyping facilitated by *high process flexibility*. Implementation of *DMLS* production presented *benefits* in individualised production, *with cost and quality improvements* over conventional casting processes.

The case highlighted the issues both up- and down-stream of the DMLS production. The company's experience in *scanning technologies and software development* enabled them to automate the design and file preparation process. However, finishing processes remained labour intensive and costly. In DMLS production, the process flexibility was significantly reduced to ensure part *quality* and *standard* conformance as the machine was restricted to a single material and product line.

Both *technology maturity* and the *RP legac*y influenced the approach to implementation defining AM acceptance both in the organisation and the supply chain. *Education and training* on technology benefits and tradeoffs have been used to bridge the gap internally, with *production planning*, *quality control* and ultimately *process certification* used to improve customer acceptance in the dental supply chain.

How do contextual differences influence the implementation process?

As a *large multinational* company with a history in machine tool inspection and metrology products, this facilitated the supply chain decision of vertical integration. The size and established *products mix* reduced the financial barriers to implementation and *the technology barriers in the supply chain*.

The *size* of the organisation resulted in a more formalised stage approach to implementation and a high level of resistance to change in both *design* and *production engineering functions*. The company's *experience and skill* in CNC and CMM enabled them to adopt production planning and control systems from its manufacturing service division. To illustrate the stage approach established at the case company, a model is presented in Figure 6.4. The model shows how activities and issues are encountered across each construct of the framework and each stage of the process.

Stage 1: Introduction to Additive Manufacturing	
Technology	Investment in FDM capacity provides a low cost entry point. One-off prototype applications. High process flexibility. No requirements for standards conformance.
Organisation	Lower skill requirement provides opportunity for open access equipment to designers. Creates a culture of speed and flexibility.
Operations	Solely used for prototyping. Open access, no production planning inputted. Little if any design for process knowledge required. Standalone systems no integration.
Supply chain	Products remain in-house, customers are internal design house. Centrally located capacity. Raw materials cost can be high due to supply restrictive practice.

Stage 2: AM for prototyping and manufacturing applications	
Technology	High capital investment in expensive SLS and DMLS capacity, as general use machines. Retains some process flexibility. Inadequacy of CAD to capture benefits of RM applications.
Organisation	Process is less user friendly and requires highly skilled operators. Not suitable for open access to designers. Cultural clash between extremists.
Operations	SLS System characteristics allow it to be used for both prototyping and production technologies. Production parts require design for process. Production planning must remain reactive to prototyping needs. Quality control issues become relevant. Due to high product design variety in process, integration not possible. For RM products process design rules and production engineering principles must become educated to workforce
Supply chain	Both internal and external customer. Process parameters for materials must be acquired from machine tool supplier. Slow disappearance of supplier restrictive practice.

Stage 3: Production Applications	
Technology	Investment in expensive equipment, DMLS capacity. Dedicated to RM application. Dedicated to a single material. Loss of process flexibility. Cost becomes important as competing with conventional processes. Standard conformance becomes greater concern. Process certification must be performed at high costs.
Organisation	Production application requiring trained operators on a certified process.
Operations	Dedicated to production of single product. Production planning and control systems in place. Integration within manufacturing process chain required, however current AM system remain standalone.
Supply chain	Supplier interaction increases as quality control and process complexity increases. Vertical integration as company enters the machine tool supplier market. Centralised manufacturing facility.

Figure 6.3 AM implementation stages at Renishaw

6.2 AM implementation at Materialise UK, Sheffield

Materialise UK were the second case study conducted in the main data collection stage of this thesis. The company had been established in the AM industry since the early years of SLA, specifically in supplying AM software. The company offered software solutions in a variety of markets and manufacturing services for polymer AM prototypes and volume production. The case was chosen to represent the typical case of the RP convertor, differing in its offering to that of the pilot study due to its history in RP software products and current established product lines for production components.

The informant at the company was the UK operations manager of Materialise UK, located in Sheffield. The researcher also visited the company's head quarters and production site in Leuven during the Materials World Conference, 2012.

6.2.1 AM Strategy

6.2.1.1 Business Strategy

The case company was founded as a spin out from the University of Leuven, Belgium. With the largest capacity of AM systems at its site in Leuven, it was the market leader for AM supporting software, known as Majics. As the company grew significantly during the last decade, it became a group, split into a number of business units specialising in distinct areas of AM.

It is the pioneering software technology which provided the company with a significant competitive advantage. The software performs the file preparation, STL file repair, model slicing, build simulation and support generation, thus providing the control required for manufacturing applications. As the informant suggested:

> *"Everything is driven by our software, it's a fundamental part of it…our research projects, our links with…all the Universities and industry...are driven by our software, we can make the machines do what they need to"*

This focus on software enabled the company to not only retain competitive advantage and protect future business, but also had significant effect on the operational and administrative activities during implementation. The founder's vision for the technology and company, along with the technology benefits and tradeoffs determined the types of products and markets served by the Materialise group. Software remained the majority of the Materialise business with AM component production a small portion of the company turnover.

Split into a number business units, as of January 2013, the company consisted of seven business units. The informant suggested this allowed the company to better serve its diverse range of customers with a dedicated team and solutions in the fields of:

- jigs and fixtures systems
- Software support
- Orthopaedics (surgical guides)
- Dental
- Biomedical
- Art and technology
- 3D printing community including platforms for sharing and development of product designs

The company implemented a large number of polymer systems including as SLS, SLA and FDM, furthermore developed a large SLA machine in-house known as the "mammoth". These large SLA machines were used for the production of consumer products including high value lighting, along with large prototypes (both size and volume) facilitated by large build volumes.

The company at the time of enquiry had only worked in polymers, but had the ambition to move into metals AM through its core skills in software. It also had targets of doubling the number of staff and turnover in the next two years.

The informant summarised the position of the company in the industry:

> *"…the biggest problem Materialise in the UK has got is low profile. We're seen as a software company who makes Majics, but realistically if we got our act together we could blow out all these other companies apart. For a start they all use our software, they need us, they subcontract a lot of their work to us anyway. A lot of the companies that you see around send projects to us anyway.*

6.2.1.2 Manufacturing Strategy

The percentage of prototyping (RP) to manufacturing (AM) across the group was around 70% and 30% respectively. However, certain business groups were defined as pure manufacturing. In terms of AM processes, the company had the largest capacity of FDM machines in Europe with 30 in its manufacturing site in Leuven. These systems were predominantly used for prototyping as the informant suggested with surface finish seen as the reason why these processes are not suitable for production.

The mammoth SLA machines developed in-house were not sold by Materialise. The systems were used in-house for a number of artistic product applications, including high value lighting at volumes around 15 units per day. Further to this, the company had another 40 SLA machines of varying sizes. The company did not have any metal machines with a definite focus on polymers, with the informant suggesting that the metal process "*are still too immature*". However, the company did have ambition to work on the software side of metal machine development, targeting control software for metal machines with multiple lasers.

6.2.1.3 R&D Strategy

With a central R&D facility, regular strategy meetings between business unit managers were used to refine company strategy. The company strategy was heavily based on the continuous launching of new processes, new materials and new products. Research and development activities were moving towards metal AM systems software tool development. The informant suggested with such a scope for areas of development, one of the main challenges was prioritising which areas to focus research and development effort.

Table 6.7 Summary of strategic issues and activities at Materialise

Factor	Issues/Activities
Business strategy	• Split into a number of business units serving different markets from prototyping through tooling to production. • Continuously launching new products, materials and technologies. • Products and markets served by the company driven by the directors view of technology benefits. • Issues with being seen as a RP software company.

Manufacturing strategy	• Focus on polymer machines with large capacity of SLS, SLA and FDM. • Operations and technology adopted were highly influenced by their antecedents in software. • Combined prototyping and production product mix. High variety and short product life cycles.
R&D strategy	• Continuously launching new products, new materials and product. • Growing interest in metals.

The case supports the implementation framework proposition that organisation must align the technology benefits with the business strategy of the company. Specifically, the case shows how the flexibility of polymer processes has supported the diversity of the various business units. Through the in-house core skill in software development, the company has captured the technology benefits and developed a diverse offering for different market requirements. Again, the company followed a combined top-down/bottom-up approach to strategy formulation, where market requirements were matched to technology benefits.

The company's focus on research and development, particularly the focus on new product introductions supports the proposition that AM processes should be seen as a process innovation facilitating product innovations and it is through this approach business success may be achieved.

6.2.2 Organisational Change

6.2.2.1 Size

In terms of company size, the number of employees grew rapidly in the seven years prior to enquiry; the case company has grown from around 500 employees worldwide to over 1000. As a privately owned company, the directors at the case company were the original inventors who developed the company's core software technology. To cope with this growth each office acted effectively as a separate company with a director and staff from various business units.

6.2.2.2 Organisational Structure

As UK operational manager the informant had been at the company since 1997 and over that period the company experienced significant change. The informant's previous experience was in engineering, working at a technology centre funded by the government. The team at the site consisted of 12 members all from a RP background. The team composition included engineers and other technical staff with a background in AM:

- applications engineer
- software service and salesmen (of a technical nature)
- biomedical engineers,
- admin staff,
- sales consultant/application engineers type people.

Attracting the right skills and experience of employees for their changing company was the key challenge for Materialise. The informant explained:

> *"…we are always having trouble seeking employees…we are now evolving in to a production company (so) they need to understand the production side of it and the engineering side of it and you're making such a step change in the way that people do things you can't just find somebody off-the-shelf. And they don't teach it at the universities very much. Universities can't keep up with the equipment and lecturers haven't been in it."*

When questioned on their approach, the informant suggested the strategy was to bring people from engineering and educate and train them in the technology capabilities. This was potentially aided by some universities providing courses on rapid product development, though this approach had yet to be proven. The informant suggested they would "*...the jury's still out*", as at the time of enquiry this organisational change was still occurring.

The nature of the work resulted in the requirement for "technology evangelists", employees able to sell the possibilities of the technology to potential customers and assist in communicating the business benefit of AM processes. In order to support the company's R&D activities they also required highly educated staff members and employed a large number of postgraduate level staff.

6.2.2.3 Organisational culture

The organisations culture was heavily influenced by the beliefs of the company founder:

> *"there's a very philosophical view of the world, we're not allowed to do anything for military purposes. We sponsor villages and schools...surgeons in Baghdad",*

This view is embedded throughout the organisation, with the informant suggesting he has come to accept the view that AM can be used to help people with social needs along with industrial and engineering needs, and importantly still be financial sustainable. The second cultural factor evident at the case company was the RP culture, a key issue influencing the HR policy at the organisation and operational activities.

> *"Because we come from a prototyping culture, we (are) suddenly now taking orders for half million pounds at a time for production parts of a low volume run of parts and everyone of them has to be bang on accurate."*

This presented a number of challenges throughout the implementation process for adopter, principally obtaining the right skills and experience in the various engineering roles and establishing production working practices.

Table 6.8. Summary of organisational issues and activities at Materialise

Factor	Issues/Activities
Size	• Experienced high growth from new start up and became a large multinational • Business units used to maintain innovativeness.
Structure	• Defined business units to serve different product markets • Human resource policy used to support R&D strategy • Production experience remained an area of significant experience and skill gap. • Production engineer vs technologist
Culture	• Challenge in changing the prototyping culture (related to quality control and manufacturing strategy). • Culture led by the values of the CEO.

The findings show how the company maintained a high level of flexibility and responsiveness (agility) even as the company grew to a large multinational. Both structure and technology were used to achieve this through definition of business units and its software assisting in speeding up decision making. The findings support the proposition that the size of the organisation is a key factor in implementation of AM and provides some insight into how high growth organisations can achieve the balanced flexibility/control culture proposed by Lewis and Boyer [181] and McDermott & Stock [151] through technology investment. This case also suggests software companies may not necessarily conform to the characteristics often attributed to large multinational organisations.

Both structural and cultural challenges with moving from prototyping to production are again shown to result in significant challenges for the RP convertor. The case has further provided detail on the relationships between the strategic decision to become a production company and the organisational factors during the implementation process. The framework should therefore capture these issues for project managers so that organisational change plans become a critical construct of the implementation plan, particularly for the RP convertor.

6.2.3 AM Technology

6.2.3.1 AM Standards

Regarding standards compliance, the company has achieved a number of ISO standards for quality management, particularly those required in medical device production. Medical production standards reduced the process flexibility and resulted in dedicated production facilities. The informant also suggested that technology standards would allow systems to be switched over to different materials and process parameters without re-certification.

6.2.3.2 Benefits and Tradeoffs

When discussing the benefits and tradeoffs of the process the informant proposed the requirement for high levels of post-processing and the slow process speed being the major tradeoffs of metals machines. In terms of polymers the informant suggests the major drawbacks were again speed along with powder cost, with particular reference to SLS. Again, SLS was highlighted as a *"real manufacturing technology"* and one which could be applied to engineering applications. Making products lighter and more functional was the key driver for the adopter's aerospace customers. The potential for individualised production, from scanning to part, was the key benefit for the case company's dental and surgical guide applications with the company also developing the supporting software tools to asset in product design.

6.2.3.3 Technology Maturity

The company focused on the use of SLA and SLS production, when compared to metals AM, these systems were relatively well understood. In particular the SLA process had been around for over 25 years and the founders were among the initial innovators. This was reflected in the level of machine development, size of build platforms (therefore machine capacity), number of curing tools and thus the productivity of the systems. However, the nature of the SLA process often meant components were not suitable for engineering applications and were applied to high value consumer products.

SLS was viewed by the informant as a production technology capable of producing engineering components. However, powder costs, process speed and surface finish were perceived to be areas requiring improvement, reflected in the companies R&D strategy. The informant viewed surface finish of components as a process characteristic (due to the layer-by-layer nature of AM), unlikely to change much with maturity. The informants view on metals AM was reflected in the lack of metal AM production and systems; the perception that processes were too immature to be accepted as manufacturing process.

The technology maturity also influenced the company's operational activities, particularly in their engineering service operations. The informant described the major challenge of AM as the process of changing the customer mindset. This issue drove the company to adopt a stage approach to implementation in each of the potential markets. This often began with replicating what could already be done through conventional means, i.e. like for like parts, followed by optimisation and design for process as confidence and further understanding was achieved. Furthermore, it started with supporting existing production processes (e.g. tooling, fixtures) rather than direct production through AM. The informant stated:

> *"The biggest impact at the moment is the processes to support the process of manufacture. So you're still manufacturing parts and designing parts but they're not actually be used by then end customer."*

6.2.3.4 RP Legacy

Related to customer acceptance of AM, the RP legacy added to the challenge faced by the implementer. The RP legacy affected not only the customer perception of the process, but also the skill base available to the company with the main issue highlighted being acquiring the skill and experience in both production and AM process knowledge. This is linked to the prototyping legacy of the systems and the process benefits and tradeoffs.

Table 6.9 Summary of technology issues and activities at Materialise

Factor	Issues/Activities
Standards	• Achieved technical and medical production standards to ensure product quality. • Dedicated medical production facilities.
Benefits and Tradeoffs	• Technology benefits across business units: - Design freedom, lighter more functional parts and creative designs. - Potential for individualisation – Scanning to printing - Speed from CAD to part • Tradeoffs (polymers): - Process speed - Powder costs - Surface finish - Part properties (SLA)
Maturity	• Maturity of SLA processes has resulted in reduction in process tradeoffs • Issues with changing engineering customer mindset
RP Legacy	• Prototyping legacy in engineering sector reduces acceptance as manufacturing technology • Issues in finding suitable skills and experience due to technology legacy

The project manager's clear understanding of the polymer AM benefits and tradeoffs is evident and the development of software tools to assist in capturing the technology benefits represents one of the key success factors for the case. The proposition that project managers should understand which process characteristics are likely to be inherent and those which are down to maturity is also shown in this case.

As identified by Hopkinson et al [5], the rejection of the concept of using AM for manufacturing due to the RP legacy of the processes is evident from the case findings. The findings support the framework proposition that organisations must work closer with customers to overcome this entry barrier. The case details how this can be achieved through a staged approached to technology introduction – from like-for-like tooling components to optimised production components.

6.2.4 Systems of Operation

6.2.4.1 Production planning and quality control

The company used its core skills in software to develop supporting tools for planning production activities and dealing with the high variety in product mix. The informant explained the details of the product mix and the challenges in planning and control:

> *"Well it could be anything, that could be 5 a day or it could 500 a day. But realistically when you do more than that you start to wonder if its viable. or its 50 a month or 20 a month but then its not possible to the same thing every month. Because the design can change, the features can change, the products have evolved far quicker because you can just change the CAD design for the features to change and products evolve. You can build in functionality."*

The quality control for medical applications required dedicated machine for certain product lines, with production development centres focusing on specific product lines. The quality control challenge was influenced by the company's history in RP.

6.2.4.2 Product design

The company's core product, Majics, is used at the product design and file preparation stage of the AM process chain. The software enables the detection and repair of file faults which result from conversion from native CAD file formats to STL. If these repairs are not conducted they can often results in defects in the component caused due to surface errors. The software is also used to automatically generate support structures and anchors to resist distortion. In this case the AM software enabled the company to capture the product design benefits of the process, reduce quality issue resulting from poor file conversions and provided significant competitive advantage through licensing.

To capture user requirement for product, the company employed the use of co-creation sessions. The informant described how these sessions were used in product design and particularly in changing the customer mindset:

> *"So what we launched, we do co-creation sessions. Where we will get together with the customer have a meeting… with their designers there, our specialists are there, their decision makers are there. And we spend the day, we go through what do they do. What sort of problems do they have with some of the parts and manufacturing processes they use? And we will look at specific things, and we choose the selection of things to look at. We may have a factory visit/walk round and say we can do that…..we don't wanna give all our cards away. But its amazing. You can make step changes in the way they do whatever they do."*

Outside the successful production applications, these co-creation sessions became an important tool in applications development projects and success of implementation. The informant described these sessions in the context of changing customer mindsets:

> *"And they started to overcome their traditional inbred 'we always do it this way' type of practice and then they're thinking, well I wonder if we can do that and can we do this and then their actually...and then you start to design for the technology, rather than just replicating what you do in-house, and that where you get the real benefit. You can make some serious changes.*"

6.2.4.3 Integration

The company's history in software engineering enabled them to integrate their operational activities. The informant suggested the company's in-house database provided many benefits in decision making, speed of order fulfilment and other areas of business. The integration of processes, partly facilitated by their core competencies in software, was a key determinant of implementation success:

> *"Because we're a software house...we've got fantastic databases...we can broadcast information on the intranet, per business unit, per office. It's a central collection, via a share point, all the valuations are online.....you can propose changes in a decision and they can be online audited and assessed. You can click*

drag people into a meeting and have a virtual meeting or web conference in minutes."

Table 6.10 Summary of operational issues and activities at Materialise

Factor	Issues/Activities
Design	• Co-creation session used to capture customer requirements • Software solutions facilitate design for process
Production planning	• Production planning challenges are significant due to the volume and product mix. • Bespoke planning and control software developed in-house
Quality control	• Full part traceability linked to company background in software development. • Quality issues reduced through implementation of file repair software.
Integration	• Integration of process enabled by software tools creating free flow information through internal database • Organisational structure facilitates integration of business units

The findings confirm the importance of design for AM [61, 155, 156]specifically for this case the role of software to standardise the process and ensure component quality at early stages of product development. Furthermore, the case provides detail on how organisation may work with customers (both internal and external) to develop applications through the use of co-creation sessions with designers, production staff and AM specialists.

6.2.5 AM supply chain

6.2.5.1 Customers

Through developing its core capability in software, Materialise tailored products and supporting services from individual business unit serving each customer segment. However, the company still had challenges with being viewed as a RP software company rather than a manufacturing company. For engineering products, the key challenge identified by the UK operations manager was the changing of the customer mindset, this then drove the operational activities at the company and resulting systems it employed. This process was described by the informant;

"You're trying to encourage people that have, well I class them as a twenty pee shape trying to push them up a very steep hill. Because they will go up, then up then a little bit more, then they will struggle with that last bit. Its really hard work. You're having to challenge, you're having to drag the energy out themselves to keep pushing, pushing and pushing. And you have successes, but it's quite a long hard gestatation period."

6.2.5.2 Suppliers

Materialise chose to develop their own in-house systems, the mammoth SLA, and co-develop the polymers used in the process. This provided some protection against the price sensitivity of the materials market. However, restrictive practices by polymer machine suppliers remained an issue with other systems, and influenced part costs and production suitability:

"There's a big problem with some of the machines that are almost like inkjet printers, and they have a certain type of ink cartridge, the one the manufactures make. Well I don't think that's the right thing to do.."

The company did not sell the mammoth SLA, only the products from them. This is likely partly due to the fact that the existing patents on the SLA process were owned by 3D systems (large US based AM equipment supplier).

6.2.5.3 Location of manufacture

Manufacturing was located in a centralised production facility in Leuven, Belgium. The informant suggested he had considered having a local manufacturing capacity, however, the speed at which parts could be sourced enabled them to focus on the services around the products:

"…we can get them so quick there's no need, I've thought about it in the past. I usually get the parts next day or the day after. If you plan correctly you may as well have the specialist concentrate on the service. Our production department alone is huge."

Table 6.11 Summary of supply chain issues and activities at Materialise

Factor	Issues/Activities
Customers	• Issues with changing customer mindset influenced operational activities • Perception of being an RP software company, not a manufacturing company
Suppliers	• Issues with materials restrictive practices for some systems motivated in-house R&D focused on own system development. • Developed in-house AM systems, mammoth SLA • Co-developed polymer materials
Location of manufacture	• Centralised production facility • Speed of process and delivery removed requirement to have a facility in UK. • Allowed focus on being service specialists.

The case confirms the framework propositions that a key determinant of implementation success for manufacturing applications will require significant increase in collaborative relations with customers. The theories presented in the framework, and the work presented by Walters et al [59], are only supported in part by this case study. Centralised production remains the decision at the case company even for those processes which may be perceived to be relatively mature, such as SLA. This suggests that for manufacturing applications, even where demand would result in high utilisation, product finishing requirements along with speed of delivery services mean that distributed production remains uneconomical.

6.2.6 Summary of the case study

The case findings show the experience of an RP convertor with a history in prototyping and supporting software. To summarise the case study, the research questions are again laid out to define the case study and the lessons learnt at Materialise.

What are the key factors in the AM implementation framework?

The case shows the experience of a company originally set up as an *RP company*, with core capacity and products in *RP software.* The case shows a significantly success story of AM, and the *product diversity* a company can achieve with the *technology flexibility of AM* (particularly polymer systems). One of the key determinants to the success of Materialise and therefore the implementation of AM, is the emphasis on *product, material* and *process* *innovation*. This is highly dependent on the *workforce experience and skill* which is made up of a large number of PhDs and other high qualifications. This level of *workforce experience and skill*, combined with the *group structur*e and *supporting databases* have enabled the company to remain innovative whilst experiencing rapid growth. One of the key challenges for the company is developing a *workforce with skills* both in production engineering and AM technology best practice. The case highlights that issue is related to the *education policy* of universities.

Operational activities are focused on the *interaction with the customer through co-creation sessions*, enabling the case company to capture the user requirements and change the customer mindset. The case has shown this follows a step-by-step process, starting with replicating what can be done through existing process but with improved process efficiencies, eventually moving towards *design for process* where the significant *technology benefits* can be achieved.

Along the *supply chain*, the case company experience and in-house knowledge of AM process development have enabled them to *integrate the supply chain*. Through co-development of its own materials and process efficiencies, the company matched technical development with customer requirements. For some systems, restrictive practices by suppliers created a dependency on machine vendors and restricted system flexibility and cost reductions.

How do these factors combine with technical factors to form the AM implementation framework?

The key technical dependency emphasised in the case study was the *relationship between AM technology hardware and software*. The company's specialisation in software resulted in the company being able to gain the most benefit from AM, as the software developments remove some of the technology barriers in terms of design and quality issues. These software developments facilitated the *integration* of operations and retention of organisational innovativeness. The flexibility of AM processes, specifically polymer processes, enabled a more diverse product offering.

How do contextual differences influence the implementation process?

The organisational context in which AM was implemented was one heavily influenced by the founders of the company. This defined the *culture*, *target markets and the structure* of the adopting organisation. In terms of production, AM production was implemented in a *prototyping* environment resulting in significant changes required in the *workforce experience and skill*, and changes to the *RP culture*. The company was still going through this change at the time enquiry, suggesting this remains one of the key challenges for RP convertor. The approach at Materialise was to take on staff with experience in production and provide training on AM technology capabilities. The company achieved ISO9001 and ISO14001 standards and implemented *dedicated production* facilities and *full part traceability* from design through production.

6.3 AM Implementation at Reprap Ltd

The third case study was conducted at Reprap Ltd through interviews with the founder and CEO of the company, Dr Adrian Bowyer senior lecturer at Bath University. The company specialised in the development and commercialisation of low cost 3D printers, FDM machines, using an open source business model. Though the company may be viewed as an AM system vendor it was also an example of AM implementation for production applications, as the FDM machines were used to produce components used in the manufacture of the machines systems themselves. A self replicating system.

The case company was one of the key players in one of the most interesting areas of AM, what is becoming known as the "maker community". This community involves AM end-users "printing" products at home using low cost AM systems, such as the Reprap system, and accessing online design libraries. This opportunity has been termed a new industrial revolution and has been in much debate throughout the literature in terms of its likely impact on manufacturing paradigms.

6.3.1 AM strategy

6.3.1.1 Business strategy

Being a micro SME, the AM strategy at the company was heavily influenced by the director's perception of the technology. Originally responsible for the AM equipment (mainly fused deposition fabrication machines) at Bath University, the informant described his first experience with the technology:

> *"one of the things that was fairly forcefully impinged upon my perception was that when we acquired those machines they were incredibly useful, and it was a real liberation to me to find one, because you could just design something and you could have it in your hand, but they weren't actually all that complicated and so I thought, hang on, why is this costing £30, 000?"*

The informant stated 3D printing was just another manufacturing technology, different to a degree to what had come before, but ultimately a step change. However, motivated by the his interest in biology, the vision that resulted in Reprap was creating a machine that could self replicate in an artificial context. The informant suggested this was inspired by the way in which nature performs this naturally, and if this could be achieved, 3D printing was no longer a step change, but a change in kind.

From this vision, starting out as a student project at the University of Bath, the system was commercialised in 2005 and, at the time of enquiry, was one of the most popular low cost 3D printers with "fabbers" and the maker community. The products are either sold as a kit packages (unassembled) or as assembled system. Reprap also provided training courses, where customers could learn how to assemble and use the 3D printer, at a cost depending on location.

The business model adopted was one based on open source, where all of the machine software and hardware design data could be accessed free of charge through a web-based information sharing tool, a wiki. The motivations for adopting such an approach were partly based on the director's view of customer perceived value, but mainly his vision for the technology. As the informant stated:

> *"if you've got a machine designed to copy itself, it's got to be open source. If you attempt to protect it or set restrictions....you're basically saying to the world 'I want to spend the rest of my life in court, trying to stop people from doing with my machine the one thing it was designed to do...'"*

The business strategy contrary to protecting the product and process was purely based on adding value, for Reprap this was through providing an integrated solution via the open source approach.

> *"this idea that has grown in business that you have to have some protected closed knowledge in order to make profit...this is nonsense...all you need to do is to add value....in our particular case the value that we add is that we integrate everything together so that people can get everything from one source"*

In-line with the strategy at the company, the open source approach, the company developed a wiki database used by the community to upload and share information. This includes control and file preparation software along with all information on part sourcing including the STL files for those parts the printer was capable of printing.

Since commercialisation of the Reprap system, many other companies have entered the low cost 3D printer market, and commercialised non-open source solutions based on the Reprap system design. The informant highlighted the activity of a key vendor, 3D systems, who have bought up a number of these companies in an aggressive acquisition strategy. The informant suggested, that aside, it has been relatively surprising how little the proprietary manufacturers have been affected by the work of Reprap Ltd. The informant provided the following conclusions of the open source approach:

"What this does is it gives you an instant material market...like the market for toothbrushes...where there is also no IP and well, the world proceeds....we can still clean our teeth"

6.3.1.2 R&D Strategy

Linked to the business strategy of the organisation and the director's view of the main technology benefit, R&D technologies are focused on improving the system's ability to self replicate. This involves materials and process development, focusing on the printing of new materials and system re-design to improve the percentage of parts the printer is able to manufacture. Further development is also driven by the target customers, industrialists, hobbyist and home users, with the informant suggesting much of the development work being focused on improving the system usability and the ease of assembly.

Aligned with the open source approach, the community itself performed much of the R&D on materials and processed development:

> *"The most development in this whole area has probably been done by the Reprap community by and large. Now and of course whenever they do something they post it on the blog or whatever and then suddenly it becomes completely un-patentable"*

Table 6.12 Summary of strategic issues and activities at Reprap

Factor	Issues/Activities
Business Strategy	• Open source business model • Customer perceived value is in integrated solution and it is this which differentiates the company's offering • Target customers are the maker community and industry users
R&D Strategy	• Research and development focused on new materials processing – ceramics, low melt temperature metals • Product development to improve ease of assembly • User community perform much of the development work

6.3.2 AM Technology

6.3.2.1 Technology benefits and tradeoffs

The main benefit of the technology was the capacity for self replication and the system was capable of printing around 30% of its own parts, with the key tradeoff being the limitation on materials. Further benefits included the cost of the components and the Reprap product itself, this opened up the market for many home users of the technology as the un-assembled price was around £800, the assembled printer is shown in Figure 6.5.

The production facility used Reprap system to print the components with the non-printable components sourced and assembled with relatively low skilled labour requirement. The tradeoffs were material constraints, confined to the extrusion of ABS and PLA which limited the processes self replication ability. This trade-off was reflected in the company's focus on developing new materials processes, including low melting point metals and ceramics.

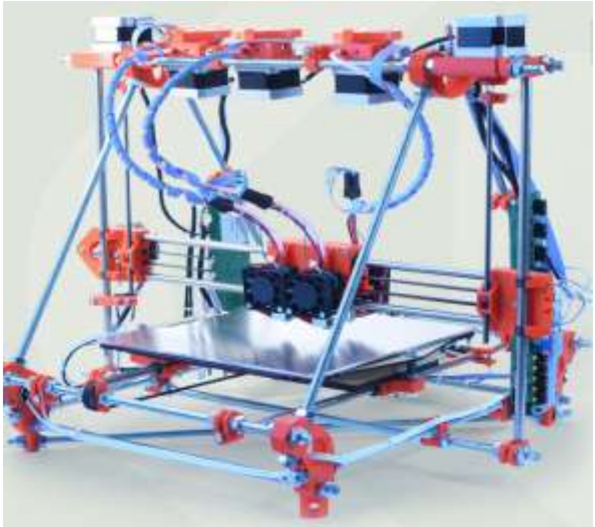

Figure 6.4 Reprap "Mendel" printer with printed components in red coloured ABS

6.3.2.2 Technology maturity

The FDM process had become a relatively mature process when compared to other AM processes. Its use in manufacturing applications was limited due to the perceived low quality of finished parts. Though quality from a conventional manufacturer perception may be low, to an end user (hobbyist), this case suggest it is acceptable if the are other value offerings in the product.

The work conducted by Reprap helped to increase the rate of technical development in the area of FDM low cost 3D printing. This increase in maturity level, facilitated through the open source approach, resulted in vast improvements in part quality, system cost and ease of use. Also, the success of Reprap low cost 3D printers helped to "publicise" AM process, overcoming to some degree the lack of industry knowledge.

6.3.2.3 RP legacy

The Reprap products were not specifically aimed at a manufacturers or production companies therefore and the products produced on the AM machines are used directly in assembly of the machines themselves. Therefore, the challenges with convincing those who believe that the technology is only good for prototype are not an issue for the company. The company itself was not initially set up as a prototyping company therefore; the reputation and cultural issues that may arise were not evident in the case of Reprap.

Table 6.13 Summary of technology issues and activities at Reprap

Factor	Issues/Activities
Benefits and Tradeoffs	• Technology benefits: - Potential for self-replicating - Low cost - Ease of use and assembly • Technology tradeoffs: - Material constraints - Part quality and mechanical properties - Speed of printing - Requirements for support
Maturity	• Relatively mature • Improved cost and complexity • High no. of competing products – but few providing an integrated solution
Legacy	• Customer acceptance as a manufacturing tool was less of an issue due to the lack of RP knowledge or experience in manufacturing.

6.3.3 Organisational Change

6.3.3.1Size and structure

The company may be viewed as micro SME; with only three employees running the business the challenges with rolling out change in such a company were reduced. There were challenges with access to resource; however, the CEOs perception was that they are happy with current resource pool. The structure included the director and inventor of the system, a production manager and an R&D coordinator focusing on developing the products to reduce product cost and improving accessibility. The structure of the organisation did not change significantly during implementation. However, the open source approach and community size and structure was particularly interesting in this case. One of the factors in the case of Reprap is sharing the knowledge and of using the product with community of users and therefore disseminated to users. Similarly, the experience and skill of the community was shared both within the community and with Reprap. This allowed the company to capture knowledge from the community and improve the product offering and AM system design.

6.3.3.2 Culture

The organisational culture was heavily influenced by the values of the founder and company director. Again, the business model, defined by the vision of the founder, influenced the culture adopted at the company. Producing an open culture of idea sharing based on providing value through an integrated approach, rather than protecting knowledge and generating IP. The culture is ultimately based on a shared vision of sharing knowledge.

Table 6.14 Summary of organisational issues and activities at Reprap Ltd

Factor	Issues/Activities
Size	• Micro SME with limited resource with open source approach providing platform to overcome resource gap
Structure	• Structure based on core skills of employees and operational activities • Experience and skill of the workforce and the user community integrated through open source approach
Culture	• Culture influenced by the founder's beliefs and values.

The case findings show that the organisational changes required during the implementation of AM were heavily influenced by the choice of business model – in this case the open source model. Cultural and structural changes identified in the framework were heavily influenced by the founder's ethos and outlook.

6.3.4 Operational Factors

6.3.4.1 Design for process

The company did not provide design-for-manufacturing training to customers during the training session. The requirement for design-for-manufacturing was somewhat mitigated through the use of online libraries of product designs. This was one of the company's key offerings, the integrated solution to 3D printing. The prominence of design libraries and how they diffuse product data, including STL files, presented one of the key enablers to the open source approach. Indeed, as the informant suggested one of instrumental members of the Reprap product development, was the founder of Thingiverse, an online library of product design, where the community upload and share designs to print through AM processes. The company's experience and skill in design-for-process was present before implementation as the product itself relied on the components which could be produced on FDM platforms - self replicating process.

6.3.4.2 Production planning

The production planning was conducted by the production manager, with scheduling conducted from online orders of Reprap systems. The simplicity of the process chain, based on the ease of assembly and the fact that products are design for process, reduced the level of complexity of process chain and issue in production planning.

6.3.4.3 Quality control

Standard process parameters were used to ensure product quality of AM produced components. As customers had access to all the CAD of the machine components (those that are capable of being produced by the system), product standards were likely to be highly affected as products are produced in different environments and on different systems. This could have potentially had an effect on product branding as parts could produced not to the standards followed at the production site run by Reprap Ltd. However, this was not a concern for the company director, as it perceived as being something that could not be controlled.

6.3.4.4 Integration

The high level of integration, both internal and in the supply chain was one of the key success drivers for the company. As the informant states:

> *"in our particular case the value that we add is that we integrate everything together so that people can get everything from one source"*

This high level of integration through the open source approach improved product development activities, reduced supply chain communication issues and helped the company overcome some of the resource constraints of the micro SME.

Table 6.15 Summary of operational issues and activities at Reprap Ltd

Factor	Issues/Activities
Design	• Open source approach reduced the requirements for customer education of design for process
Production planning	• Process chain simplicity reduced planning challenges
Quality Control	• Quality control and product branding issues in the supply chain

Integration	• Integrated solution provided through the open source approach. • User community tools integrate both operational and supply chain activities

The case findings show the operational factors at a new start company with a business model based on open source. This business model drives the operational activities during implementation, in line with the propositions of the research framework – operational systems should be designed to fit process choice and business strategy [157, 159, 160].

6.3.5 AM Supply Chain

6.3.5.1 Suppliers

The company may be viewed as an AM system vendor, who also manufactures AM products. The fact that the machine could produce a significant percentage of its own parts provided a unique scenario in terms of machine maintenance and increasing production capacity. The cost of AM filament remained a barrier to reducing part cost, however, the use of optimised process parameters and part design were used to reduce the amount of material used and therefore dependency on material suppliers.

6.3.5.2 Customers

For those customers who were not so technically adept, the company used training courses to share the knowledge of machine assembly and 3D printing best practices. These courses did not include design for process which often makes up much of the usually activity in this area. Once the customers had been trained in assembly and operation, the users were then able to access the knowledge of the community of users for design for process knowledge, including the Reprap wiki.

6.3.5.3 Location of manufacture

The company had a centralised production facility, using Reprap machines for production and a number of trusted external suppliers for non-printed components. The parts were assembled, or not, depending on order request, and delivered to the consumer. Interestingly, the nature of system and business model created a distributed supply chain, where Reprap were printed globally according to demand. Although the company did not see immediate financial gain from this activity, it was part of the integrated appeal of the product itself.

Table 6.16. Summary of supply chain issues and activities at Reprap Ltd

Factor	Issues/Activities
Customers	• Customers tend to be hobbyist and enthusiasts • Training days provided an opportunity to share best practices • Community users innovate and make public lessons learnt
Suppliers	• No restrictive practices, users are able to use any material suppliers • The open source approach provides a more integrated supply chain, as the user community have access to product information and the supplier has access to experience of the user
Location of manufacture	• Through the open source system product manufacture is distributed globally or centrallised. • Represents one of the key values of the product offering, an integrated solution.

The case study supports the factors within the supply chain construct of the research framework. The findings in this case have provided a technique for achieving the collaborative relationships identified in the research framework as key to success [168, 169]– the open source business model combined with web enabled sharing tools.

The framework proposition of decentralised implementation of AM is realised in this case study; as the product requirements, business model and technology characteristics combine in such a way in the open source environment to support distributed production. The case company retains value through its value offering, integration.

6.3.6 Summary of case study

What are the key factors in the AM implementation framework?

The founder's perception of the key technology benefit determined the business strategy and the *emerging operational and supply chain activities*. The key factor in the implementation at Reprap was the decision to follow an *open source business model.* This has driven the approach to *manufacturing strategy*, the *supply chain activities, along with the organisational context* that emerged. The *integrated solution* provided by Reprap represented the *key value to the customer*. As a new start up, organisational change was not an issue for the company.

The open source approach facilitated the training of customers. The *availability of part designs*, either directly through the Reprap website or other online libraries, such as Thingiverse, reduced the need for customers to understand *design for process.* Knowledge of machine assembly and *best practices* around FDM are shared with customer through training courses and through the user community. The open source approach also *facilitated innovation* in the community, providing the *micro SME* with the opportunity to cope with the lack of resource through using the development work done by the community. This level of *integration* is one which provided the main value to the customer and the supplier and providing competitive advantage.

How do these factors combine with technical factors to form the AM implementation framework?

The key technical factors in the case included the *relative maturity* of the process and the absence of a *perceived RP legacy* in the community. The key benefits of the product included its *low cost* and *ease of use*. These created a much wider market for the Reprap product, and when combined with the open source approach, represent the *key value* to the customer and therefore the success of implementation in the case study.

How do contextual differences influence the implementation process?

Being a *micro SME* the organisational context was one with *low resistance to change and high flexibility*. In line with implementation research, the approach and activities during the implementation process were heavily influenced by the *vision of the company director*. As a new start up the activities and issues were determined by the business model adopted by the company director and determined the products and services the company offers. The *business model, open source*, created a more integrated supply chain and a community structure where *information and data* can flow freely to both customers and the adopting organisation.

6.4 Summary of the Chapter

This chapter has presented the case analysis of three typical cases of AM implementation for production applications. The cases were varied in types of AM technology and context of implementation; in-line with the research methods proposed in this study. The first case study, revealed the experience of the "conventional manufacturer" as a defined stage process of implementation. From AM introduction with FDM and SLA machines, providing a low cost introduction for the organisation into AM, the organisation then moved to SLS implementation running both prototyping and production on the same machine. Finally, implementation of production DMLS was achieved, serving external customers with a certified process supporting software tools. Along these stages the activities and issues in the research framework were identified and relationships between the factors described.

The second case study described the approach of an “RP convertor” with core skills in software development. The case analysis showed the main factor in the success of the company was their continued R&D work in new products, materials and processes. Particular importance was placed on their software products which automated downstream process including product design and file preparation. The success and diversity of the AM products and services was driven by the vision of the company director and facilitated by the workforce experience and skill. Key issues for the adopter were rooted in both the company and technology legacy in prototyping, moving to production created an experience and skill gap in production engineering. Along the supply chain key issues were identified to being changing customer mindset, driving the operational activities of the engineering services and supplier restrictive practices. This motivated the decision to move to vertical integration to control process and materials development.

Finally, the third case in this analysis was the typical case of the new start up. The key characteristic of the AM implementation approach was the decision to use an open source business model. This has ultimately defined the customer value and created a community of users and an integrated solution for this maker community. The open source has also defined the emerging supply chain along with the systems of operations which have accompanied implementation. Ultimately, the technology benefits facilitated such an approach, as the system low investment requirement and low complexity facilitated the open source and resulted in both technical and business success of implementation.

This chapter has provided an in-depth analysis of each of the cases following the with-in case analysis defined in the research methods. In order to assess the framework’s ability to capture the variety found in these typical cases, and understand the similarities and differences of each of the cases, the cross case analysis is presented in the following chapter.

CHAPTER 7

CROSS-CASE ANALYSIS AND IMPLICATIONS OF THE IMPLEMENTATION FRAMEWORK

7.0 Introduction

Following the case analysis of the typical cases presented in the previous chapter, this chapter provides further analysis in the form of a comparison cross-case study. Specifically, it provides the cross case analysis of the three main study cases along with the pilot enquiry, with the aim of identifying the similarities and differences between the various cases. From this analysis the framework is then revisited to define process models for the various typical cases. The chapter also presents pre-implementation studies of three cases involving three companies which were in the pre- or early stage of AM implementation. One of these pre-implementation studies was based on data collection from interviews with the core engineering leader investigating the use of AM across each of the business units of a large multinational company. The others represent a change in research methodology, as the researcher was actively involved in developing implementation plans for two new start up companies which may be classified as micro SMEs. This action research was carried out through workshops and meetings with the company directors and development staff. The chapter is organised as follows; Section 1 provides the cross case analysis of the post-implementation cases presented in the previous chapters. Section 2 defines the implications of the study for the research framework and Section 3 proposes the framework applied in three pre-implementation cases. Finally, Section 4 presents a summary of the chapter.

7.1 Cross- Case Analysis

The cross case analysis used the previous case studies as the basis for analysis. The key framework factors for each case were taken from the with-in case analysis and compared along the respective dimensions of the framework, identifying contextual similarities and differences, technology similarities and differences and finally similarities and differences between approaches in terms of activities and issues. The classification of the main study cases along with the pilot case is provided in Table 7.1. The following sub-sections present the support for the taxonomy used in this study.

Table 7.1. Main study case classification

Company name	Company size	Technology	Stage of implementation	Informants/ position	Typical case
3T RPD Ltd	SME	SLS, DMLS	Fully implemented DMLS for production applications	[1] Company CEO [2] System vendor, Regional manager	RP Convertor
Renishaw Plc	Large multinati-onnal	DMLS, SLS, FDM	Fully implemented DMLS production applications	[1] RM Manager [2] System vendor, Regional manager	Conventional Manufacturer
Materialise UK Ltd	Large multinat-ional	SLA, SLS, FDM	Fully implemented SLA and SLS production applications	[1] UK Operations Manager	RP Convertor
Reprap Ltd	Micro SME	FDM	Fully implemented FDM production applications	[1] Company Director	New start-up

7.1.1 Contextual similarities and differences

The framework proposed that the size of the organisations was a key factor in understanding the implementation approach to AM, small firms cannot be considered scaled-down large ones [128–130]. The sample took two multinational companies and two SMEs. The two SMEs had similar characteristics in low levels of resource availability for R&D activities; however, two different approaches were taken related to the respective business models of two individual companies. Reprap Ltd used the open source business model to access R&D resource within the maker community, essentially free access to a resource base made up of all the customers through the integrated approach. 3T RPD Ltd, related to their business model around AM services, used prototyping to fund R&D work in production applications.

Two of the companies shared a background in rapid prototyping, 3T RPD with a history in prototype components and Materialise with a history in both RP software and components. Both companies had resulting challenges in changing the RP culture with-in their respective organisations when implementing production applications. For 3T RPD, this was most prominent in a single role, the production managers, for Materialise it was seen as an issue throughout the different business units. Both informants highlighted the challenges with accessing a suitable skill base containing both production engineering knowledge and technical AM process knowledge. For Materialise, through focusing on developing software solution for AM processes, the company retained a customer base throughout the implementation of production AM. Neither company suggested they had the company structure suitable for their changing products and services and it was seen as an ongoing development in both companies.

Both RP convertor cases spent much resource on educating customers and achieving market penetration. However, two different approaches were taken. For 3T RPD educating customer was focused on re-design of products for AM processes from the start, whereas Materialise UK focused on a stage approach to introduction to the process. The co-creations sessions used at Materialise initially began with identifying applications in supporting existing processes and product development, replicating what could be done with conventional processes, eventually changing customer mindset to design for technology.

However, in the case of 3T RPD the approach to customer education was design for process from the start. This difference is likely due to the fact that the technology benefits of polymer systems, specifically SLS and SLA, in supporting conventional (subtractive, formative, assembly) processes along with the flexibility of the process mean that the company can provide a step by step introduction to AM and reduce resistance to change. In 3T RPD, regarding DMLS, the high level of design constraints (including the requirements for supports), relative maturity of the process, and the high manufacturing costs result in an uncompetitive offering for like for like parts along with supportive tools/jigs/fixtures (importantly there are some exceptions, including complex soft tooling requiring conformal cooling channels).

This highlights one of the key distinctions between the processes and increases in resistance to change during implementation and therefore the success of AM implementation. The high level of engineering input required particularly for metal AM processes, in many cases renders the process uncompetitive for high product varieties and low volumes. Without automated software solutions, where the product engineering does not require high levels of designer, materials engineer and production engineering input, this situation is unlikely to change.

For 3T RPD, the separation of the business reflects the different focuses of each of the organisations. This bears similarities to the Materials UK case, as the company has grown, individual business units have been identified and dedicated facilities have been established for production applications.

These similarities in issues and approaches present at the two cases, even where technology differences are apparent, support the taxonomy presented in Section 3.4. In these cases the key framework factors are those related to educating customers on technology benefits [168, 169], changing the company culture and developing systems of operations for production, including production planning and quality control [159].

Only one of the adopting case studies had implemented AM with an existing customer base and an established supply chain position as a manufacturer, Renishaw. This was reflected in the company's lack of requirement for educating customers to technology benefits along the supply chain, and focus on internal customers. This was also determined to be one of the significant factors influencing the successful adoption of AM, specifically DMLS, at the adopting organisation. Contrary to the other cases, Renishaw were the only case with a history in non-AM related products and services prior to implementation. As such, the challenges with establishing a customer base and entering a supply chains were not present. Instead, education and training were focused internally, and activities included training designers on new design rules, engineers around the new materials characteristics, and production staff of the new production fundamentals of the changing processes. The cultural clash, between technology enthusiast and pessimists, was most apparent at the proposed "conventional manufacturer". The cultural change factors were proposed in the research framework [150, 173] but emerged in detail through this case analysis and were found to be the most critical factors for the conventional manufacturer. It is these organisational change barriers that are used to support the taxonomy of the conventional manufacturer as the absence of significant supply chain barriers and operations issues combined with the importance of organisational change were most apparent in this case study.

Three out of the four cases were systems vendors, two prior to implementation of production (Reprap Ltd and Materialise UK) AM and one post-implementation, Renishaw Plc. The high level of vertical integration in the sample is representative of the AM industry as a whole. For Renishaw Plc, the motivation for moving into the vendor supply market was the potential for innovation and developing a production SLM system. For Materialise UK, the motivation was protection against supplier restrictive practices and the potential for developing systems for larger components and similarly achieving higher productivity for production applications. A comparison on contextual similarities and differences is presented in Table 7.2.

Table 7.2 Contextual similarities and differences of the cases

	Organisational			Supply Chain		
	Size	Culture	Structure	Customers	Supplier	Locations of manufacture
3T RPD	SME	RP Culture	RP structure	RP customer base	External	Centralised
Renishaw	Large multinational	Both traditionalist and enthusiasts	Manufacturing structure	Established customer base	External/ Internal	Centralised
Materialise	Large multinational	RP Culture	RP Structure	Established customer base	External	Centralised
Reprap	Micro SME	Community culture	Distributed Maker community	No customer base	System vendor	Distributed

7.1.2 Technology similarities and differences

In total the case study analysis included five different AM processes, three polymer processes; selective laser sintering (SLS), stereo-lithography (SLA) and fused deposition modelling (FDM). Two metal powder-bed processes were the subject of the case analysis, direct metal laser sintering (DMLS) and selective laser melting (SLM). The distribution of AM technologies is illustrated in Figure 7.1.

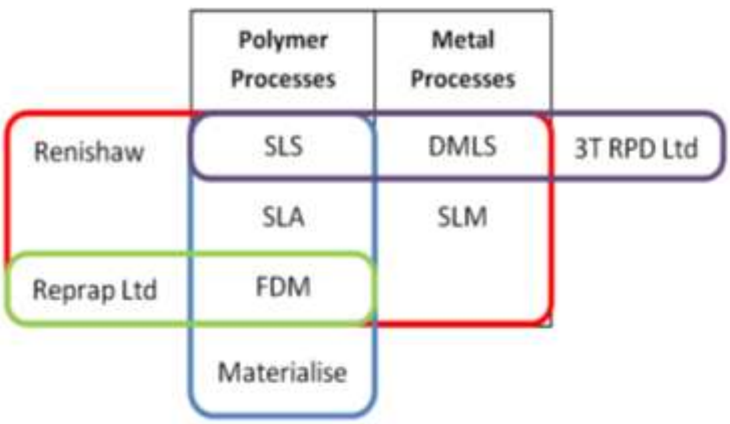

Figure 7.1. AM technologies included in the study

Two of the companies, Renishaw and 3T RPD, had implemented both DMLS and SLS. Both cases followed SLS and then DMLS implementation. Both may be viewed as a combined top-down, bottom-up approach, as one came in response to changes in the environment, and technology based arguments, whilst the other came from market-based arguments for non-precious metals along with a technology-based argument for cost advantages. However, the key difference was that one case company was established in the dental market and the other not having an established customer base for production parts. This influenced many of their respective activities during implementation and again supports the taxonomy presented in this study. Both highlighted the challenge with implementation DMLS being the relative technology maturity and the level of design constraints (due to the need for supports) and being a key technology trade-offs. Both also highlighted the product life cycle benefits as being a key benefit of the process. However, Renishaw were also able to capture the cost, quality and flexibility benefits of the DMLS process, through competing with conventional casting processes in the dental DMLS market.

Both companies used the SLS system for both prototyping and production, facilitated by the flexibility of the process and near net shape manufacturing capability. At Renishaw, this was facilitated by internal demand for both prototype and small production components, such small components were suited to the packing strategy identified as best practice.

Two of the cases, Renishaw and Materialise UK shared a focus on developing software solutions to automate the engineering knowledge required for design processes. For Renishaw, these technologies were key to reducing downstream engineering operations in production applications. For Materialise UK, the pre-processing software enabled the company to achieving competitive advantage in the RP service industry and continued to provide a product platform for the company as they moved into production. All case companies to some degree used software tools to reduce post-processing, however, the characteristics of metal systems resulted in an increased reliance on post-processing techniques due to the reduced design freedom.

All of the cases had implemented polymer systems at some stage in the implementation process. The technology maturity of polymer systems was highlighted in this study and influenced the approach taken at the organisations. The flexibility of the SLS process provided a much simpler process chain during implementation, and facilitated higher product variety and batches including both prototyping and production components.

Both metal AM system implementers achieved relatively low levels of AM system integration. The fixed production volume and product mix enabled Renishaw to achieve higher integration of processes at the front end (data acquisition and file preparation) however, the system itself remained an island of automation, with upstream post-processing remaining an antiquated time consuming process.

The research framework provided an understanding of the influence of process technologies characteristics on each of the frameworks constructs. Though the results showed significantly different approaches for different technologies (particularly the distinctions between polymer and metal AM) the framework was "open" enough to include different combinations of technologies. Indeed, this was critical to the success of the framework, as the implementation of different processes was an important characteristic of the staged approach to adoption of AM. The analysis supports a taxonomy based on organisational context, rather than technology, as all but one of the cases used more than one AM process.

7.1.3 Similarities and differences in implementation activities and issues

The framework constructs (and specific factors) were used to identify the activities and issues experienced by the adopters during the implementation process. Through the cross case analysis, similarities and differences found in each of the cases were identified which in turn supported the taxonomy used in this thesis. The previous sections have provided the understanding of contextual and technology similarities and differences. The following sub-sections discuss the similarities and difference in issues and activities.

The cross case analysis provides a number of characteristics of the RP service providers and an understanding of how this group of implementers will develop an implementation plan:

- *Changing the customer perception of the company* – the strategic decision to become a production company will often be met by resistance/scepticism from existing or potential customers. Developing the correct systems of operations will assist in improving perception but from the cases presented in this study it will likely be a long process of confidence building, supported by applications in like-for-like components or supportive processes.

- *Changing the customer perception of the technology* – as Hopkinson et al. [5] predicted, the rejection of production AM is often down to the perception of prototyping technologies not capable of production requirements. The approach found in the RP convertors in this study suggests changing the organisation perception activities outline above should be the approach to building confidence in both company and technology.
- *Changing the RP culture* – both cases identified RP culture as one of the main issues faced by the companies, specifically understanding of how control orientated values, quality and cost, can be permeated through the organisation. Training and involvement of employees on new working practices were used to change this culture.
- *Developing the systems of operations* – for the RP convertors, developing operational systems to support production was identified as key to implementation success. Both experienced significant increases in process complexity and product quality requirements ultimately process flexibility was reduced and resulted in dedicated production systems for application areas.
- *Acquiring the staff* - prototyping skills are not necessarily transferrable to production. Characterised by designers and technologists, both RP service provides identified the skilled AM engineer with a production background as being key to implementation success.

For the new start up, Reprap Ltd, the business model became the key factor in the implementation framework and the open source approach influenced all activities and issues defined in the case analysis. Though the new start up shared some of the challenges presented in RP convertors, the organisational culture was dictated by the ethos of the founder in line with framework propositions. Similarly, the business strategy also reflected the founder's vision and beliefs. The key implementation factors for the new start up included:

- Defining the business strategy – the business model of open source has ultimately determined the supply chain structure, R&D strategy along with organisational characteristics of the firm. For the new start implementing AM the business strategy will be the key success factor.
- R&D strategy – the business strategy of open source has led to a community of users capable of performing research and development activities for materials and process

improvements. For new start-ups with limited access to resource, this approach provides an opportunity to develop systems and products when resources are scarce.

- Product quality control in the supply chain – brand reputation may be an issue due to the lack of control of Reprap product data and component traceability.

The conventional manufacturer had a number of differences in its approach to both the RP convertors and the new start up supporting the taxonomy proposed in this study. Key issues and activities for the conventional producer included:

- Changing the technology perception (internally) - The perception at Renishaw remained that the metal AM systems were still essentially prototyping platforms and this became a motivating factor for the firm to enter the vendor supply chain. Internal rejection of the technology beyond prototyping resulted in resistance to change.
- Changing the company culture – one of the key challenges for the Renishaw was changing the company culture. With both technology enthusiasts and conservatists, the company focused on developing a culture of understand based on finding a "middle ground" between these conflicting view points.

There were a number of technology related issues identified throughout the implementers, related to the benefits and tradeoffs factor in the research framework. For powder metal systems implementation, the following were identified:

- Design guidelines for process – communicating these internally and externally
- Lack of process monitoring and control results in unknown product output
- Material inflexibility results in dedicated machine for production applications
- Competing technologies – high speed CNC and casting processes

Through comparing the case results, a number of supply chain related issues were also found in all cases, supporting their inclusion in the research framework and consideration by AM project managers from any organisation context. These included:

- Supplier restrictive practices – influencing product cost and market penetration
- De-coupling of manufacturers, vendors and materials suppliers – its impact on technology and materials development
- Lack of industry knowledge of the process - operational activities focused on education and communication of benefits and tradeoffs

- Quality control – material and component traceability through supply chain

This section has provided the cross case analysis of the case studies, including all post-implementation case studies. The analysis provides a comparison of cases including similarities and differences along the contextual, technology and implementation approach dimensions of the research framework. The cross case analysis has provided an assessment of the framework factors in each of the case companies and has proposed a taxonomy based on importance of these framework factors in three groups of implementers:

1. The RP convertor – the framework proposes that implementers must work more closely with customers and suppliers for success implementation. This is largely due its lack of customers (for production applications) and the organisations and the technology perception of "only good for RP". Secondly, organisational change is another key success factor for this group – specifically changing the "prototyping culture" along with the revised operational activities to ensure cost and quality control.

2. The new start up – for these implementers the business strategy is the key determinant of implementation success as ultimately this will define the value of the company offering and its success in entering a new supply chain. Similar to the RP convertor, communicating technology benefits and tradeoffs to customers and suppliers are a key to success for this group.

3. The conventional manufacturer – with an established supply chain and production system, the resistance to change will be internally for these adopters. Workforce involvement and training are key to implementation success. Staged introduction of the process will assist for these adopters, from prototyping to production, reducing resistance to change and assisting in developing the organisational culture required to achieve the technology benefits.

7.2. Implications of the Framework

Using the analysis presented in the previous sub-sections, the framework was then re-visited to establish if and how all of the case scenarios were captured in the framework. Specifically, the following sub-sections look to develop process models for project managers to use based upon this analysis.

7.2.1 The framework revisited - process of AM implementation

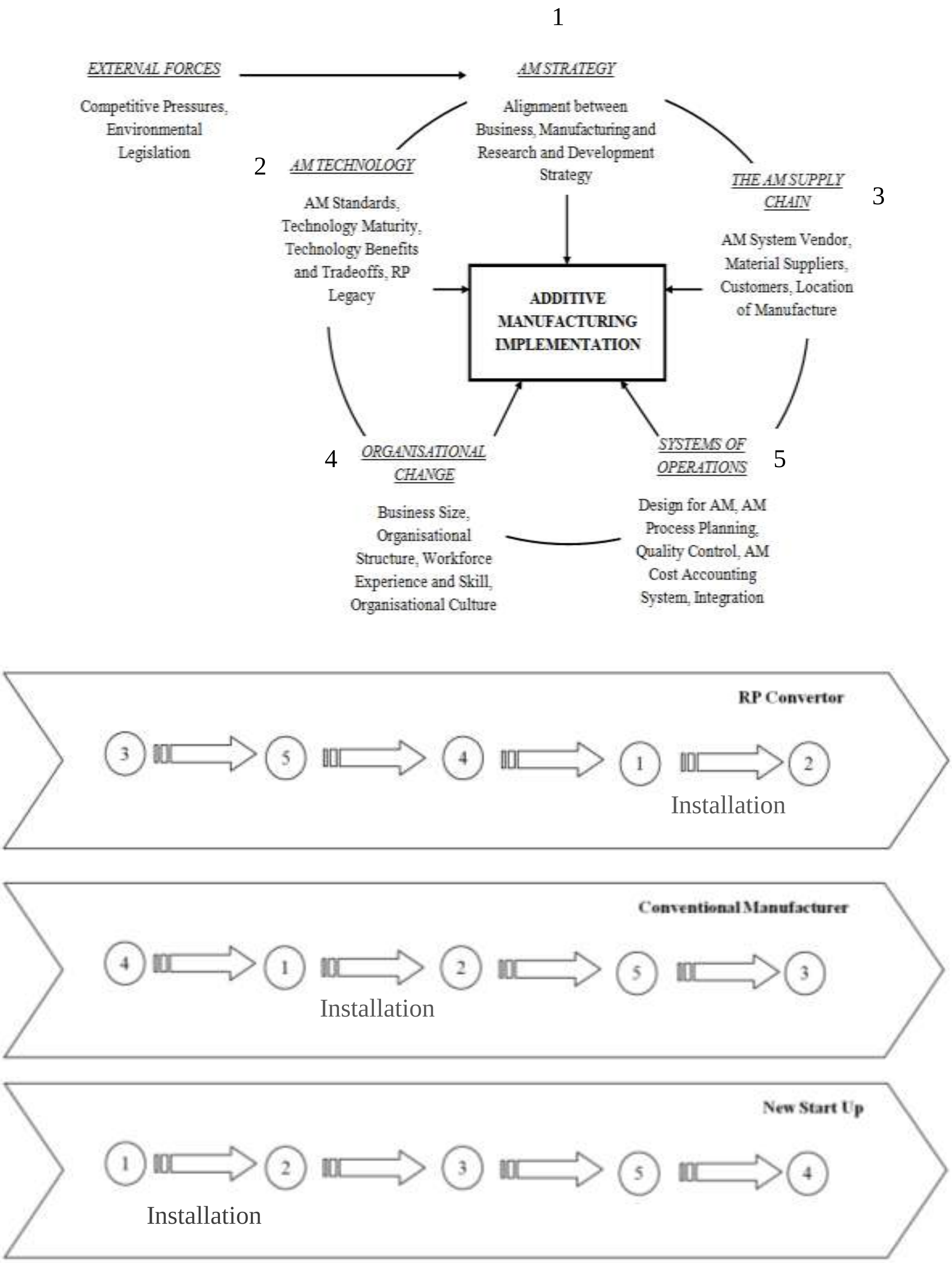

Figure 7.2 Implementation stages for Additive Manufacturing

From the results and analysis presented in the previous section, the framework was revisited with an effort to develop a normative process model for the implementation of AM. This approach to identifying framework factors and developing process planning models is well established in technology and manufacturing strategy research [24, 83, 84, 179]. The implementation stages are illustrated in Figure 7.2, grouping 5 main stages to the implementation process. Based on the cross case analysis and in depth study of the typical cases, process models are presented to illustrate the proposed order of importance for the adopting organisation and the timing of installation of AM for production.

These stages are now described in detail in the following sections.

7.2.2 Developing the business case

The research framework captured this process in the alignment between business, manufacturing and technology strategy. How this business case is developed and presented is dependent on contextual and technology characteristics of the adopter. For large multinationals it is likely this process will be a more formalised approach, whereas in SMEs and new start-ups, it will likely be less formal and based on the key decision makers opinion of the technology benefits and tradeoffs.

Strategies for justification of investment will also be driven by the technologies under consideration:

- *Low cost 3D printers (including FDM)* – low capital investment cost will reduce barriers to entry into AM for these technologies. The ease of use and low running costs will also reduce the risk of failure and the need for a detail approach to justification.

Applications along the product development cycle will likely be limited to prototypes for engineering components, visual aid for designers and fit and possibly some functional testing. In non-engineer applications, additional value may be found in customised or personalised production. As product quality remains comparatively low and production costs (at volume) remain high, when compared to conventional process (such as injection moulding), businesses should look to identify how implementation can capture value in innovative business models. This includes, personalised and customised products, facilitated by a distributed supply chain.

- *Laser-based polymer processes (including SLS and SLA)* – technology characteristics include higher capital investment, higher skill requirement of the workforce and higher running costs. Higher capital investment will likely require higher machine utilisation of the machine, particularly for SMEs considering implementation. The flexibility of the SLS process facilitates higher utilisation as there is a reduce amount of engineering time during product design, no requirements for supports or fixturing.

Applications along the product development life cycle can be vast, ranging from early stage prototyping to production of end-use components. Again, product characteristics will be the key determinant of what stage of the product life-cycle these process can be applied; volumes must be considered in this analysis along with batch variety. The flexibility of the SLS process, including no requirements for supports creates the opportunity for higher batch varieties, including both prototype and production applications. For engineering components, SLS is suited to production of components with a high level of complexity but poor surface finish may restrict the application areas. Ultimately, materials characteristic requirements will define the suitability in terms of engineering applications.

- *Laser-based metallic processes (including DMLS and SLM)* – High capital investment cost, running costs and process complexity will require a detailed, thorough approach to justification of investment for most companies.

Applications will likely be further down product development cycles as production applications or potential tooling solutions for high complexity soft tool. Materials range is a key determinant in measuring part suitability, though there are now a large variety of materials available they are often not the same as conventional materials and are specific alloy combinations for AM processes. Again, volume and value remain the key considerations in justifying implementation of the process. At lower volumes there remains a key issue in justifying the level of engineering costs required to develop usable components. The high cost and non-compatibility with conventional processes (in terms of product design) will reduce suitability for prototyping applications. For production, the initial investment justification will often be judged on direct replacement of a conventional process such as casting or CNC machining. Such direct comparisons for like-for-like parts will often result in an uncompetitive AM offering unless the part selected is already suited to AM production –

such as high level of complexity, high skilled labour requirement, individualised or customised design (with “base” design).

At this stage of implementation the type and role of AM implementation should be identified. From here, companies may then look to developing the action plans along the various operational, organisational and supply chain dimensions. These are described in the following sub-sections.

7.2.3 Developing the systems of operations

Following the identification of the business opportunities and successful presentation of the business case, the project manager must then look to developing the operational action plan and determine the required systems of operations. This should begin with mapping of the current process chain, and then comparing to that of the AM solution. For new products, and new business models project managers will develop new process chains. Along this process chain the potential issues (risks) should be identified and activities to reduce operational failure should be conducted. Figure 7.3 presents a process chain map to be used by project managers.

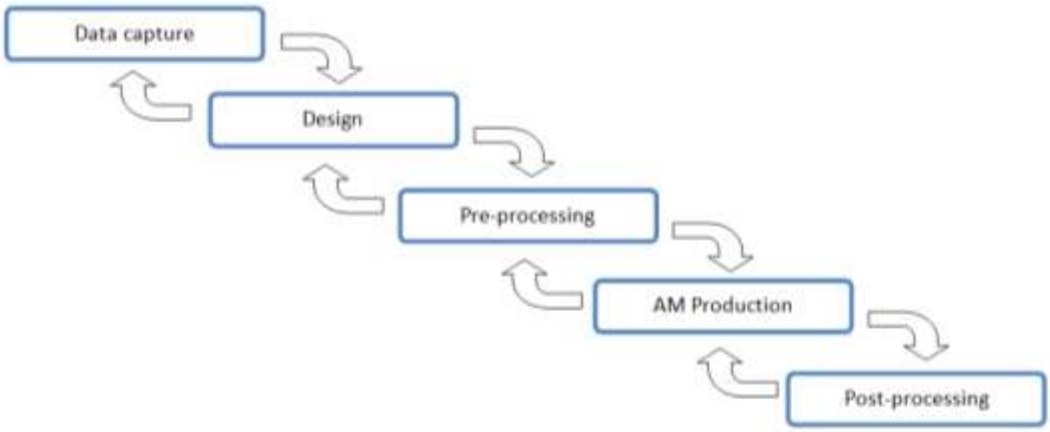

Figure 7.3 The typically AM Process Chain

Though the generic process chain may be captured in the above steps, the complexity and number of processes within each of these stages will be dependent on the AM technology being implemented and the product application.

7.2.3.1 Design and Engineering Processes

It is the engineering and design knowledge which presents the key challenge to achieving the benefits of AM processes for the majority of production applications. Though this may be alleviated in like-for-like business cases, for metal systems (and to a lesser degree plastics) the major benefits of the process require new designs and the re-engineering of products. Developing the design guidelines for the process will dependant the maturity and complexity of the process. For some processes these design guidelines are not well established so developing the systems to implement them will be more challenging. Supplier selection will be important to capture the initial design and engineering knowledge through training. However, for certain processes it should not be assumed that the vendor will have all the knowledge of the process design and engineering considerations.

The level of this design and engineering knowledge will be technology and product dependant. For applications with less stringent quality requirements the design and engineering knowledge may be reduced. Also, this is a geometry dependant knowledge gap, for larger parts with internal features, the level of engineering and design considerations required is likely to be vast as risks of failures due thermal stress, unknowns and build strategies, are increased.

Design engineers should be aware that tolerances are a function of part size for AM processes due to the nature of the heat and cooling cycles. Without simulation tools this will often require prototyping to establish characteristics such as deflection, mechanical properties and stress relieving requirements. Importantly, prototyping should be done in the orientation that will be used in production, orientation itself should be a key design decision and involve engineers and production staff alike to understand both quality and cost implications of the decisions. Similarly, the stacking of parts within a build chamber will change the thermal characteristics of the process and ultimately part performance. Therefore, prototyping should be done in production batches.

The design and engineering time and resource required to develop applications will be determined by product characteristics and technology selection. For example, developing highly complex product with high quality requirements at low volume through a technology with relatively unknown processes such as SLM will only be justified on products at high costs. Small changes in design often require vast amounts of engineering time to ensure a quality output, therefore this is only justified if the customer is willing to pay for this added cost.

7.2.3.2 Production processes - planning, quality control and AM

Production planning and quality control systems are imperative for production applications of AM processes. For those cases where AM represents a replacement to the conventional approach then the activities will likely be reduced in complexity and present less issues for the company, i.e. for a company with existing production process in place. Production planning techniques are likely to be similar to that of previous processes.

Optimal use of the build platform will be a balance of production cost and quality control upon selection of the technology. It is important that development staff are aware that design guidelines used in prototyping, such as orientation, if changed during production for cost reasons, will change the properties of the component and its performance. Best practice is determined to be developing standard process parameters and adjust CAD rather than continually changing process parameters for each build. This will help to ensure quality assurance between batches.

Furthermore, quality standards should be adopted prior to production, for the conventional producer, this task is likely to be a repeat exercise with some adjustment for the process characteristics. However, for the RP convertor with a lack of standard quality control process in-house this challenge is likely to be greater.

The lack of current in-process monitoring and feedback in AM technologies is a challenge which needs to be overcome by the implementer. Build failures are often not detected until they have caused issues with the entire batch. For high complexity and low level of maturity AM processes, such as DMLS, this absence will be most prominent. Developing supporting systems and quality control practices will be key to overcoming the current lack of in-process monitoring and feedback.

Potential solutions to the absence of in-process monitoring and feedback may include:

- Batch sampling techniques
- Standardised packing techniques

- Standardised process parameters such as scanning strategies
- Materials quality control

Raw materials quality control remains a key determinant of product quality, therefore along the supply chain quality assurance should include raw material traceability and appropriate inspection techniques. Particle size distribution is of particular importance in laser based processes, and this should form the basis for any supplier review in the supplier review process.

7.2.3.3 Integration of processes

The integration of information and processes is one of the key challenges facing AM adopters in developing the operational systems required for production. The current "piecemeal" approach in many applications, which may be suitable in prototyping applications, will have a negative effect on productivity and thus production costs in a manufacturing environment.

Therefore, along the process chain, the nature of front end processes (such as product design, engineering and production planning) may be integrated through the development (or acquisition) of appropriate software tools to automate these resource consuming processes and reduce the requirement for employee involvement. The capacity to develop such tools will be determined by organisations in-house capability, for those with an in-house software development capacity machine vendors should be consultant in the development process.

Due to the "physical" nature of back-end processes such as post-processing, integration of processes will likely require accompanying processing innovations such as automated part handling, stress relieving, support removal and finish machining. Through quality front-end processing, the requirement for these processes may be reduced and therefore the level of integration required. Again, product characteristics will determine the level of post-processing required. At the applications development stage engineers should determine the quality requirements of the components, these include; mechanical properties, surface roughness, tolerances. Table 7.4 below provides a summary of the operational issues and activities for each of the typical cases identified in this study.

Table 7.3. Summary of the operational issues and suggested activities for the typical cases

	RP Convertor	**Conventional Manufacturer**	**New Start-Up**
Issues	1. Increase in process chain complexity 2. Applications Development 3. Integration of AM into production system 4. Post processing requirements	1. Lack of design for process knowledge 2. Design guidelines 3. Engineering processes 4. New production rules	1. Lack of defined process chain 2. Design guidelines 3. Applications development
Contextual factors	History in RP services results in RP systems of operations	Established products but conventional processes	New products and processes
Activities	Quality standards activities	Vertical integration	Quality standards activities
	Process chain mapping		
	Standardised build parameters Dedicated production machines – certification of materials and processes		
	Development of design guidelines including orientation, packing strategies, feature tolerances etc.		
	Identify key customers and collaborate for applications development	Materials development activities	
	Software development for front-end process automation		
	Materials handling automation		
	In process monitoring and feedback development		
	Developing integrative technologies for post-processing time reduction		

7.2.4 Building a supportive structure and culture

The organisational antecedents to implementation will ultimately determine the structure and culture within the organisation. This will determine the established norms and ways of doing things that will ultimately determine the resistance to change and the organisational activities through the implementation stages.

Conventional manufacturers will have to overcome the “this is the way we have always done things” attitude and develop a culture of understanding. Ultimately, this comes down to communication, and education and training of the workforce. To reduce resistance to change this study identified a number of approaches to developing a supportive culture:

- ***Implementation for prototyping/tooling applications*** – staged approach to implementation, provides an introduction to AM process characteristics. To reduce the risk of failure, low capital investment machines, such as polymer extrusion based systems provide an opportunity for experience and knowledge development of AM processes. As development tools for designers, this will provide an important learning step for designers.
- ***Implementation for like-for-like parts*** – contrary to direct design optimisation activities, replicating what can be done with existing processes will reduce the level of change and therefore the likely resistance. Using like-for-like materials will also likely reduce the level of resistance to change. This provides a staged approach to changing the three key dimensions of AM production– product design, process and materials and the established practices in design, engineering and production.

Along these stages, the resistance to change will be reduced, developing a supportive culture through changing the work force mindset. The three key areas of change identified in this study were:

- ***Design*** – New design freedom, but new constraints; design guidelines
- ***Engineering*** – New materials; new metal alloys and polymers, new material properties, new performance characteristics; directionality of mechanical properties.
- ***Production*** – new production rules; new cost drivers, part costs do not necessarily reduce with volumes, new quality drivers; tolerances are a function of part size.

Once again, cultural challenges will be determined by the company's antecedents. From the analysis performed in this study, two dimensions have been developed to describe the values and ways of working which may be present at AM adopters who have an existing organisational culture. For the new start-up although there may not be a previous culture present in the organisation, the supply chain in which they are entering will have, therefore activities in changing culture may be more focused on customers and suppliers values and attitudes.

The cultural clash in AM implementation for production applications will be as a result of a lack of understanding. The case studies show two camps of employees in the design and production roles. Production engineers by their very nature tend to be more conservative in their outlook, with cost and quality being key values the perception of AM technologies will often be heavily influenced by the RP legacy of the processes. Conversely, designers tend to be more "liberal" in their outlook and it is likely that they will embrace the opportunities of AM design freedom, but well be oversold the "complexity for free" philosophy of AM without understanding the cost and quality implications of the process. This has been shown in Section 6.2 of this study.

Activities in this process of cultural change will be determined by the organisational context of implementation. Table below provides an activity and issue for guidance of the project manager.

Table 7.4 The organisational issues and suggested activities for the typical cases

	RP Convertor	**Conventional Manufacturer**	**New Start-Up**
Issue	Speed and flexibility key values in the RP culture	Conservativism – "it's the way we have always done it" attitude Cultural clash of evangelists and conservatives	Developing a balanced culture – both flexibility and control
Contextual reason	History in RP services	History of conventional production	New organisation – culture often based on values of the founder
Activities	Communicate the importance of cost and quality values	Communicate the technology benefits and tradeoffs to designers, engineers and production staff	Communicate the importance of cost and quality values
	Implement standard work practices for quality management	Staged introduction to the process – RP to AM	Implement standard work practices for quality management
	Recruitment of production engineers from target sectors (e.g. aerospace)	Identify gaps in current processes and where AM can fill them	Recruitment of production engineers from target sectors (e.g. aerospace)
	Dedicated production facilities		Dedicated production facilities

7.2.5 Developing the AM supply chain

As part of the technology assessment the company should look at existing supply chains to understand any issues or gaps in the acquisition and implementation process. The initial step in the analysis is the question of whether the company should adopt the technology itself or buy from a capacity seller, the make or buy decision. This decision will likely depend on the company's current approach to manufacture of the product, whether it is currently produced in-house or through a supplier. Importantly, assessment of the capacity seller should include their ability to achieve the production metrics required by the adopter, including quality and reliability etc. A typical AM supply chain is shown Figure 7.4, illustrating the often fragmented supply chain.

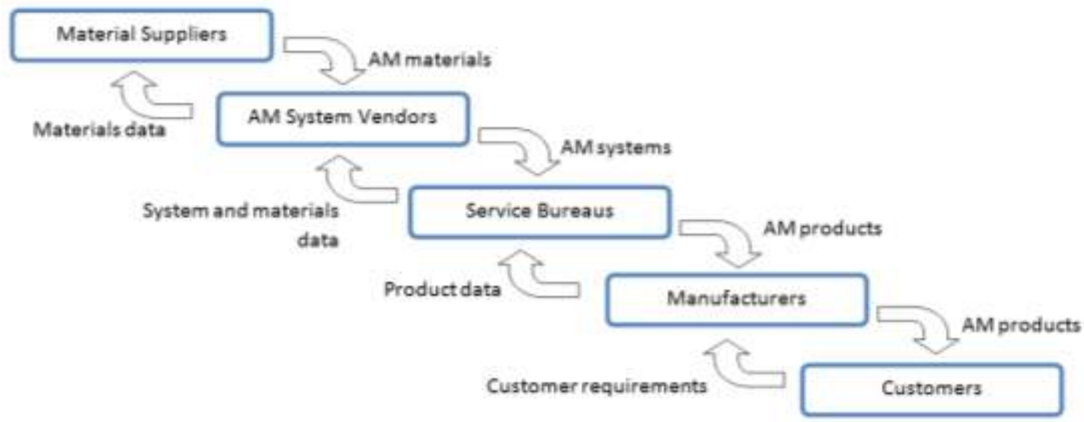

Figure 7.4. The fragmented AM supply chain

Supplier selection is also critical supply chain activity in the implementation process. Due to the lack of maturity of the technologies a number of key characteristics will likely provide a narrow scope of potential suppliers. These include materials availability, restrictive practices, process constraints (build platform size etc.) and the system offering in terms of productivity and quality control. The conclusions of this assessment may support a decision to vertically integrate and acquire or develop an AM system during the implementation process.

The use of RP service bureaus provides an opportunity for applications development prior to investment. For higher capital investment cost machines, such as SLM and DMLS, this provides some level of risk mitigation in developing the business case. Importantly, where manufacture will be conducted will be a key decision along the supply chain included in the make or buy analysis. Once the process has been proven through service bureaus (i.e. product requirements are met in terms of quality and costs etc.), the decision to invest will or continue to use capacity sellers should take into account the usual make or buy analysis tools. Tuck et al. provides a case of such an assessment and correctly point out the costing issues with direct quotation from service bureaus as a base for decision making.

Characteristics of the AM industry which have been identified during this study which should be considered in this analysis include the following:

- The service bureaus ability to meet production requirements – many applications development centres will have a history in RP services which will ultimately determine their in-house capabilities. The assessment of systems of operations will determine the ability of the supplier to effectively move up the supply chain as a manufacturer.
- Service bureaus design approach – during the application development cycle the design guidelines used by the capacity seller, such as orientation, will affect the product characteristics such as cost, mechanical properties etc. This data must be captured are retained when moving to production as any changes in the various build parameters and envelope optimisation will result in product changes
- Level of design, process and material change – the degree to which the three dimensions of the operations change will determine the resistance to change within the organisation, therefore this will be a key determinant in the decision to implement in-house or use a bureau.

Distributing manufacturing according to demand will be dependent on the technology and product characteristics. For example, distributing DMLS production of aerospace components is not achievable given the current maturity of the process, current tradeoffs of AM systems and the requirements for a support production system. However, for non-engineering and non-safety critical components, such gift items etc., the distributed production of components is already a reality. Products with short process chains and low quality levels can be distributed according to demand with relatively low levels of capital investment and space requirements. Thus for certain products/application the distributed AM supply chain is possible; however, manufacturers should still evaluate the benefits of such an approach.

Table 7.5 Supply chain issues and suggested activities for the typical cases

	RP Convertor	**Conventional Manufacturer**	**New Start-Up**
Issue	Lack of established supply chain Perception of prototyping service bureaus	Cost of AM materials Fragmented AM supply chain	Entering new supply chains
Contextual reason	History in RP services	Established supply chain	New organisation
Activities	Develop the systems of operations	Vertical integration	Develop the systems of operations
	Identify key customers and collaborate for applications development	Materials and process development	Integrate product offering
	Develop supporting customer facing technologies: software solutions	Joint ventures for supply chain development	Open source approach
	Communicate requirements effectively to machine vendor		Identify key customers and collaborate for applications development

7.3 The Framework Applied in the Pre-implementation Cases

The section provides a review of the pre-implementation cases investigated as part of this study. Four cases were taken, representing early stages of the implementation cycle and different case scenarios identified through this thesis. Two of the cases were new start-ups, one with target applications in the engineering sector and one in the food and gift sector. For these cases, the researcher was actively involved in each of the cases and provided support in developing implementation plans for the new start-ups, moving towards an action research approach to research methodology.

The remaining case was large multinationals with an existing product mix, established customers base and manufacturing processes. This case the research methodology followed the interview with the AM project managers, as in the previous study. Table 7.7 below provides characterisation of the three cases used in the pre-implementation study.

Table 7.6 Characterisation of the pre-implementation case studies including informants

Company name	Company Size	Type.	Stage of implementation	Informants/ position	Typical case
BAE Systems	Large Multinational	SLA	SLA used for prototyping	[1] Core engineering team leader	Conventional Manufacturer
HiTA Tech Ltd	Micro SME	None	Not implemented any AM systems	[1] Director [2] Engineering Manager	New start-up
ChocEdge Ltd	Micro SME	Extrusion based process	Not implemented any AM systems	[1] Director [2] Business development manager	New start-up

7.3.1 BAE Systems

7.3.1.1 Introduction to the case study

The interview was held at the case company manufacturing site in, and the informant was the core engineering team leader, a team put together to focus on investigating the use of AM across each of the business lines. The case company was a large multinational with approximately 15,000 employees. The organisation was split into three lines of business:

- Combat air
- Defence information, training and services
- F-35 aircraft

Production volumes were identified to be 2000-3000 F15 aircraft, 200-300 Typhoons (upgrading around 100-200 parts annually) and 20-40 UAVs (unmanned air vehicles). The mission statement of the company was stated by the informant:

"*Working as an integral part of the team delivering superiority and effective air power, our aim is to give real advantage to our customers worldwide. Trusted to deliver always*"

At the time of inquiry the AM activity at the company was limited and the informant admitted "we are a little behind". At this time the company had only an SLA capacity used for prototyping and tooling for the past 10-15 years. As expected the applications of SLA were driven by time savings in new product development.

7.3.1.2 Developing the Business Case

The approach to implementation was focused on establishing joint funding for technology developments; these included University collaborations and the use of applications development centres (or service bureaus). The engineering team was set up three years prior to the interview and was composed of design engineers, aerodynamics engineers, materials specialist and a structural engineer. The informant suggests the team is structured to cover all the required expertise.

As a large multinational, the business case development was a formal process requiring detailed justification for implementation. Further, an emphasis on the business case was highlighted given the contextual factors of the case study. Contextual factors included the challenge in the current financial climate, with the informant advocating budgets across the business units were much tighter and therefore:

> "*the business case has to be right*"

The main drivers proposed by the informant for using AM technologies as a manufacturing technologies were cost, lead time and engineering efficiencies. At time of enquiry the focus was on non-structural parts and developing the business case on a number of pilot components. Cost/benefit analysis was used in the business case development.

The standard process for developing a business case at the company was to prove the process on a like-for-like part, followed by optimisation of the part for the process. The challenge stated by the informant was that AM processes were often not competitive on like-for-like parts.

Existing processes in-house were mainly CNC and this is where the in-house core capability lies. The informants perceived the metal AM technology barriers to be build speed is highlighted as an area of improvement due to contribution to part cost and the build size whereas in polymer systems the build size was seen as less of an issue.

Developing the business case for AM implementation at the case may follow a staged approach to identifying applications at the case company:

- ***Low volume production*** - When competing with CNC, the arguments for lack of tooling become less convincing. One area of technology benefit on which AM may provide significant benefit prior to design optimisation is the material usage argument. Large billets of titanium are often machined down significantly and buy to fly ratios of 9:1 are often cited in the aerospace cases. Therefore, the business case may be made on the AM potential for 100% material utilisation. In practice, a level of virgin powder is likely required per AM build, however compared to machining significant benefits may be achieved. Therefore, machine suppliers should be consulted to understand the requirements for virgin powder and R&D activities either internally or through development centres should follow this theme. The measure of this benefit should include; reduced material holdings (associated risk), work-in-progress, material waste costs etc. For Titanium this argument is enhanced by the relative high cost and market volatility as highlighted by the informant.

- ***Design optimisation*** - either combined with the above, or following implementation for like-for-like parts the business case for design optimisation should be assessed. Again the competing processes should be considered, in this case CNC. Depending on the type of CNC, 5-axis etc., the design constraints on the product should be assessed and the possibilities for engineering efficiencies identified.

7.3.1.3 Developing the Systems of Operations

Quality control is central given the target product applications at the case study. Managing part variability was a major concern for the project leader. This understanding of the quality factors in AM represents one of the key activities for the AM implementer. An initial focus on Titanium (Ti-64) components puts a focus on metallic AM process for manufacturing application, given the focus of this research, powder-bed processes were the main consideration as a manufacturing technology. How to manage part variability was a key challenge as safety is critical in the application area. Aluminium alloys were also considered at the case however as it is easy to process and low cost it was deemed that the business case would not be as strong. Technology standards will be developed in-house given the applications of the processes, and although the absence was noted, the company would often only reference an external standard rather than use it directly in part validation.

At the product design stage the company used CATIAVS design package, an industry standard design solution. The challenge for the case company was that this package did not lend itself to AM design guidelines; therefore its suitability was questionable for design tasks during implementation. A significant knowledge and experience gap highlighted during the interviews was the lack of design for process knowledge, with one of the main challenges being the development of design and material guidelines for AM processes, requiring new design and structural analysis tools. Within these design guidelines product specifications must include the orientation of the part in the build chamber and how the products are fixtured to the platform. Given the product applications and order winners, the following operational activities were identified to be central to AM implementation success at the case company:

- Process chain mapping
- Developing the design guidelines for each product
- Developing standardised build parameters, again, for each product
- Dedicated production machines – certification of materials and processes
- Materials development activities
- In process monitoring and feedback development
- Integrating supportive technologies for post-processing time reduction

7.3.1.4 Building a Supportive Structure and Culture

On structural changes, the informant suggested that it would not be a structural change in engineering but possibly more in manufacturing. This was supported by the characteristics of the organisational context with its current in-house manufacturing activity being based around CNC in titanium. Therefore, similar to Renishaw, the cultural challenges were most apparent in manufacturing given the level of change along this dimension. The staged approach outlined in the previous section provides an opportunity to reducing resistance to change along with reducing risk of implementation failure. Also, the use of capacity sellers and universities would continue to develop the applications whilst reducing the risk of investment failure.

7.3.1.5 Developing the AM Supply Chain

With an established customer base the company did not have issues with attracting customers; supply chain issues were therefore further upstream on the supply side. Key issues with the current AM supply chain for the company were identified as cost and quality management. These include:

- ***Material traceability***. Due to the critical nature of the products, quality management throughout the supply chain was a product requirement.

- ***Cost of AM materials*** when compared to conventional billet/stock materials. Though this is somewhat mitigated with establishing what is already an expensive material, Titanium, the argument for Aluminium becomes less convincing along this issue.

- ***Whether to make or buy.*** Again this will be made based on a product case by case base; however given the current AM industry characteristics this assessment should follow the guidance within the previous section.

Activities proposed during the supply chain development process were materials and process development through joint ventures with application development centres and universities. This would reduce the risk for the adopting company given their relative low level adoption.

7.3.2 HiTA Technologies Ltd

7.3.2.1 Introduction to the case

The case company was a new start up as an IP generating company for heat exchanger and heat engine products designed for metallic AM production (DMLS, SLM) with target markets in automotive, aerospace and combined heat and power. The key challenge for the company was identified as access to finance and resource, the business strategy was based on developing products using various funding streams including government grants.

Based on the analysis of new start-ups the key to achieving success of implementation is the business model adopted. The business model is one based on the design freedoms of AM and protecting the knowledge and design of products. This is obviously contrary to the case of Reprap therefore though the "typical case" does not reflect the same business strategy the importance of the implementation factors may well be the same.

7.3.2.2 Developing the business case

The business case for the company is based on new product innovation, developing new products with increased engineering performance and potential cost savings in AM. Design optimisation was the key to the product offering and the company core business of IP generation and licensing. The technologies considered during this business case development were powder-bed metal laser systems, SLM and DMLS. High capital investment cost, running costs and process complexity create a barrier to investment for the micro SME and therefore support the strategy of using application development centres at the early stages of adoption. Target applications were automotive and aerospace customers and the business case for each was outlined:

- ***Aerospace (Commercial and Defence):*** the business case is made on the potential for reducing component size and weight resulting in mass fuel savings along the product life-cycle and increasing the range aircraft. Volumes in this area around 100 units a year and component costs tend to be high therefore the case for AM implementation is high. Quality remained the major concern in this application case because of the risk of product failure.
- ***Automotive:*** the business case for the automotive sector was based on engineering efficiencies, cost savings and weight savings for range extended electric vehicles. Volumes in this market were potentially 50,000 units a year, for these reasons this application was key to implementation success and were the focus of this case study, identifying activities and likely issues along the implementation process.

7.3.2.3 Developing the Systems of Operations

As the company do not have an existing product base or manufacturing system the company must develop the process chain itself and this is conducted through process chain mapping, from CAD to final part production. Along this process chain the various supporting systems of operations are developed.

Through collaboration with service bureaus and machine vendors the company developed an internal knowledge base for AM design guidelines, using a wiki knowledge transfer tool; this communication also helps educates engineer on material considerations and mechanical properties of AM components.

Running in parallel with the application development (product) the company also develops the manufacturing process with both service bureaus and machine vendors, with key activities including:

- Quality standards activities
- Standardised build parameters
- Materials development activities
- In process monitoring and feedback development
- Batch sampling techniques

7.3.2.4 Building a Supportive Structure and Culture

As a new start up, the culture of the company will be heavily influenced by the beliefs of the company founders. As such, founders focus on the values of flexibility and control, flexibility for speed of decision making but maintaining quality and cost control. As a new start-up based on AM product ideas it is likely the company will have technology evangelists, required to effectively sell the technology to potential customers and investors. However, the company should work to develop the understanding of when conventional processes are more suitable. A balance of production engineers and design engineers will assist in this culture development, as a micro SME, communication between employees is aided and employees are naturally more empowered.

7.3.2.5 Developing the AM Supply Chain

One of the key challenges for the company was the lack of an established customer base and therefore how to enter the required supply chain. With target applications in the automotive and aerospace sectors, the two industry groups present very different challenges and resulting approaches. Aerospace customers were already aware of the technologies the case company is using and therefore the resistance to change is lower. However, long certification periods represent a key challenge to the organisation, this was particularly evident as the case company products represent both a design and manufacturing process change, along with potential a material change.

In the automotive sector, the challenges of technology acceptance and the perception of "only good for prototyping" are more apparent. The key order winners in the automotive sector are cost and quality with typical defects rates of zero expected. As such the systems of operations along with the continued communication and collaboration with systems vendors were identified as key determinants of implementation success.

7.3.3 Choc Edge Ltd

7.3.3.1 Introduction to the Choc Edge Ltd case study

This case study represents a unique technology in the field of 3D printing and pioneering research in exploiting a digital co-creation approach in order to realise its commercial adoption. In 2007 Dr Liang Hao, a senior lecturer in materials at the University of Exeter, conceived the idea of combining 3D printing and chocolate processing to promote new applications and develop a disruptive manufacturing technology capable of creating unique, artistic and personalised chocolate products whilst capturing commercial opportunities.

Groups of engineering students at the University of Exeter developed an experimental ChocALM prototype machine and following some key technical developments (reducing system cost, improving usability etc.), Dr Liang Hao founded a spin-out company called Choc Edge Ltd to commercialise 3D chocolate printing technology. In April 2012, the company made the first commercial 3D chocolate printer, named the Choc Creator 1 (Figure 7.5).

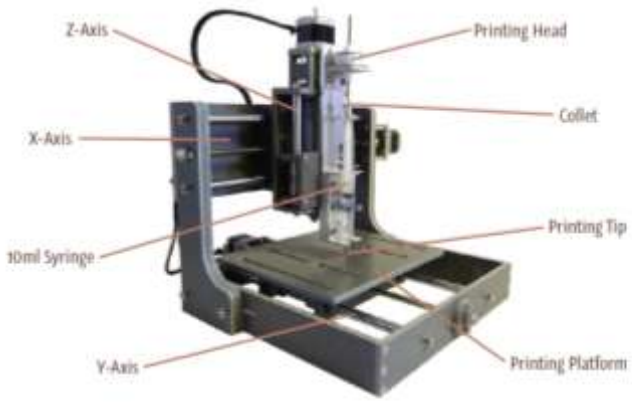

Figure. 7.5 Overview of Choc Creator One 3D printer

The project led by Exeter University, also developed a web-based utility, Coco Works, to allow users and designers to create chocolate products through a downloadable design tool. Based on Google Sketch up, a unique add-on user interface was developed ago enable users with no design experience to design 3D chocolate products.

Coco Works also provides the facility for designers to share their designs with other users, facilitating the co-creation of chocolate products. Users may also access the gallery of chocolate designs and order the physical product through a built in quotation and scheduling system. These products are then manufactured and distributed to customers through one of two options; either through the centralised manufacturing facility managed by the company Choc Edge Ltd or through Choc Creator 1 printer owners.

7.3.3.2 Developing the Business Case (model)

The case study showed a new start-up company based on a technology innovation; apply the principles of 3D printing with a new raw material - chocolate. The first decision along the business strategy dimension was to determine the product offering of the company, whether to be a machine vendor or AM product producer. This assessment should consider the potential application areas and routes to market, including:

- ***Customised products*** – for the case company the opportunity to produce customised products at a competitive cost is one of the key opportunities in the market. Competition in this application will be conventional methods of customising – hand piping by trained workers. The process will therefore likely be assessed based on process speed and product quality. Both these parameter should be a focus of R&D should this be the chosen business model.
- ***Low volume production*** – conventional moulding process limit product applications in the low volume markets as moulding costs result in high product costs. The removal of such cost for ChocEdge creates a market opportunity for producing low volume products at a lower cost than conventional processes. In this case process speed and cost may be less of an issue.
- ***High value/innovative designs*** – the new design freedom allowed by AM in this application creates opportunities for high value/innovative designs ones which customer may be willing to pay a premium price due to novelty. This business model relies on the design being core skill of the organisation, therefore this should be reflected in the organisational and operation actions plans.

Furthermore, there is opportunity to adopt the business model of open source to support the above, similar to the Reprap case, adding value to the product offering through providing an integrated solution for the customer. However, the key difference is the application area, food products, which may not hold the same value to the 3D printing hobbyist community as plastic components. Furthermore, the core technology benefit is not self replication, but added value to existing products or developing new products, therefore the consideration on whether to adopt an open-source approach will be determined by the target applications described previously.

7.3.3.3 Developing the Systems of Operations

The process chain from design to production is described below:

Step 1: Conceptualisation and digitisation of 3D design

The product idea and design can be conceptualised and digitised through any of a number of means; designed in 3D modelling software, reversed engineered through 3D scanning technology, 2D image converted to 3D model, or downloaded from file sharing websites.

Step 2: Conversion to STL file format

The design, or data, generated in the previous step is then converted into an STL.

Step 3: Import into system software

At this stage the STL file is imported into the machine control software package. In this case study the software was a modified open source package called Replicator G

Step 4: Machine set-up

Depending on the product features and specification the machine parameters are then set using the machine control software.

Step 5: Production

The raw material is then prepared, the chocolate is heated, tempered and loaded in the syringe system. Once loaded and located in the correct position, the manufacturing cycle is then initiated. The G-Code generated by the control software, controls the movement of the stepper motor system according to the original model file. The part is build up in successive layers until the final layer is produced.

Step 6: Product completion

Once the manufacturing cycle has finished the part is left to cool and is ready for consumption or shipping.

The application choice will drive the system of operations choices to be made during implementation. Key issues along the process chains along with potential activities to develop the systems of operations are provided below:

Design and Engineering Processes

One of the key issues along the process chain is capturing the customer data and transferring this into a useable 3D file for the printing process. The choice of application area will ultimately drive what data is to be captured and from there software tools should be developed to streamline front-end processes ensuring that the number of steps and human interaction with the process is reduced to keep down costs, whilst ensuring the quality of the data is maintained throughout the process.

Production planning and quality control

The technology maturity is the key determinant to quality control in the case study. Quality control issues are mainly around material quality control, process parameter optimisation and design file quality. Through quality front end process, the quality of the systems product may be increased. Furthermore, the adoption of best practices for material preparation and storage along with standard process parameters will reduce failure and improve defect rates.

Integration of processes

The business model will ultimately determine the level of process integration required. For production applications, higher volumes will require higher levels of integration to ensure quality and cost targets can be met. Software tools should be developed to integrate front end processes including data capture, product design and process planning. Processes including material loading, part removal and packaging may be integrated through automation activities and further technical development.

7.3.3.4 Developing the Supply Chain

The supply chain issues and activities during implementation will ultimately be determined by the business model choice. For production applications the key decision for the case company is whether to make the products in-house or work with key technology users and collaborate to develop the technology maturity. The later will reduce the risk of market failure but likely require result in longer development cycles to tailor product offerings to customer requirements. Furthermore, there is a requirement for customer training on the technology benefits and tradeoffs; with technology awareness in the target sector was particularly low, the knowledge gap is an issue which must be overcome during this collaborative activity.

Without licensing fees associated with the product, how the company continues to generate income from selling machines should be considered. Producing products in-house may protect the knowledge and value of the case company product offering. To attract and maintain customers, integrated solutions should be developed for key customers, including; software solutions, materials handling processes and materials development (including optimised parameters for customer chocolate compositions).

Distributing manufacturing according to demand is facilitated by the technology characteristics of low levels of post-processing. However, the lack of an established customer base and technology maturity remained constraints to this approach to supply chain development. Therefore, collaboration with key users remains the more attractive supply chain solution in the short term.

7.4 Summary of the Chapter

This chapter has provided the cross-case analysis of the proposed three typical cases, the RP convertors, the conventional manufacturer, and the new start-up. Key issues and activities were compared along the various contextual and technology dimensions and the analysis provided an understanding of the process of AM implementation in each of these cases, and proposed justifications for different approaches. This analysis was then used to develop a process model for the AM implementer, along the different typical cases. Four stages of implementation were developed including; developing the business case, developing the systems of operations, building a supportive structure and culture, and finally developing the AM supply chain.

Using this revised AM process framework, three further cases studies were then conducted to test its performance for companies at the early stages of adoption. Specifically, this work provided results of how the framework can be used in the two of the typical cases to develop implementation plans, to reduce the risk of failure and assist project managers in understanding the likely issues and required activities in the implementation of AM. The cases used in this analysis fit into two of the typical case study categories of new start-ups and conventional manufacturer. A limitation of this section of the study is that it did not include an RP convertor. The following, and final, chapter of this study further describes the contributions and limitation of the study.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.0 Conclusions

The final chapter of this thesis concludes the study by discussing the main contributions of the research. It also describes the limitations of the study and the methods by which the study's findings were enhanced. Finally, the implications of the study and the future directions of research are provided.

The objectives set out in the first chapter of this thesis have been fulfilled. The first objective was achieved through the development of a normative framework for the implementation of AM technologies for manufacturing applications. The framework, presented in Figure 5.5, divides implementation activities and issues into five key dimensions; strategic, technological, organisational, operational and supply chain and identifies four key phases of AM implementation; the development of the business case, developing the organisational action plan, developing the operational action plan and developing the AM supply chain.

The second objective, to capture the key technical and non-technical factors in the process of AM implementation, was achieved through the development of a generic process of implementation activities and issues. The process model presented in Figure 7.3 defines the relationships between the technical factors and the organisations, operational, strategic and supply chain practices of the adopting organisations.

Finally, the third objective, to identify where these key factors have been encountered and managed in different organisations, was achieved through the defining and utilising cases with different organisational contexts. Investigating their implementation approach, identifying key issues and activities encountered at the various stages of AM implementation.

8.1 Contributions of the Study

The study offers three possible contributions to the field of AM research. The first and most significant is the normative framework for the implementation of Additive Manufacturing. The framework describes the main activities of AM implementation and describes the how these activities are related to the contextual and technical factors of the process. Moreover, it explains how AM project managers in the manufacturing sector may use the model in developing their own implementation plans along the strategic, technology, organisational, supply chain and operational dimensions. At the time of writing there has been very few studies focusing on the study of AM implementation, and no studies using real data from cases studies (or through any other method) to describe the AM implementation process.

The study also shows the similarities and differences between frameworks for other manufacturing technologies, such as the group known as AMTs. The main distinctions that can be made from the AMT implementation approaches include the following:

- The significance of the RP legacy – in terms of how the industry has evolved, the processes themselves, their perception and finally the organisation that have implemented. Therefore, the implementation framework must include this important factor.
- The new design, engineering and production principles required for AM implementation are different to those that have come before - As such the implementers understanding of these differences are critical to the success of adoption. The significant changes in manufacturing operations identified in this study influence the approach to implementation and therefore support the requirement for a new framework.
- The diversity of AM systems benefits and tradeoffs and therefore the role they can play in different applications and new business models - Specifically, the opportunities in open source, distributed production and true customisation must be considered in the AM implementation framework if AM project managers are to capture the benefits of these processes.

The study has also highlighted the vast differences between implementation of AM for production to those implementing for prototype. Some of these are to be expected, and are embedded in the definitions of both "prototyping" and "production". However, the nature and context under which implementation has occurred has provided an insight into the challenges with moving from prototyping to production along the organisation, operational, supply chain and technology dimensions.

The second contribution of the study is the comparison of the technology differences of different AM processes and their effect on the implementation process adopted. Furthermore, the comparison also includes the contextual differences apparent in the AM industry and definition of three different approaches to AM adoption according to these contextual differences. The explanation highlights the key issues experienced by the three typical cases, how they differ and the contextual and technological reasons for these issues, identifying the areas where more emphasis should be given by the project managers. Within the technology context of AM, the study has not only explored the differences between conventional (subtractive and formative) processes and AM, but has also between the various AM technologies. Specifically, the study provides a comparison between implementation of the polymer and metal systems shown in section 7.2. Furthermore, the study has provided an approach to achieving the technology benefits and tradeoffs of the different AM processes through staged implementation.

Finally, the third contribution of the study is the identification of the research problem in AM implementation. The study highlights the lack of AM implementation studies in the literature, specifically highlighting the lack of socio-organisational aspects of the technology deployment. As was highlighted in the literature review and research framework chapters of this study, innovation does not ensure success. The study has highlighted that the successful adopters of potentially disruptive process innovation often share contextual and technology similarities along with conducting activities in a certain way. This study has provided some insight into how organisational aspects of AM influence the implementation process.

8.2 Limitations of the Study

This study although providing an important insight into the implementation process, has a number of limitations and has highlighted many potential fruitful areas of future research. One limitation is the sample size. Although the research has justified its selection of cases, and used a robust research methodology, the size of sample may limit the generalisability of the findings and may limit its acceptance with project managers. However, using background theory combined with the case study analysis has reduced the risk of misinterpretation of the case findings.

A significant limitation of the study is the assessment of the supply chain factors in the implementation process. Time and resource constraints did allow the researcher to explore all potential supply chain factors that may be incurred by the groups presented in the taxonomy. However, a foundation for future research has been built from the perspective of the adopting organisation. Specifically, supply chain factors in this study focused on the relationships between suppliers and vendors, the level of vertical integration and the location of manufacture. Further work should consider the effects of AM implementation on both materials and data flows throughout the supply chains and how this may affect the implementations at the typical cases.

Another limitation is the study did not include all AM processes within the sample cases, processes such as Electron Beam Melting (EBM) have been applied for production applications of AM and were not included in this study. However, the processes selected during the case selection process were those identified to be the most "potentially disruptive" based on informal interviews with industry experts. Furthermore, there are many similarities between EBM and SLM for example which suggests the issues and activities encountered by project managers will likely share some similarities.

8.3 Implications of the Study

The study adds to the state-of-the-art knowledge of AM implementation and has a number of implications in research community. Studies to date have focused on the technical aspect of AM, including materials and process development along with design guidelines. This study moves beyond this limited understanding of implementation and raises the organisational aspects of the process. The study is the first of its kind in AM research, with real case studies of AM implementers, developing AM implementation models from the experiences of project managers. Cases were selected to represent the typical cases of AM implementation and had achieved some level of business success through implementation.

In addition, where issues have been identified in earlier technology implementation research, such as resistance to change, the study defines the details of this resistance and provides relationships between them and other unique issues/activities to form the framework of AM implementation process. The study has also shows that the process is not only a technical implementation, i.e "just another tool in the workshop". Rather, the study has shown that to achieve the greatest value of AM technology, it should be considered as a manufacturing strategy implementation process, with all supporting infrastructural and structural changes implemented during the process. One significant finding in this study was the implementation of AM for mass customisation and how this had been achieved in the case of Renishaw.

Depending on the organisational context and technology choice the study has a number of implications for project managers of AM implementation. As a structural change in manufacturing strategy, the study proposes a process model, Figure 7.3, for project managers to understand the role of AM in their organisation and the process the project manager they can ensure the technology is embedded in organisation successfully. Firstly, and perhaps most importantly, is that AM managers should understand how to build the business case for AM technologies. Cost-benefit analysis, with a comparison to competing technologies, is one common method used during this justification process. The "level" of implementation (prototyping – production) will define the length and resource requirement of this process. Importantly, cost benefit analysis and comparison to competing technologies should include potential product benefits, enabled through the design freedom including product life-cycle analysis. The typical case taxonomy will provide guidance as to how this process can be conducted.

Furthermore, the typical case taxonomy provides project managers with a tool to assess the issues and activities prior to implementation. The process models presented in the study may be used by project managers to develop organisation and operational actions plans during the implementation process.

8.4 Future Research Direction

One area of future research, which may provide useful insight, is the additive manufacturing impact of supply chains and supply chain management practice. This study confined the supply chain study to the understanding of the issues and activities related to customer and suppliers relationships, and the decisions of where to locate manufacturing. Not considered in depth in this study, was the impact of stock levels and inventory costs etc. associated with the integration of components and de-materialisation of the supply chain [20]. Holstrom et al. [13] discussed these impacts in their works and although they were not investigated at length in this study, the researcher believes they would present a significant contribution to the field of AM research and provide potential adopters with key data on the impact of AM implementation.

Future research may also take different sources of evidence. Rather than rely on retrospective accounts of AM project managers, future studies may focus on direct observation of the implementation process. Direct observation may reduce some of the inaccuracy that may have occurred through using retrospective accounts of project managers; however there will still be possibilities of misinterpretations of the process. Researchers following such an approach should take such an approach as to reduce the likelihood of the event proceeding differently because it is being observed. Indeed this approach was taken in the pre-implementation cases presented in this study. However, although these cases provided insight into how the process models could be used for further cases, the author concedes the action research methodology used in this study could be improved and further work is required in this area.

Future studies may also look to increase the size of the sample taken. Furthermore, they may also repeat this study in different settings including manufacturing sectors in different countries. As reported in Wohler's report [25] there are a large number of countries using these technologies in different continents. These approaches may strengthen the normative framework of AM implementation and increase the generalisability of the findings.

Although there are a growing number of companies considering and adopting AM technologies, equally, there are many manufacturing organisations that have not adopted and do not consider AM as viable manufacturing process. Taking a sample of non-adopters, potentially including implementers who have implemented for prototyping and then chosen not to use the technologies for production, may also provide further insight into the process of implementation.

With AM still far from being an accepted manufacturing technology in many industries, yet at the same time experiencing rapid growth in terms of industry size, there are likely to be many fruitful areas for research in both technical and non-technical fields of study.

REFERENCES

[1] ASTM Standard, “Standard Terminology for Additive Manufacturing Technologies,” vol. 10.04.

[2] S. Bradshaw, A. Bowyer, and P. Haufe, “The Intellectual Property Implications of Low-Cost 3D Printing,” *SCRIPTed*, vol. 5, no. 7:1, 2010.

[3] E. C. Santos, M. Shiomi, K. Osakada, and T. Laoui, “Rapid manufacturing of metal components by laser forming,” *International Journal of Machine Tools and Manufacture*, vol. 46, no. 12–13, pp. 1459–1468, Oct. 2006.

[4] I. Gibson, *Additive Manufacturing technologies rapid prototyping to direct digital manufacturing*. New York: Springer, 2010.

[5] N. Hopkinson, R Hague, and P. Dickens, *Rapid manufacturing : an industrial revolution for the digital age*. Chichester England: John Wiley, 2006.

[6] L. Hao, S. Mellor, O. Seaman, J. Henderson, N. Sewell, and M. Sloan, “Material characterisation and process development for chocolate additive layer manufacturing,” *Virtual and Physical Prototyping*, vol. 5, no. 2, pp. 57–64, 2010.

[7] “Print me a Stradivarius,” *The Economist*, 10-Feb-2011.

[8] “Solid print: Making things with a 3D printer changes the rules of manufacturing,” *Economist*, London, Apr-2012.

[9] M. Campbell, “Absolutely fabricated: the sceptic’s guide to 3D printing,” *New Scientist*, vol. 216, no. 2895, pp. 46–49, Dec. 2012.

[10] R. Ehrenberg, “The 3-D printing revolution: Dreams made real, one layer at a time,” *Science News*, vol. 183, no. 5, pp. 20–25, 2013.

[11] J. Holmström, J. Partanen, J. Tuomi, and M. Walter, “Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment,” *Journal of Manufacturing Technology Management*, vol. 21, no. 6, pp. 687–697, 2010.

[12] E. Atzeni and A. Salmi, “Economics of additive manufacturing for end-usable metal parts,” *he International Journal of Advanced Manufacturing Technology*, vol. 62, no. 9, pp. 1147–1155, Oct. 2012.

[13] D. E. Cooper, M. Stanford, K. A. Kibble, and G. J. Gibbons, “Additive Manufacturing for product improvement at Red Bull Technology,” *Materials & Design*, vol. 41, pp. 226–230, Oct. 2012.

[14] V. Petrovic, J. Vicente Haro Gonzalez, O. Jordá Ferrando, J. Delgado Gordillo, J. Ramón Blasco Puchades, and L. Portolés Griñan, “Additive layered manufacturing: sectors of industrial application shown through case studies,” *International Journal of Production Research*, vol. 49, no. 4, pp. 1061–1079, 2011.

[15] M. Ruffo, C. Tuck, and R. Hague,, “Make or buy analysis for rapid manufacturing,” *Rapid Prototyping Journal*, vol. 13, no. 1, pp. 23–29, 2007.

[16] M. Ruffo and R. J. M. Hague, “Cost estimation for rapid manufacturing — simultaneous production of mixed components using laser sintering,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 221, no. 11, pp. 1585–1591, 2007.

[17] M. Ruffo, C. Tuck, and R. Hague, “Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 220, no. 9, pp. 1417–1427, 2006.

[18] C. Tuck and R. J. Hague, “The pivotal role of rapid manufacturing in the production of cost effective customised products,” *International Journal of Mass Customisation*, vol. 1, no. 2–3, pp. 360–373, 2006.
[19] C. J. Tuck, R. J. M. Hague, M. Ruffo, M. Ransley, and P. Adams, “Rapid manufacturing facilitated customisation,” *International Journal of Computer Integrated Manufacturing*, vol. 21, no. 3, pp. 245–258, 2008.
[20] C. Tuck, R. Hague, and N. Burns, “Rapid manufacturing: impact on supply chain methodologies and practice,” *International Journal of Services and Operations Management*, vol. 3, no. 1, pp. 1–22, 2007.
[21] A. Gunasekaran, “Agile manufacturing: A framework for research and development,” *International Journal of Production Economics*, vol. 62, no. 1–2, pp. 87–105, May 1999.
[22] A. Gunasekaran, “Agile manufacturing: enablers and an implementation framework,” *International Journal of Production Research*, vol. 36, no. 5, pp. 1223–1247, 1998.
[23] P. Rochus, J.-Y. Plesseria, M. Van Elsen, J.-P. Kruth, R. Carrus, and T. Dormal, “New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation,” *Acta Astronautica*, vol. 61, no. 1–6, pp. 352–359, June, 2007.
[24] C. A. Voss, “Implementation: A key issue in manufacturing technology: The need for a field of study,” *Research Policy*, vol. 17, no. 2, pp. 55–63, Apr. 1988.
[25] Wohlers Associates, “Wohlers Report 2013,” 2013.
[26] M. P. Groover, *Fundamentals of Modern Manufacturing.*, 3. ed. Hoboken NJ: Wiley, 2007.
[27] J.-P. Kruth, M. C. Leu, and T. Nakagawa, “Progress in Additive Manufacturing and Rapid Prototyping,” *CIRP Annals - Manufacturing Technology*, vol. 47, no. 2, pp. 525–540, 1998.
[28] A. K. Sood, R. K. Ohdar, and S. S. Mahapatra, “Parametric appraisal of mechanical property of fused deposition modelling processed parts,” *Materials & Design*, vol. 31, no. 1, pp. 287–295, Jan. 2010.
[29] P. Kulkarni, A. Marsan, and D. Dutta, “A review of process planning techniques in layered manufacturing,” *Rapid Prototyping Journal*, vol. 6, no. 1, pp. 18–35, 2000.
[30] G. N. Levy, R. Schindel, and J. P. Kruth, “Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state-of-the-art and future perspectives,” *CIRP Annals - Manufacturing Technology*, vol. 52, no. 2, pp. 589–609, 2003.
[31] A. Y. C. Nee, J. Y. H. Fuh, and T. Miyazawa, “On the improvement of the stereolithography (SL) process,” *Journal of Materials Processing Technology*, vol. 113, no. 1–3, pp. 262–268, Jun. 2001.
[32] K. Chockalingam, N. Jawahar, U. Chandrasekar, and K. N. Ramanathan, “Establishment of process model for part strength in stereolithography,” *Journal of Materials Processing Technology*, vol. 208, no. 1–3, pp. 348–365, Nov. 2008.
[33] “Rapid Prototyping - Stereolithography (SLA).” [Online]. Available: http://www.custompartnet.com/wu/stereolithography. [Accessed: 01-Mar-2014].
[34] J. Wang and L. L. Shaw, “Rheological and extrusion behavior of dental porcelain slurries for rapid prototyping applications,” *Materials Science and Engineering A*, vol. 397, no. 1–2, pp. 314–321, Apr. 2005.
[35] L. M. Galantucci, F. Lavecchia, and G. Percoco, “Experimental study aiming to enhance the surface finish of fused deposition modeled parts,” *CIRP Annals - Manufacturing Technology*, vol. 58, no. 1, pp. 189–192, 2009.

[36] K. Thrimurthulu, P. M. Pandey, and N. Venkata Reddy, “Optimum part deposition orientation in fused deposition modeling,” *International Journal of Machine Tools and Manufacture*, vol. 44, no. 6, pp. 585–594, May 2004.
[37] C. Bellehumeur, L. Li, Q. Sun, and P. Gu, “Modeling of Bond Formation Between Polymer Filaments in the Fused Deposition Modeling Process,” *Journal of Manufacturing Processes*, vol. 6, no. 2, pp. 170–178, 2004.
[38] R. Anitha, S. Arunachalam, and P. Radhakrishnan, “Critical parameters influencing the quality of prototypes in fused deposition modelling,” *Journal of Materials Processing Technology*, vol. 118, no. 1–3, pp. 385–388, Dec. 2001.
[39] “Fused Deposition Modeling (FDM).” [Online]. Available: http://www.custompartnet.com/wu/fused-deposition-modeling. [Accessed: 01-Mar-2014].
[40] K. Senthilkumaran, P. M. Pandey, and P. V. M. Rao, “Influence of building strategies on the accuracy of parts in selective laser sintering,” *Materials & Design*, vol. 30, no. 8, pp. 2946–2954, Sep. 2009.
[41] “ATKINS - Manufacturing a Low Carbon Future,” *A feasibility study report published by Loughborough University and Econoloyst in subnission for DTI funding. Available online at: www.econoloyst.co.uk/pdf/publications/ZEEFSReportN0012J.pdf*.
[42] “Rapid Prototyping - Selective Laser Sintering (SLS).” [Online]. Available: http://www.custompartnet.com/wu/selective-laser-sintering. [Accessed: 01-Mar-2014].
[43] K. A. Mumtaz and N. Hopkinson, “Selective Laser Melting of thin wall parts using pulse shaping,” *Journal of Materials Processing Technology,* vol. 210, no. 2, pp. 279–287, Jan. 2010.
[44] “DMLS - Direct Metal Laser Sintering.” [Online]. Available: http://www.custompartnet.com/wu/direct-metal-laser-sintering. [Accessed: 01-Mar-2014].
[45] O. L. A. Harrysson, O. Cansizoglu, D. J. Marcellin-Little, D. R. Cormier, and H. A. West II, “Direct metal fabrication of titanium implants with tailored materials and mechanical properties using electron beam melting technology,” *Materials Science and Engineering: C*, vol. 28, no. 3, pp. 366–373, Apr. 2008.
[46] B. Mueller and D. Kochan, “Laminated object manufacturing for rapid tooling and patternmaking in foundry industry,” *Computers in Industry,* vol. 39, no. 1, pp. 47–53, Jun. 1999.
[47] S. Mellor, L. Hao, and D. Zhang, “Additive manufacturing: A framework for implementation,” *International Journal of Production Economics,* vol. 149, pp. 194-201, 2014.
[48] E. Rogers, *Diffusion of innovations*, 4th ed. New York: Free Press, 1995.
[49] G. Moore, *Crossing the chasm*, 2. edition, repr. Oxford: Capstone, 2007.
[50] S. Mellor, L. Hao, and D. Zhang, “An Overview of Business Models and Strategy of Additive Manufacturing,” in *Proceedings of the Eleventh National Conference on Rapid Design. Prototyping and Manufacturing*, Lancaster, 2010, pp. 153–162.
[51] T. Grimm, *User’s guide to rapid prototyping*. Dearborn Mich.: Society of Manufacturing Engineeers, 2004.
[52] J. Giannatsis and V. Dedoussis, “Additive fabrication technologies applied to medicine and health care: a review,” *International Journal Advanced Manufacturing Technology,* vol. 40, no. 1, pp. 127-116, Jan. 2009.
[53] R. Bibb and J. Winder, “A review of the issues surrounding three-dimensional computed tomography for medical modelling using rapid prototyping techniques,” *Radiography,* vol. 16, no. 1, pp. 78–83, Feb. 2010.

[54] P. S. D'Urso, W. J. Earwaker, T. M. Barker, M. J. Redmond, R. G. Thompson, D. J. Effeney, and F. H. Tomlinson, "Custom cranioplasty using stereolithography and acrylic," *British Journal of Plastic Surgery*, vol. 53, no. 3, pp. 200–204, Apr. 2000.
[55] B. Vandenbroucke and J.-P. Kruth, "Selective laser melting of biocompatible metals for rapid manufacturing of medical parts," *Rapid Prototyping Journal*, vol. 13, no. 4, pp. 196–203, 2007.
[56] D. H. Freedman, "Layer by layer," *MIT Technology Review*, vol. 115, no. 1, pp. 50–53, 2012.
[57] P. Reeves, "Additive Manufacturing - A supply chain wide response to economic uncertainty and environmental sustainability," in *7th International Conference on Industrial Tools and Material Processing Technologies*, Ljubljana, Slovenia, 2009.
[58] J. Munguia, J. de Ciurana, and C. Riba, "Pursuing successful rapid manufacturing: a users' best-practices approach," *Rapid Prototyping Journal*, vol. 14, no. 3, pp. 173–179, 2008.
[59] M. Walter, H. Jan, and Y. Hannu, "Rapid manufacturing and its impact on supply chain management," in *Logistics Research Network Annual Conference*, Dublin, Ireland, 2004.
[60] N. Hopkinson and P. Dickens, "Analysis of rapid manufacturing - using layer manufacturing processes for production.," *Journal of Mechanical Engineering Science*, vol. 217, no. C1, pp. 31–39, 2003.
[61] R. Hague, S. Mansour, and N. Saleh, "Material and design considerations for rapid manufacturing," *International Journal of Production Research*, vol. 42, no. 22, pp. 4691–4708, 2004.
[62] W. Skinner, "Operations Technology: Blind Spot in Strategic Management," *Interfaces*, vol. 14, no. 1, pp. 116–125, Feb. 1984.
[63] J. Friar and M. Horwitch, "The emergence of technology strategy: A new dimension of strategic management," *Technology in Society*, vol. 7, no. 2–3, pp. 143–178, 1985.
[64] O. D. Jones Smith, "Strategic Technology Management in a Mid-corporate Firm: the Case of Otter Controls," *Journal of Management Studies*, vol. 34, no. 4, pp. 511–536, 1997.
[65] A. Drejer, "Frameworks for the magement of technology: towards a contingent approach," *Technology Analysis & Strategic Management*, vol. 8, no. 1, pp. 9 – 20, 1996.
[66] L.-A. Lefebvre, A. Langley, J. Harvey, and É. Lefebvre, "Exploring the strategy-technology connection in small manufacturing firms," *Production and Operations Management*, vol. 1, no. 3, pp. 269–285, 1992.
[67] R. H. Hayes and W. J. Abernathy, "Managing Our Way to Economic Decline," *Harvard Business Review*, vol. July-Aug, pp. 138–149, 1980.
[68] W. Skinner, "Manufacturing - missing link in corporate strategy," *Harvard Business Review*, vol. May-June, pp. 136–45, 1969.
[69] M. E. Porter, "Towards a dynamic theory of strategy," *Strategic Management Journal*, vol. 12, no. S2, pp. 95–117, 1991.
[70] J. D. Goldhar and M. Jelinek, "Computer Integrated Flexible Manufacturing: Organizational, Economic, and Strategic Implications," *INTERFACES*, vol. 15, no. 3, pp. 94–105, 1985.
[71] R. Hayes and S. C. Wheelwright, *Restoring our competitive edge : competing through manufacturing*. New York: Wiley, 1984.
[72] S. Davenport, C. Campbell-Hunt, and J. Solomon, "The dynamics of technology strategy: an exploratory study," *R&D Management*, vol. 33, no. 5, pp. 481–499, 2003.

[73] A. De Meyer and C. H. Loch, “Technology strategy,” in *Handbook of New Product Development Management*, Oxford: Butterworth-Heinemann, 2008, pp. 27–48.
[74] M. Dodgson, *The management of technological innovation : strategy and praxis*, [2. ed.], completely rev. and updated. Oxford UK: Oxford University Press, 2008.
[75] K. Pavitt, “What we know about the strategic management of technology,” *California Management Review*, no. Spring, pp. 17–26, 1990.
[76] D. Ford, “Develop your Technology Strategy,” *Long Range Planning*, vol. 21, no. 5, pp. 85–95, Oct. 1988.
[77] J. Solomon, “The Role of Technology Strategy in the Evolution of Competitive Advantage in Successful New Zealand Firms,” Master of Management Studies Research Project, Victoria University of Wellington, New Zealand, 2001.
[78] L. Steele, *Managing technology : the strategic view*. New York: McGraw-Hill, 1989.
[79] F. Betz and Knovel (Firm), *Managing technological innovation competitive advantage from change*. Hoboken, NJ :: John Wiley,, 2003.
[80] P. Tingling and M. Parent, “An exploration of enterprise technology selection and evaluation,” *The Journal of Strategic Information Systems*, vol. 13, no. 4, pp. 329–354, Dec. 2004.
[81] J. C. Anderson, G. Cleveland, and R. G. Schroeder, “Operations strategy: A literature review,” *Journal of Operations Management*, vol. 8, no. 2, pp. 133–158, 1989.
[82] R. H. Hayes and R. Jaikumar, “Requirements for successful implementation of new manufacturing technologies,” *Journal of Engineering and Technology Management*, vol. 7, no. 3–4, pp. 169–175, Mar. 1991.
[83] R. Hayes and G. Pisano, “Beyond World Class: The New Manufacturing Strategy,” *Harvard Business Review*, vol. 72, no. 1, pp. 77–86, 1994.
[84] I. Chen and M. Small, “Implementing advanced manufacturing technology: An integrated planning model,” *Omega*, vol. 22, no. 1, pp. 91–103, Jan. 1994.
[85] Small and M. M. Yasin, “Developing a framework for the effective planning and implementation of advanced manufacturing technology,” *International Journal of Operations & Production Management*, vol. 17, pp. 468–489, May 1997.
[86] R. B. Handfield and M. D. Pagell, “An analysis of the diffusion of flexible manufacturing systems,” *International Journal of Production Economics*, vol. 39, no. 3, pp. 243–253, May 1995.
[87] E. Mansfield, “The Diffusion of Flexible Manufacturing Systems in Japan, Europe and the United States,” *Management Science*, vol. 39, no. 2, pp. 149–159, 1993.
[88] E. Mansfield, “New evidence on the economic effects and diffusion of FMS,” *Engineering Management, IEEE Transactions*, vol. 40, no. 1, pp. 76–78, 1993.
[89] W. Belassi and A. Fadlalla, “An integrative framework for FMS diffusion,” *Omega*, vol. 26, no. 6, pp. 699–713, Dec. 1998.
[90] S. Saberi, R. M. Yusuff, N. Zulkifli, and M. M. H. M. Ahmad, “Effective Factors on Advanced Manufacturing Technology Implementation Performance: A Review,” *Journal of Applied Sciences*, vol. 10, no. 13, pp. 1229–1242, 2010.
[91] A. Hill, *Manufacturing operations strategy.*, 3rd ed. /. Basingstoke: Palgrave Macmillan, 2009.
[92] P. M. Swamidass and M. A. Waller, “A classification of approaches to planning and justifying new manufacturing technologies,” *Journal of Manufacturing Systems*, vol. 9, no. 3, pp. 181–193, 1990.
[93] Y. Kim and J. Lee, “Manufacturing strategy and production systems: An integrated framework,” *Journal of Operations Management*, vol. 11, no. 1, pp. 3–15, Mar. 1993.

[94] G. S. Dangayach and S. G. Deshmukh, “Manufacturing strategy: Literature review and some issues,” *International Journal of Operations & Production Management*, vol. 21, no. 7, pp. 884–932, 2001.
[95] C. A. Voss, “Alternative paradigms for manufacturing strategy,” *International Journal of Operations & Production Management*, vol. 15, no. 4, pp. 5–16, 1995.
[96] W. Skinner, “The focused factory,” *Harvard Business Review*, vol. May-June, pp. 3–14, 1974.
[97] J. G. Miller and A. V. Roth, “A Taxonomy of Manufacturing Strategies,” *Management Science*, vol. 40, no. 3, pp. 285–304, Mar. 1994.
[98] M. T. Frohlich and J. R. Dixon, “A taxonomy of manufacturing strategies revisited,” *Journal of Operations Management*, vol. 19, no. 5, pp. 541–558, Oct. 2001.
[99] R. H. Hayes and S. C Wheelwright, “Link manufacturing process and product life cycles,” *Harvard Business Review*, vol. Jan-Feb, pp. 133–140, 1979.
[100] J. Woodward, *Industrial organization : theory and practice*, 2d ed. Oxford ;;New York: Oxford University Press, 1980.
[101] R. Schonberger, *World class manufacturing : the next decade : building power, strength, and value*. New York: Free Press, 1996.
[102] P. Burcher and K. Stevens, “Measuring up to world class manufacturing,” *Control*, vol. 22, no. 1, pp. 17–21, 1996.
[103] J. Meredith, “Building operations management theory through case and field research,” *Journal of Operations Management*, vol. 16, no. 4, pp. 441–454, Jul. 1998.
[104] R. Yin, *Case study research : design and methods*, 3rd ed. Thousand Oaks Calif.: Sage Publications, 2003.
[105] C. Voss, N. Tsikriktsis, and M. Frohlich, “Case research in operations management,” *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 195–219, 2002.
[106] K. M. Eisenhardt, “Building Theories from Case Study Research,” *The Academy of Management Review*, vol. 14, no. 4, pp. 532–550, Oct. 1989.
[107] W. Schramm, “Notes on case studies of instructional media projects,” in *Working Paper for the Academy for Educational Development*, Washington, DC, 1971, vol. December.
[108] I. Benbasat, D. . Goldstein, and M. Mead, “The case research strategy in studies of information systems,” *MIS Quarterly*, vol. 11, no. 3, pp. 369–386, 1987.
[109] C. Flyvbjerg, “Five Misunderstandings About Case-Study Research,” *Qualitative Inquiry*, vol. 12, no. 2, pp. 219–245, 2006.
[110] C. Nachmias and D. Nachmias, *Research methods in the social sciences*, 4th ed. London: Edward Arnold, 1992.
[111] J. D. Linton, “Implementation research: state of the art and future directions,” *Technovation*, vol. 22, no. 2, pp. 65–79, Feb. 2002.
[112] R. J. Bateman, “Devolved Manufacturing: A novel approach and implementation methodology for mass customization,” PhD thesis, Leeds Metropolitan University, 2005.
[113] R. Narasimhan and J. Jayaram, “Reengineering service operations: a longitudinal case study,” *Journal of Operations Management*, vol. 17, no. 1, pp. 7–22, Dec. 1998.
[114] P. Åhlström and C. Karlsson, “Change processes towards lean production: The role of the management accounting system,” *International Journal of Operations & Production Management*, vol. 16, no. 11, pp. 42–56, 1995.
[115] R. S. Weiss, *Learning from strangers: the art and method of qualitative interview studies*. New York: Free Press, 1995.

[116] M. D. Myers and M. Newman, “The qualitative interview in IS research: Examining the craft,” *Information and Organization*, vol. 17, no. 1, pp. 2–26, 2007.
[117] U. Flick, E. von Kardorff, I. Steinke, and U. Flick, *A companion to qualitative research*. London; Thousand Oaks, Calif.: Sage Publications, 2004.
[118] H. Matsumoto and D. Wilson, “Testing a rigorous execution of grounded theory using comparative cross-cultural case studies of strategic global IS managament of investment banks,” in *4th European Conference on Research Methodology for Business and Management Studies, Université Paris Dauphine, Paris France*, 2005, pp. 323–336.
[119] R. R. Harmon, H. Demirkan, and E. Chan, “Redefining market opportunities through technology-oriented service innovation,” *Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET ’11:*, pp. 1–10, Jul. 2011.
[120] S. A. Zahra and J. G. Covin, “Business strategy, technology policy and firm performance,” *Strategic Management Journal*, vol. 14, no. 6, pp. 451–478, 1993.
[121] A. S. Sohal, “A longitudinal study of planning and implementation of advanced manufacturing technologies,” *International Journal of Computer Integrated Manufacturing*, vol. 10, no. 1, pp. 281–295, 1997.
[122] P. T. Ward and R. Duray, “Manufacturing strategy in context: environment, competitive strategy and manufacturing strategy,” *Journal of Operations Management*, vol. 18, no. 2, pp. 123–138, Feb. 2000.
[123] C. K. Carlson, E. P. Gardner, and S. R. Ruth, “Technology-Driven Long-Range Planning,” *Journal of Information Systems Management*, vol. 6, no. 3, pp. 24 – 29, 1989.
[124] K. Pandza, A. Polajnar, and B. Buchmeister, “Strategic management of advanced manufacturing technology,” *The International Journal of Advanced Manufacturing Technology*, vol. 25, no. 3–4,pp. 402 - 408, 2004.
[125] R. Parthasarthy and S. P. Sethi, “The Impact of Flexible Automation on Business Strategy and Organizational Structure,” *The Academy of Management Review*, vol. 17, no. 1, pp. 86–111, Jan. 1992.
[126] V. Sonntag, “The role of manufacturing strategy in adapting to technological change,” *Integrated Manufacturing Systems*, vol. 14, no. 4, pp. 312–323, 2003.
[127] M. J. Maffei and J. Meredith, “The Organizational Side of Flexible Manufacturing Technology: Guidelines for Managers,” *International Journal of Operations & Production Management*, vol. 14, no. 8, pp. 17–34, 1994.
[128] H. Noori, *Managing the dynamics of new technology : issues in manufacturing management*. Englewood Cliffs N.J.: Prentice Hall, 1990.
[129] T. Federici, “Factors influencing ERP outcomes in SMEs: a post-introduction assessment,” *Journal of Enterprise Information Management*, vol. 22, no. 1/2, pp. 81–98, 2009.
[130] P. Schubert, J. Fisher, and L. Uwe, “ICT and Innovation in SMall Companies,” in *Proceeding of the 15th Europoean Conference on Information Systems*, St. Gallen, 2007, vol. June 07–09, pp. 1226–1239.
[131] J. Y. L. Thong, C.-S. Yap, and K. S. Raman, “Top Management Support, External Expertise and Information Systems Implementation in Small Businesses,” *Information Systems Research*, vol. 7, no. 2, pp. 248–267, 1996.
[132] J. A. Welsh and J. F. White, “A Small Business is Not a Little Big Business,” *Harvard Business Review*, vol. 59, no. 4, pp. 18–32, 1981.
[133] A. Ghobadian and D. N. Gallear, “Total quality management in SMEs,” *Omega*, vol. 24, no. 1, pp. 83–106, Feb. 1996.

[134] J. Tidd, J. Bessant, and K. Pavitt, *Managing innovation : integrating technological, market and organizational change*, 3rd ed. Hoboken: Wiley, 2005.
[135] M. L. Tushman and P. Anderson, *Managing strategic innovation*, 1st ed. [s.l]: Oxford University Press, 1997.
[136] M. E. Burkhardt and D. J. Brass, "Changing Patterns or Patterns of Change: The Effects of a Change in Technology on Social Network Structure and Power," *Administrative Science Quarterly*, vol. 35, no. 1, pp. 104–127, Mar. 1990.
[137] N. Rosenberg, *Technology and American economic growth*. New York: Harper & Row, 1972.
[138] D. R. Dalton, W. D. Todor, M. J. Spendolini, Gordon J. Fielding, and L. W. Porter, "Organization Structure and Performance: A Critical Review," *The Academy of Management Review*, vol. 5, no. 1, pp. 49–64, Jan. 1980.
[139] J. W. Dean, S. J. Yoon, and G. I. Susman, "Advanced Manufacturing Technology and Organization Structure: Empowerment or Subordination?," *Organization Science*, vol. 3, no. 2, pp. 203–229, 1992.
[140] Abdul Ghani K., Jayabalan V., and Sugumar M., "Impact of advanced manufacturing technology on organizational structure," *Journal of High Technology Management Research*, vol. 13, pp. 157–175, Sep. 2002.
[141] Sun Xiao-lin, Tian Ye-zhuang, and Cui Guo-gang, "The Empirical Study on the Impact of Advanced Manufacturing Technology on Organizational Structure and Human Resources Management," in *Management Science and Engineering, 2007. ICMSE 2007*, pp. 1548–1553, 2007.
[142] R. Millen and A. S. Sohal, "Planning processes for advanced manufacturing technology by large American manufacturers," *Technovation*, vol. 18, no. 12, pp. 741–750, Oct. 1998.
[143] J. Hage and M. Aiken, "Program Change and Organizational Properties a Comparative Analysis," *American Journal of Sociology*, vol. 72, no. 5, p. 503, 1967.
[144] A. Gupta, I. J. Chen, and D. Chiang, "Determining organizational structure choices in advanced manufacturing technology management," *Omega*, vol. 25, no. 5, pp. 511–521, Oct. 1997.
[145] A. H. van de Ven, "A Framework for Organization Assessment," *The Academy of Management Review*, vol. 1, no. 1, pp. 64–78, Jan. 1976.
[146] P. T. Ward, G. K. Leong, and K. K. Boyer, "Manufacturing Proactiveness and Performance*," *Decision Sciences*, vol. 25, no. 3, pp. 337–358, 1994.
[147] M. K. Malhotra, M. L. Heine, and V. Grover, "An evaluation of the relationship between management practices and computer aided design technology," *Journal of Operations Management*, vol. 19, no. 3, pp. 307–333, May 2001.
[148] Joseph R. Muscatello, Michael H. Small, and Injazz J. Chen, "Implementing enterprise resource planning (ERP) systems in small and midsize manufacturing firms," *International Journal of Operations & Production Management*, vol. 23, no. 8, pp. 850–871, 2003.
[149] H. Zhao and H. C. Co, "Adoption and implementation of advanced manufacturing technology in Singapore," *International Journal of Production Economics*, vol. 48, no. 1, pp. 7–19, Jan. 1997.
[150] E. Schein, *Organizational culture and leadership*, 2nd ed. San Francisco: Jossey-Bass, 1992.
[151] C. M. McDermott and G. N. Stock, "Organizational culture and advanced manufacturing technology implementation," *Journal of Operations Management*, vol. 17, no. 5, pp. 521–533, Aug. 1999.

[152] Adedeji O. Esan, Mohammed K. Khan, Hong S. Qi, and Craig Naylor, "Integrated manufacturing strategy for deployment of CADCAM methodology in a SMME," *Journal of Manufacturing Technology Management*, vol. 24, no. 2, pp. 257–273, 2013.
[153] J. Bailey, *Managing people and technological change*. London: Pitman, 1993.
[154] A. Gunasekaran, "Implementation of computer-integrated manufacturing: a survey of integration and adaptability issues," *International Journal of Computer Integrated Manufacturing*, vol. 10, no. 1, pp. 266 – 280, 1997.
[155] A. Gunasekaran, H. B. Marri, and B. Lee, "Design and Implementation of Computer Integrated Manufacturing in Small and Medium-Sized Enterprises: A Case Study," *The International Journal of Advanced Manufacturing Technology*, vol. 16, no. 1, pp. 46–54, Jan. 2000.
[156] R. Hague, I. Campbell, and P. Dickens, "Implications on design of rapid manufacturing," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 217, no. 1, pp. 25-30, 2003.
[157] S. Mansour and R. Hague, "Impact of rapid manufacturing on design for manufacture for injection moulding," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 217, no. 4, pp. 453 –461, Apr. 2003.
[158] T. Vollmann, *Manufacturing planning and control systems*, 4th ed. New York: Irwin/McGraw-Hill, 1997.
[159] J. Olhager and M. Rudberg, "Linking manufacturing strategy decisions on process choice with manufacturing planning and control systems," *International Journal of Production Research*, vol. 40, no. 10, pp. 2335 – 2351, 2002.
[160] W. L. Berry and T. Hill, "Linking Systems to Strategy," *International Journal of Operations & Production Management*, vol. 12, no. 10, pp. 3–15, 1993.
[161] D. M. Schroeder, S. W. Congden, and C. Gopinath, "Linking Competitive Strategy and Manufacturing Process Technology," *Journal of Management Studies*, vol. 32, no. 2, pp. 163–189, 1995.
[162] G. C. Stevens, "Integrating the Supply Chain," *International Journal of Physical Distribution & Logistics Management*, vol. 19, no. 8, pp. 3–8, 1993.
[163] D. R. Towill, "The seamless supply chain - the predators strategic advantage," *International Journal of Technology Management*, vol. 13, no. 1, pp. 37–56, 2003.
[164] J. Ben Naylor, M. M. Naim, and D. Berry, "Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain," *International Journal of Production Economics*, vol. 62, no. 1–2, pp. 107–118, May 1999.
[165] E. D. Rosenzweig, A. V. Roth, and J. W. Dean, "The influence of an integration strategy on competitive capabilities and business performance: An exploratory study of consumer products manufacturers," *Journal of Operations Management*, vol. 21, no. 4, pp. 437–456, Jul. 2003.
[166] J. Bessant, "Towards total integrated manufacturing," *International Journal of Production Economics*, vol. 34, no. 3, pp. 237–251, Jun. 1994.
[167] T. F. Burgess, H. K. Gules, and M. Tekin, "Supply-chain collaboration and success in technology implementation," *Integrated Manufacturing Systems*, vol. 8, no. 5, pp. 323–332, 1997.
[168] J. M. Utterback and W. J. Abernathy, "A dynamic model of process and product innovation," *Omega*, vol. 3, no. 6, pp. 639–656, Dec. 1975.
[169] M. Zairi, "Measuring Success in AMT Implementation Using Customer-Supplier Interaction Criteria," *International Journal of Operations & Production Management*, vol. 12, no. 10, pp. 34–55, 1993.

[170] M. Zairi, “Supplier partnerships for effective advanced manufacturing technology implementation: a proposed model,” *Integrated Manufacturing Systems*, vol. 9, no. 2, pp. 109–119, 1998.
[171] R. R. Lummus and R. J. Vokurka, “Defining supply chain management: a historical perspective and practical guidelines,” *Industrial Management & Data Systems*, vol. 99, no. 1, pp. 11–17, 1999.
[172] M. H. Small and I. J. Chen, “Economic and strategic justification of AMT inferences from industrial practices,” *International Journal of Production Economics*, vol. 49, no. 1, pp. 65–75, Mar. 1997.
[173] J. D. Ford and J. W. Slocum, “Size, Technology, Environment and the Structure of Organizations,” *The Academy of Management Review*, vol. 2, no. 4, pp. 561–575, Oct. 1977.
[174] R. F. Zammuto and E. J. O’Connor, “Gaining Advanced Manufacturing Technologies’ Benefits: The Roles of Organization Design and Culture,” *The Academy of Management Review*, vol. 17, no. 4, pp. 701–728, Oct. 1992.
[175] K. A. Ghani and V. Jayabalan, “Advanced manufacturing technology and planned organizational change,” *The Journal of High Technology Management Research*, vol. 11, no. 1, pp. 1–18, Spring 2000.
[176] J. Miltenburg, *Manufacturing strategy : how to formulate and implement a winning plan*, 2nd ed. New York: Productivity Press, 2005.
[177] R. J. Bateman and K. Cheng, “Rapid Manufacturing as a tool for agile manufacturing: application and implementation perspectives,” *International Journal of Agile Manufacturing*, vol. 9, no. 1, pp. 39–52, 2007.
[178] R. J. Bateman and K. Cheng, “Extending the product portfolio with ‘devolved manufacturing’: methodology and case studies,” *International Journal of Production Research*, vol. 44, no. 16, pp. 3325–3343, 2006.
[179] R. Bateman and K. Cheng, “Devolved Manufacturing,” *Concurrent Engineering*, vol. 10, no. 4, pp. 291–298, 2002.
[180] T. Hill, *Manufacturing strategy : text and cases*, 2nd ed. Basingstoke: Palgrave, 2000.
[181] M. W. Lewis and K. K. Boyer, “Factors impacting AMT implementation: an integrative and controlled study,” *Journal of Engineering and Technology Management*, vol. 19, no. 2, pp. 111–130, Jun. 2002.

APPENDIX A

RENISHAW INTERVIEW TRANSCRIPTS

Company: Renishaw

Informant: JP

Position: Rapid Manufacturing Manager

SM: what is your specific role at Renishaw, and within AM?

JP: the department has been going about seven years and we started off initially just prototyping in electronics so it was all about getting the product development lead times down and very much just prototyping and not production, just electronics, PCBs stuff like that...erm... then we moved into 3D printing or Additive Manufacturing for plastics initially with an FDM machine...erm.. which was a nice low cost entry point and then we added to that out SLS machine our EOS SLS machine which was obviously at much higher cost and at that stage then it became applicable for manufacturing, production work not just prototyping. So what we tend to do is we run the two of them together. So we still do prototyping and we do manufacturing as well. Now in some cases the fact that they are done concurrently is quite useful and SLS lends itself to that process very well because you have this three dimensional build envelope, you can build parts on top of parts because there are no support. Obviously when it comes to metals production you have supports, anchors, supports erm so that then becomes a restrictive and your costs go up and your capacity is reduced by that, but SLS lend itself quite well, so what we can do, what we very often do is we will put large parts be they production or prototype it doesn't matter in the build envelope but then of course a lot of the cost comes from the powder that is used so it is the Z height of the total build so what we tend to do is to put smaller parts around the big bits to try and keep the cost down. Now the mix of the parts that we get to build every week is obviously different because it depends whatever has come up that week we don't sort of schedule it months in advance or whatever because we have to be reactive to prototyping needs so what we do is we have a number of production parts which are smaller and we pack them into the build envelope where we can space wise and then we literately put them aside and make them available on as a kanban supply. So somebody phones up and they say I want these and you go yeah alright and you open up the toting tray and there are some bits already made and you just ship them off and you replace them with other bits. Now one of the characteristics of Additive Manufacturing, especially SLS, being a thermal process is that to get the proper of level consistency like you would need with certifying parts for aerospace and stuff like this you have to replicate the conditions for the build. So in the case of packing bits around other bits, if you've got small bits that are next to big bits, the big bit hold the heat later the whole cooling characteristics will change and the cooling characteristics define the way that the parts distort and form as they cool that is the critical phase erm so the bits that we pack around are bits with large tolerances. So if there's anything with small tolerances we can't do that now if we were using the machine for production all the time we could tighten up the tolerances by dedicating an area of the build or the entire build to just production and having the layout the same every single time erm and that would make it more repeatable. But one of the other things with SLS is that the tolerances you can hold are a function of the size of the part so with big parts you're holding slacker tolerances than you are with small parts. So you have to take that into account so that then becomes a design consideration so if its the case of outer covers and things like this there large its just a matter of explaining to the designer well this is gonna change by plus or minus 3mm now this a different way of thnking from a design perspective than CNC and injectuion moulding and stuff like this because in those cases its right what are the tolerances in my CNC machineand then you get back answercould be whatever it is, plus or minus twenty microns, what you don't get is an answer than comes back that says, it depends on the bit. But with Additive it does. And that's the same in metals as it is in plastic. This is where one of things fall down, where people say about Additive Manufacturing of one offs, now if you're gonna make a one thats fine but to a certain extent you don't know what you're gonna get until it goes out of the machine, now you can put anchors on and learn all sorts of little things like part orientation and stuff like this, that's great that will get you a to a sensible guess of the best way to build it but really and honestly you need to build a bit, then inspect it and compensate either with the build parameters or preferably the STLs so you're not always chasing build parameters in the machine, erm and then rebuild. So when people say oh we can make one-off high value items it can but your tolerances, you're not gonna know exactly what you're gonna get out. So that kind of falls down. So in the case of jewellery and some stuff like that its doesn't matter we get morph all over the place and certainly if you look at Shapeways for example we interviewed the CEO of Shapeways a little while ago and he said I don't care about accuracy and my customers don't care about accuracy you know they want bits which are repeatable and robust and obviously at the right price, or atleast at the right price to make a profit on. So he really doesn't care about it. So the priorities are different for him than they would be for a normal manufacturing stream where you want to get it right first time and you understand the characteristics of the process. The process for Additive changes all the time, and that fine, if you can live with that. You can design around it, its not problem but have to take that into account.

SM: So what kinds of volumes to do you get on the production work?

JP: Well in the case of the dental one erm we kind of average about a hundred and twenty units a day, now if you've got a twelve unit bridge, that's twelve units if you've got a single coping thats one unit. So its not necessarily one hundred and twenty work pieces, its one hundred and twenty units it could be up to hundred and eighty, a hundred and nineity or it could be way down but its about a hundred and twenty is an average.

SM: and that's on how many DMLS systems? You have one machine at the minute?

JP: Yeah one machine at the minute. We run each evening.

SM: So you get higher machine utilisation by running it in the evening?

JP: It's all about the lead time of the parts, because we get the parts and we ship them off to the dental labs. Now in that case you're competing against investment casting and a lot of the larger dental labs have investment casting in-house so there used to short lead times. And what you can do on the DMLS basically you're only replicating the same sort of lead times you can have with investment casting you're not necessarily beating them but what you are doing is your taking people out because of the people who have to be there and prep up the waxes and all that sort of thing and thats where you're cost advantage, its not in terms of timescales or anything like that.

SM: Is there a quality improvement too, removing people from the process?

JP: Yeah there is, in terms of consistency, because obviously with investment casting its abit hit and missed depending on the operator. Whereas with this its hopefully its reproducible and again because dental lends itself quite well because the parts are so small whereas with you know hip implants replacement bones and stuff like that you get a much larger part so distortion are much more pronounced. But of course the other thing if you're making bones additively you can create the internal structures. So you can sort assist in osteo integration and stuff like this because there is. Because there is quite a, the natural bone is a very cunning lightweight structure and when your sort of doing facial implants and things like this replacement jaw bones there finding that the weight differential in an implant and a natural bone does make quite a difference over the life time of the patient.

SM: So is the design for that done in-house? For the dental product or do you supply software...?

JP: We actually manufacture are own software, are own CAD software erm which then goes out to the dental labs and we make our own scanning machines but that neither here nor there because you can use other peoples scanning machines. But once you got the geometry of what's called the prep, thats the stuff the dentist leaves once he's ground it away erm the CAD software is virtually automated in terms of how is knowcks out the parts and puts in the cement gaps and stuff like that . The final shape that the person has to live with is still dictated by the technicians in the dental who puts the porcelain on, so all we're doing is looking basically to cover the prep and join them together and the final tooth shape cavity and how it matches and meshes with the upper teeth and the opposite teeth is still dictated by the lab technicians.

SM: Do you have a process planning tool for the production system?

JP: yes again thats done with our own in-house software so the CAD and the automated planning and the automated billing stuff is written by us so the lab literally just does there own designs, submits the part and then that then erm creates several files, one of which is the prescription that then goes to the patient and theres things like customer information, and one of those files is the STL file which when then used to build and thats automatically generated by our software.

SM: And as far as finishing did you have to acquire a lot of machining skill or machining equipment?

JP: the finishing is done by hand.....so when a part, well we will go in and have a look but when the parts come off the machine you'll see they still got the supports on. A single unit can be taken off straight away but when you get to erm multi units the distortion, the thermal distortion is much higher so what you have to do is put it through a stress reliever before you can take the supports off. So those supports are then broken off literally using pliers, again we will go look at this next door, and then hand ground. Because again you're not looking for the final geometry so basically what you are looking to do is just take off the support and then its bead blast and sent out. That is still a very antiquated and labouring process when you consider its you know a half million euro machine and its all you know so say high tech and then you've got some poor bugger sat in there literally hand grinding these pieces down its very antiquated.

SM: So how many people are on this team?

JP: In this department there are ten. So what we try and do is wherever possible we have open access equipment. So the design team provide their own resource to come down and do prototyping and obviously that doesn't apply to production work. Workstations such as the SLS erm are too highly skilled for the designers so we operate that and we run it once a week or twice a week depending on how many jobs are coming through but things like our FDM machine and our polyjet printers and stuff like that and laser cutters the design team come down and use that themselves.

SM: So what was the motivation behind getting the dental. Was it because you were already established in dental so it was a natural move?

JP: So to give you the full story. We had what was called a Digitalising Product Division so we build scanning machines and probes to reverse engineer parts so you could take a geometry like that it would inspect that and create a file and machine to reverse engineer for injection mould tools things like that. That technology when it is was bought out was all fast and wonderful and great but then obviously time flew buy and it becamse slow and number of machines cells went down so we were then arpproach by a company called Preser Forte (check name) to create a single tooth scanner so what they wanted they wanted a machine that would take a single coping and basically digitised that for them. So that went to out digitising product division, they then developed this product which then went out as a Forte product not a Renishaw product and we essentially made those for them, that then gave us an entry from digitising into the dental market. What we then did we started to create our own scanning machines so went from a single tooth scanner to a whole bridge scanner so now we've got ones that will take a whole jaw if you like. An that again was going back to Renishaws core technology that we developed for scanning and recording geometries. Now once that was done and we had then at the point a bigger presence in the dental market we then identified that we wanted to go into manufacturing of Zirconia crowns and bridges so what we did is we basically erm did some further engineering on our scanning platform and turned it into a machining platform so what you end up having is you have a cutter at the base and the mechanism that actually drives the work piece over that static cutter to cut the tooth form is the same mechanism that was used in the scanner only this time was being driven by CAM program. So we did that and then once we'd then established ourselves in the market as suppliers of ceramic tooth parts in the UK the ratio of ceramic to non-precious metals not all cobalt chrome but non precious metals is about nine to one so there's nine, its completely different ratios depending on where you are in the world over in the states there's much higher ratios of ceramic because people are prepared to pay the premium price erm so the non precious metals are a cheap alternative but the volumes are higher so we decided to get into metals. Now we looked at all sorts of alternatives in terms of machining and casting and all sorts of things like that and basically ended up deciding to go on the DMLS route for two reasons. Firstly, the fact that you can process so many parts on a single machine at once, with a milling machine your basically one part at a time so the potential throughputs are higher and secondly because we already had a DMLS machine here. So that machine was then converted to becoming a dental machine cause before that it was a general use machine. Now that conversion basically meant spending something like twenty eight thousand euros on software and training and also the machine had to be completely stripped, loads of parts replaced, at a cost of another thirty five or forty thousand to completely decontaminate replace the filtration unit and everything to make it up to a medical standards. And then we had to go through the design plans and the certification to get us upto the level where we like ISO 13485 compliant. Now we already had that compliance for zirconia so that made it easier for us so effectively it was a repeat of an exercise we had been through before, so that made life erm slightly easier erm and thats where we are now.

SM: Ok is that purely UK you distribute to?

JP: No there is some place in Europe we only manufacture in the UK. Erm and most of our work comes from the UK though there are some other places like spain and Italy and Norway and stuff like which we get work from. Its pretty stuff on the outside. Now we did, do have a strategic alliance for want of a better word three i part of erm oh god big medical group the name completely escapes me anyway it was the medical arm of this large medical group sorry i have forgot the name. Errr and we were supposed to be creating a joint venture company with them and the idea was that we would have DMLS machines, one in Ital, Spain and one of two over in the States, but that fell through because of allsorts of other commercial tie ins which unfortunately didn't come to pass but at the moment we are still only manufacturing in the UK, but because the machine we have at the moment isn't full to capacity theres no need for us to put one out in Italy or Spain, the level of business doesn't warrant it. One of the biggest markets for dental in Europe is Germany, there spend on dental is huge in terms of metals compared to other places. But at the moment we can serve the German market from here. But you know should it grow to sufficient levels then that's what we'll do we will put other manufacturing plants out there.

SM: So you are manager of this department? How long have you been in this position?

JP: Yes I've been in the company 25 years, and this departments being running for seven years.

SM: Do you have a career background in other manufacturing processes?

JP: My background was CNC manufacturing, so I used to erm support CNC and then I started actually developing CNC processes with Renishaw because in0house developments that we did in terms of automating CNC and things like that so thats very much my background as a manufacturing engineer.

SM: Is that mainly what this team composed of manufacturing engineers?

JP: No, we've got one guy who's a model maker, so his background is as an artist and then he became a model maker and now he's into engineering. We've got an electronics technician there who's background is an applications engineer. We've got a CNC machinist whose originally from Rolls Royce. We've got a guy who is an injection mould designer and we've got another guy a development engineer who came from Dyson and a laser expert whose also come in our area and now works in electronics. So its mostly manufacturing with the exception of two of the people. Or three of the people. Not necessarily in Renishaw. Now our role is very much as a development team.

SM: Can we go through the strategy behind the MTT acquisition?

JP: Yeah I think we've wanted to have a manufacturing process for a quite large number of years. We've done a lot of in-house development with CNC and stuff. And obviously we have a large expertise in CNC and we have a large expertise in CMM, now the problem is we have no particular desire to be a machine tool producer for a couple of reasons. Firstly, the market is flooded with machine tools. You know there's lots of them out there. Erm Renishaws business model very much realise on patents so we can create products which nobody else can, we're the only people in the market we then drive the technologies forward so that we're always protected by these patents and you can then charge according to what its worth to the customer, what value it brings to them, rather than having to be five percent cheaper than Fred Bloggs Engineering down the road who's doing the same thing. The other reason for not wanting to get in to it is because a lot of out major customers are machine tool suppliers and a lot of our major customers are CMM suppliers. We supply probing and accessories for machine tools and probing and accessories for CMM so we don't, it would be a bad position for us to become, as there suppliers, to also become their competitiors because they'd then presumably go into producing theire own probes or buy their probes from someone else who isn't a competitor. In terms of Additive Manufacturing we don't have that problem because none of the big Additive Manufacturing people are customers of our, some of them our suppliers because we've got EOS systems here, we've got stratysus, we've got Envisiontec, we've got Z-Corp, we've got all sorts of stuf. Erm so that wasn't a problem, the other thing was if you look at the world of Additive Manufacturing there's still a lot of development that needs to be done, there's alot of between here and where it could go, which is still green field sites in terms of developing technology. One of the big problems you have with Additive Manufacturing is all of the A|dditive Manufacturing platforms including ours, are basically prototyping machines. So people are trying to manufacture things but their prototyping machines so there is clearly an opportuinity there to come up with a manufacturing solution as opposed to prototyping solution. Now is you speak to people like Terry Wohlers and so called Gurus in the industry they would say that the only difference between Rapdi Prototyping and Rapid Manufacturing as it used to be called was that with a prototype you use it in house for testing extra and with a rapid manufacting it goes an end-use product. That is so naive its unbelievable, because the other implication of going between prototyping and manufacturing is you then need production quality systems, you need production control, you need prdocution planning, your then talking about production quantities, you're then talking about a whole different level of accountability for the quality of your products because you're going to an external customer instead of internal. So to say its just what happens to the end product is nonsense. I mean if you look for example aerospace, clearly the output from the controls and expectations and the quality of the output on that is very very high which I'm glad about because I go on aeroplanes and I don't want them to fall out the sky. And the same is true for medical, now there are a number of companies which will provide medically compatible or biocompatible materials and they go great! We've got, Objet did this, they released a material last year and they said its biocompatible, brilliant, now you can make things for medical use and whatever. Its nonsense. The materials only one elemnt of it, it has to be the process that is certified and that will depend where it is, how you run it, the environment around it. Not just on the material. So yeh its quite tough.

SM: I remember seeing a presentation you did on cultural changes with Additive Manufacturing, is this something you have gone through here?

JP: We're still going through, it is a big cultural change, because it's not helped by some of the hype and nonsense that's around Additive Manufacturing where people say for example "complexity for free", and they completely ignore the post-processing, and material applications and stuff like that, particularly for metals. And things like manufacture for design, instead of design for manufacture, that's non-sense you still need to design for manufacture, because you still have the same things of costs are implied at the design stage, manufacturing-ability is implied at the design stage, production yield rate at the design stage and things and to make the utilisation of the possibilities that Additive Manufacturing gives you over subtractive again you need to do that at the design stage. So from a cultural point of view, there is still a big difference. Some of that comes from lack of understanding and some of it comes from the legacy of the way that engineering has developed around teh processs that are available, so for example in terms injection moulding parst people are used to being able to knock stuff out for pence if its high volume and they make the initial investment. With Additive Manufacturing those models don't apply because the initial investement isn't there but the high cost is so when it goes to high volume it doesn't mean that your cost go down and so whether a part is suitable for Additive Manufacturing is not just about the cost per part or the value added of the operational quantities and whatever. The other point from a cultural point of view is if you look at CAD systems and CAM systems there all based around what is fundamentally prismatic approaches. Now you can create freeform structures and things like this with CAD but if you took something like thats pretty much in realm of experienced CAD users. If you take something like google sketch up and you wanetd to create a form like thid for example, a computer mouse, you can start of with a blob and then you can kind of pull it on the screen until you get that kind of ratio rgith and then squeeze it on the screen until you get that sort of ratio right and thats fine. If you said to a CAD operator, I want you to create that form he'll have a nightmare cause there's load of different radius' on there, and of course in CAD you have to define the optimum values of the actual size, so you need to know the actual sizes are, what that angle is and the whole idea, it looks about right doesn't marry up well with CAD an the amount of time that's spent trying to define an object in CAD is OK, again if its an investment you're gonna make hundreds and thousands of these things but if you said well actually I want a different mouse for each individual operator well all of a sudden building that way in CAD becomes completely impractical because you can't spend a day or two on each piece unless you're selling them for a hell of a premium and if you're selling them for a hell of a premium you're no longer competing with products like that. So there is a cultural difference when designs don't necessarily understand that. The other thing is we get designers and they still come down to us and say can you make this what is in essence a washer, you know, they won't call it a washer it'll be some sort of specific, some specific diameters and whatever. But you look at it and you go that's a washer its an internal diameter and an external diameter whatever but they have this approach with Additive Manufacturing you can make anything which is nonsense for a start, therefore you can make these washers can I have ten of these please. And you go there's a lathe over there; no no you're supposed to make everything we don't need to make things anymore and whatever. We can doesn't mean we should and I think this is a big difference between the academic approach and the industrial approach. The academic are there and their trying push the envelope and say what is possible. Thats great and thats their role and industry benefits and we all benefit from it. But in turn, but when you get down to the industrialist he's not looking at what can be done he's looking at when is it the right time to do it and when should it be done. If people say to me, in a years there will be factories of Additive Manufacturing machines, yeah there will, there will, and there probably are already, but they are specialist bureaus who do nothing but Additive Manufacturing. Its not that you will find that in every factory it's not going to, CNC machining did not make injection moulding obsolete and injection moulding did not make CNC machining obsolete. Additive Manufacturing will not make this obsolete, CNC machine mill/turn centres we've got some here, they're wonderful things, with seven axes and all the rest of it but there's still a place for manual labour. So there is a need for a culture of understanding and what we've basically done is we have another alternative, one of the strengths of Additive Manufacturing is it fills the gaps well that conventional manufacturing leaves behind so things like medical parts where every part is different, brilliant great, things where things do need to be highly complex or lightweight in aerospace you add value by making it lightweight the reduction in fuel costs and stuff like this. Have you seen the Atkins project?

SM: Yes, with Phil Reeves looking at the Life Cycle stuff

JP: yeah well Phil's a very clever guy, but just looking at that, well actually if I take weight out of this component with this honeycomb structure it makes that component more valuable because when it goes on the aircraft it's going to save X thousand of fuel and carbon emissions over the lifetime of the product it doesn't mean that every part you do should be Additive Manufacturing. So again there is this cultural clash where you have some people who say everything should be machined and what you do is just prototyping and you have other people who everything should be made on your machines because you can make whatever you want. Its still the case, you still need that, teher's still a role for production engineering that says this is the right process for that. Now those rules are changing over time because what you can make with Additive Manufacturing is expanding as more materials are coming along, more clever people come along and more applications that nobody had thought ofbefore and stuff like that. So the rules are constantly shifting as to when its right to Additive Manufacture and whens its right conventionally manufacture but you have to realise that that devide is still there. And like I say this is where some of the hype surrounding Additive Manufacturing is not particularly helpful.

SM: So when that happens, how do you select suitable parts?

JP: The two questions that we ask straight away, obviously you look at the stl. File and its a metre by a metre, or if its got a wall thickness of a metre buy a metre its out. But once you get past that stage, two questions that we ask are what is this part for? Which will go a long way to dictate the material, the surface finish thats required which will then dictate how much post-processing is needed excetra and what are the quantitites. Because again if its a big long run then you could say, do you know what that should be made CNC manufacture. OK. Or injection moulding or forging or costing or whatever it is at which point you have the designer saying it can't be done with that because its got a square hole in the middle, well really you should go back and redisgn that, its worth redesigning it. Where as if its a one-off and its got a square hole in the middle, forget CNC you gotta do it by this or wire cutting or whatever it is. So that's the two critical questions that we ask, whats it for? And how many do you want? One of the problems from a prototyping point of view that people have a problem understanding is the differences in the material and mechanical properties of the parts produced, OK. So somebody comes along, there's a famous, don't know how famous it was, but there was a case in Dyson where they made a cable retainer you know the sort of grommet if you like. OK. So they drew the design up and they went to the model shop and said can you prototype this so they vac cast them one, they then put it on a live test rig and they whipped it up and down and they got ninety thousand cycles out of it and they went great yeah this is brilliant its done ninety thousand cycles fantastic that i'll last the life of the product no problem. So then they went off and had it injection moulded in an elastomer because that was the sort of quantitites they want. Dyson vacuum cleaner. Put it back on the life rig and they were getting forty thousand, now its because one of them was an elastomeric and the other is polyurethane. So the life is different. And in the case of Additive Manufacturing when you come to get away from the prototyping board, build orientation makes a difference, it makes a difference to the post processing but it also makes a difference to the mechanical properties of the part so somebody can prove out a part and they can say they can build it in a x, y or mostly x, y orientation and they say yeah thats what we want erm now we want thirty a week, in the case of thirty a week if you build it upright liker that you can fit thirty so a largely z orienetation you can build thirty on a single platform all of sudden, you say I'm gonna productionise this now I nolonger want it lying across the platform I want it upright but your properties have changed, the build orientations changed so the cross-sectional area between each layer is like that, the stresses as its being built are away from there so theres far more distortion.

SM: So are you gonna be developing the new MTT machine and they will based with you?

JP: The way it's working is going to take on the process development and MTT are gonna maintain hardware and materials development so in terms of building benchmark tests for customers you know they say I want thirty of them we'll take them away and inspect them and decided whether wanna buy a machine of not we'll do that here. The other thing is is somebody comes along and says I want a machine build plastic cups, metal cups we say OK right so then we would develop the process in terms of whats the best way to orientate it, what are the costs gonna be what sort of repeatability do you get or if we turn it round can we get it better and then we go to the customer and say here you go. This is what their gonna look like this is the way gonna build em here are the build parameters dad a dada now there's obviously gonna be crossovers because we're gonna be going back to MTT and saying if we have this facility on the software it will inable us to do it much quicker and these material properties people now want more thermally stable parts can you launch a dveleopment program in inconel or whatever it may be so metrology the materials we use elsewhere but the actually development of the hardward and the machines itself is still gonna be done by MTT.

SM: What's your opinion on the current AM supply chain regarding current machine supplier practice? Such as locking down powders etc.

JP: Locking down the powders is dissapearing slowly. I have a certain sympathy for machine suppliers because people want the powders at low cost of course they do you know because then the rules change of when it becomes economic to do Additive Manufacturing those breakeven points change and your cost go down the problem is though if you look at a company like Objet theydo the polyjet processing they are the only suppliers of resins for Objet machines OK there's not a huge number of Objet machines out there so y ou're 3Ms and BSAS big chemical companies have got no interest in selling a couple of tonnes a year so they have to do it themselves and what they have to do is they have to recoup rather there development costs so material costs are higher there not necessarily they haven't got the economies of scale of being able to knock out them out at low costs like your 3Ms and people like that have. So their production costs are relatively high and the volumes which they have to recoup their development costs are relatively low so the development costs per kilo that they have to recoupgoes up. So I have a certain sympathy with the high cost but as these machines become more and more common then the volumes go up so the rate at which they recoup their development cost come down so they can then lower the RandD return per kilo that they sell now if you look at SLS there are a nyumnber of companies now that supply SLS powders that aren't SLS manufacturers. So to start with it was just DTM which was then bought out 3D Systems then EOS came along and they were the only people selling powders then you have people like CRM with their Windform material, then you have companies like Exceltec big French petrochemchical company coming along and saying we're gonna sell powders and other people sell powders and other people sell powders and as that goes along then the costs will go down but iot needs those quantities of machines and quantities of uses to dreive that to make that happen.

SM: what would you say you're in-house core capability is?

JP: Still CNC machining, in-house.

SM: One thing I wanted to ask was that why do you put micro moulding, and also vacuum casting under additive manufacturing?

JP: No we don't count that as additive, what it it is erm MTT do micro moulding machines and they also do vacuum casting machines. So when we bought MTT we bought it as a lump. The injection moulding the SLM and the vacuum casting all at the same time. So they are lumped together as MTT which are now our Additive Manufacturing products division so they all sit in the same division. But no there no additive processes. Of course vacuum casting is a prototyping method but its not additive.

SM: So what percentage of prototyping to production do you do within this department?

JP: Well about, is you take out dental its about 20 percent production to 80 percent prototyping, that number is steadily growing.

SM: So that's all plastics?

JP: Yes, so that's steadily increasing. Because one of the other cultural problems that we had was that because we were perceived as a prototyping area it was perceived that therefore it was that our quality levels were low, our repeatability levels were low because we're just knocking rapid prototypes then putting them on a test bed and it doesn't really matter. So its taken quite a while for us to basically gain credibility that we could put parts into production, that we can supply them reliably and that the parts aren't of poor quality.

SM: And that's through getting the systems of operations right?

JP: Yes, so what we do in the case of production we employ the same erm production controls as per used in our manufacturing services division. So ERP for example we use the same ERP system as they use. We use the same quality controls and quality recording that they use. But it takes a while for people's confidence level to grow and they actually yeh they can actually do production not just mickey mouse stuff but real stuff

SM: So with Dental does that increase to...

JP: The amount of production increases at that point. If you looked at it in terms of number of units, its quite large because on a single SLS build we might make fifty, sixty parts ofcourse you're making double that every night in dental. So yeah just by volume alone iits high.

SM: So has the dental been successful financially?

JP: Yeah its make a profit yeah its doing Ok. It took us about 3 months to get the quantities on the machine where we were above the breakeven point and then we had that sort of growth. And the growth it sort of slowed off since then but it hasn't dipped back down below the breakeven point so they are turning a profit.

SM: So when was the DMLS put online?

JP: April 2010

SM: So if the machine was able to process more materials then you would be able to capture more of that market?

JP: What you would have to do is you would have to have a separate machine because you can't have any cross –contamination of materials.

SM: Could we now go over the process chain you follow here? Particularly for dental.

JP: Sure.

JP and SM move over to one of the workstations

JP: So that will go through our central, which is our own software and then comes to us. So what we then do is that we extract those stl files. So we extract the stl like that and each file we then put through majics. So thats our software for stl. So in there we can decimate the files we can repair them excetra. Now the ones that come from our own CAD system don't need much repairing because weve been able to sort things out and take things out with faults that come through .

APPENDIX B

3T RPD INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis.

1. Face-to-face interviews with the chief executive officer were performed at the company's head office in Newbury.
2. Follow up telephone interviews were also performed with the company chief executive officer.
3. Face-to-face interviews with the system vendor's regional manager were also performed.

APPENDIX C

MATERIALISE UK INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis. The following interviews were performed during the course of the case study:

1. Face-to-face interviews with the company UK operations manager at the company main UK head office in Sheffield.

APPENDIX D

REPRAP LTD INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis. The following interviews were conducted during this case study:

1. Face-to-face interviews with the founder at their workplace at Bath University
2. Follow up telephone interviews with the company founder.

APPENDIX E

BAE SYSTEMS INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis. The following interviews were performed during course of the case study:

1. Face-to-face interviews with the core engineering team leader at the company's site located in Warton, and follow up phone interviews.

APPENDIX F

CHOC EDGE LTD INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis. The following interviews were conducted during the case study at the company head quarters at the University of Exeter:

1. Face-to-face interviews with the chief executive officer and founder.

APPENDIX G

HITA TECH LTD INTERVIEW TRANSCRIPTS

The information contained in the interview transcripts is confidential and therefore cannot be published in this thesis. The following interviews were conducted at the company's main site in Bristol:

1. Face-to-face interviews with the engineering manager
2. Face-to-face interview with the chief executive officer.