Additive Manufacturing: A Framework for Implementation

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Abstract

As mass production has migrated to developing countries, European and US companies are forced to rapidly switch towards low volume production of more innovative, customised and sustainable products with high added value. To compete in this turbulent environment, manufacturers have sought new fabrication techniques to provide the necessary tools to support the need for increased flexibility and enable economic low volume production. One such emerging technique is Additive Manufacturing (AM). AM is a method of manufacture which involves the joining of materials, usually layer-upon-layer, to create objects from 3D model data. The benefits of this methodology include new design freedom, removal of tooling requirements, and economic low volumes. AM consists various technologies to process versatile materials, and for many years its dominant application has been the manufacture of prototypes, or Rapid Prototyping. However, the recent growth in applications for direct part manufacture, or Rapid Manufacturing, has resulted in much research effort focusing on development of new processes and materials. This study focuses on the implementation process of AM and is motivated by the lack of socio-technical studies in this area. It addresses the need for existing and potential future AM project managers to have an implementation framework to guide their efforts in adopting this new and potentially disruptive technology class to produce high value products and generate new business opportunities. Based on a review of prior works and through qualitative case study analysis, we construct and test a normative structural model of implementation factors related to AM technology, supply chain, organisation, operations and strategy.

Keywords: Additive Manufacturing, Rapid Manufacturing, Technology Implementation, Case Study.

1.0 Introduction

Additive Manufacturing (AM) is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” [1]. Synonyms found in the literature include additive processes, additive techniques, additive layer manufacturing, layered manufacturing, and freeform fabrication. There is now a large number of technologies which employ this method of manufacture, some of the more widely used include, stereolithography (SL), fused deposition modelling (FDM), selective laser sintering (SLS) and 3D printing (3DP). Since the development of many of these technologies has occurred simultaneously, there are various similarities as well as distinct differences between each one [2]. Reviews of the numerous AM technologies have been performed in previous works [3–5].

With over 20 years of history, in its early years AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP). These prototypes were most commonly used as communication and inspection tools, producing several physical models in short time directly from computer solid models helped to shorten the production development steps [6]. RP remains the dominant application of polymer AM processes and is well established in the market. Many of the aforementioned technologies are limited to Rapid Prototyping as they do not allow common engineering materials to be processed with sufficient mechanical properties (polymers, metals, ceramics, and composites thereof) [7]. The concept of Rapid Manufacturing (RM) – “the production of end-use parts from additive manufacturing systems” [8] – is emerging today; though its economic impact remains modest [9]. There are few-large scale applications of RM, many of which are for producing personalised products in the medical field [10]. Ruffo et al [11] provided a summary of the pitfalls which exist for companies looking at the use of RM 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. 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. However, it is not the aim of this study to rediscover these issues, rather this paper seeks to build on this, 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. The remainder of the paper is organized as follows. In the next section, a short overview of AM technology and applications is presented along with an introduction technology implementation theory. Then the research framework is presented with a detailed description of the constructs and supporting literature. The data collection process is then described and the results of the framework test are described. Finally, the paper closes with conclusions, limitations of the study and suggestions for future research.

2.0 Background

2.1 AM technologies and applications

As previously stated the numerous AM systems share some similarities but have a number of distinctions. The first AM system to be commercialised was SL, whereby a concentrated beam of ultraviolet lamp is used to solidify a liquid photopolymer by tracing a two dimensional (2D) layer in the form of a contour and then an infill. Once the beam has completed a single layer the build platform will then move downward in the z axis, a new layer of photopolymer is distributed and the process is repeated until the final layer is completed. Laser sintering and laser melting processes work in a similar manner, whereby polymer or metallic powders are selectively melted in 2D layers, through high power lasers until a solid part is complete. Another popular process, particularly with hobbyists, is the FDM process. In this method, materials, usually polymer filaments are extruded through a heated nozzle to "print" 2D layers successively, one on-top of another, until the part is complete. Whether through melting of metallic powders or through extrusion of polymer filaments, all AM process share the additive principle of building components. It is possible to identify a number of key steps in the AM process sequence. Gibson et al. [3] define eight key steps in the generic process of CAD to part:

- Conceptualization and CAD
- Conversion to STL
- Transfer and manipulation of STL file on AM machine
- Machine setup
- Build
- Part removal and cleanup
- Post-processing of part
- Application

Holmstrom et al. [12] 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 [13]. Atzeni and Salmi [14] 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 laser sintering. The authors showed the cost benefit at low to medium production volumes, illustrated in the breakeven analysis shown in Figure 5 below. The benefits of AM have been captured in the production of race car gearboxes [13]. AM facilitates the manufacture of smooth internal path ways, providing faster gear changes and reducing component weight by 30%. Similarly, Cooper et al [15] illustrate the potential for improved functionality in their study on formula one technology, applying AM to hydraulic component manufacture gaining efficiency of fluid flow of 250%.

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 (RM), 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. RM has also been applied to the production of 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 notable metal-based process) and reducing the weight of components through design optimisation [16]. Other areas include, automotive, jewellery, architecture and defence applications

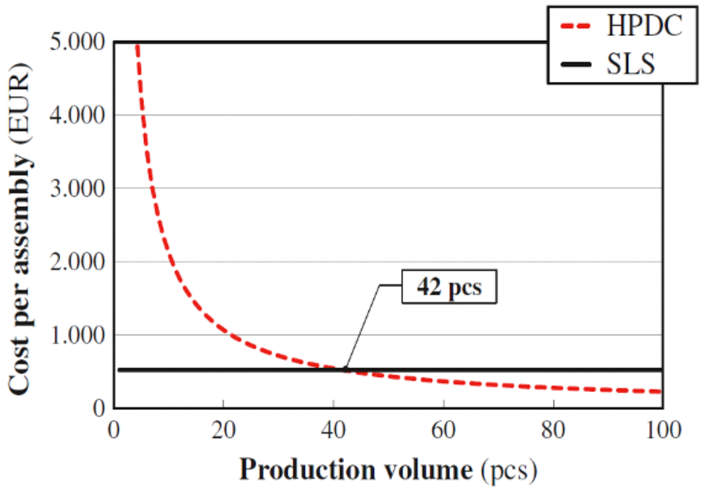

Figure 1. Breakeven analysis performed by Atzeni and Salmi comparing HPDC and SLS processes [14]

2.2 New technology implementation: theoretical background

Skinner [17] was one of the first to propose that innovation in production technology can be used strategically as a powerful competitive weapon, suggesting that it can bring to bear many other strategic factors besides achieving low costs including, superior quality, shorter delivery cycles, lower inventories, lower investments in equipment, shorter new product development cycles and new production economics. In Porters [18] influential work on competitive strategy he suggested technology is perhaps the most important single source of major market share changes among competitors and is the prominent cause of the demise of an entrenched dominant firm.

Voss [19] provided seminal work on proposing implementation as a distinctive area of study of process innovations. The focus on AMT implementation in the 90s was a direct result of many systems failing to meet their initial promise, with project managers unhappy with the system performance. In more recent years, the advent of ERP systems and RFID technology have generated a plethora of research articles on implementation as academics have sort to create process models and frameworks to assist managers in implementing new innovations successfully. Though AM as a manufacturing technology remains in comparatively low levels of exploitation, with AM production representing only a very small percentage of global manufacturing, some authors suggests the breakthrough is eminent. In order to take a pro-active approach to research we focus on developing an implementation framework based on current innovators in this area in order to facilitate this breakthrough.

3.0 The research framework

The conceptual framework for AM implementations put forward by the authors is illustrated in Figure 1. The framework proposes that both external forces and internal strategy drive the consideration of AM as a method of manufacture and the approach to AM implementation will be influenced by factors which may be grouped in to five constructs. These constructs are laid out described in the following sections:

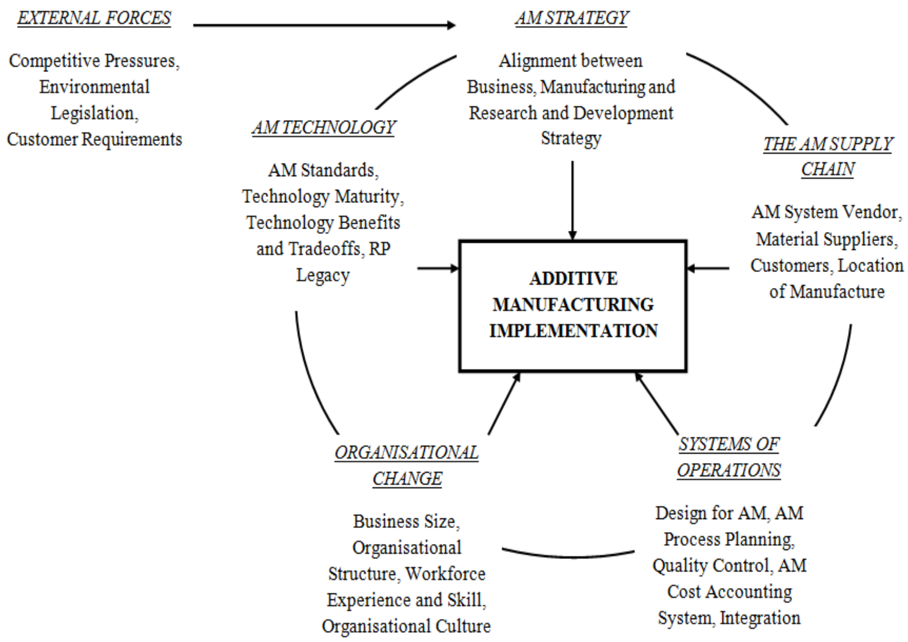

Figure 1. The proposed framework of AM implementation

3.1 Strategic factors

The decision to invest in Additive Manufacturing technologies must be linked to the market and product characteristics. High utilization underpins any technology investment [20], if the process will not be highly utilized on one product it must meet the manufacturing and business needs of other products. Authors in the field of AM management have proposed a number of product characteristics which affect the types of products suitable to AM production. Generally, the product characteristics are:

- Products with a degree of customisation
- Products with increased functionality through design optimisation
- Products of low volume

The implementation of AM must be preceded by strategic alignment of the business, manufacturing and R&D strategy. The technology benefits must be linked to the capabilities required of the manufacturing unit, capabilities derived from the business strategy, 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.

3.2 Technological factors

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 technologies possess a number of benefits, as previously stated in section 2 of this paper. However, as shown in previous work by Sonntag [21] it is equally important that the adopting firm also understands the trade-offs in using new manufacturing technology, for AM process (in general) material range remains low, machine and material costs remain high and process speeds are relatively slow. The lack of technical standards also presents a major barrier to adoption. Some of these characteristics of AM are likely due to their relative immaturity and managers should be aware of this when deciding whether to adopt.

There is also an inherent RP legacy with AM system which may result in a psychological barrier to adoption, as management only see the technology-class as being suitable for RP applications. 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.

3.3 *Organizational factors*

The size of an organization 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 [22–25]. Therefore, the approach to implementation for an SME is likely to be different to that in a large multinational company. Linked to size, previous study into new manufacturing technology implementation suggests that the structure of an organization is the key factor to successfully implementing manufacturing technology [26–31], and that companies that adopt without first re-designing organizational structures and processes encounter high difficulties [31], [32]. Therefore, it is proposed for 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.

Many authors have advocated that new technologies challenge established norms and strategic options. Linked to structure, organizational culture defines the complex set of knowledge structures which organization members use to perform tasks and generate social behaviour [31]. Hopkinson et al. [5] suggest possibly the largest but unknown impact could be on company culture and how it changes to accommodate rapid manufacturing (RM). Using AM processes as a manufacturing technology requires designers and engineers to re-think design for manufacturing (DFM). 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. AM requires users to match product with process and to understand new technology process capabilities. Therefore the workforce experience and skill is also proposed to be a key factor in AM implementation.

3.4 *Operational factors*

As proposed by Bailey [33] a change in an organisations technology will influence both its operational and administrative structures to change. One area of operations which has been proposed by many authors to be significantly changed with the adoption of AM is product design. A number of authors have commented on the impact of Additive Manufacturing on the design of products and designers themselves [8], [34], [35]. 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 [36]. 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 be taken into account when designing products for AM processes. It is proposed that the designers understanding of the new design for “additive” manufacturing constraints will be an influential factor in AM implementation approach.

Another area of operations which is likely to change significantly with the adoption of AM is production planning and quality control. Research on AM process planning is still lacking, though Ciurana and Riba [37] investigated processing planning strategies employed at 36 Additive Manufacturing centres in Northern Spain. The authors used survey analysis, supported by personal interviews with technicians, to identify strategies used AM process planning including; part orientation strategies, build volume strategies, layering strategies, Support generation and minimization. However, as the authors conceded a limitation of this work is that the majority of the activity in this study was RP and RT.

Hayes and Jaikumar [38] 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. A number of authors [37], [39], [40] 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. Ruffo et al [41] provided seminal work on the cost estimation of AM processes and extended this research for simultaneous production of mixed components using laser sintering [42]. However, for other systems such as metal based processes there remains a significant gap in this knowledge.

In the context of AM no technology is currently capable of creating net shape parts, thus post-processing (such as support removal, heat treatment etc.) are required, therefore the integration of AM within a supportive production system is proposed to be key to implementation success.

3.5 Supply chain factors

Additive Manufacturing 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. On the subject of new process technologies implementation, Bessant [43] has argued that for the technology to deliver its full potential significant organizational changes are required such as the restructuring of relationships with suppliers towards more collaborative forms. It is proposed that the implementation of AM technologies manufacture will require increased collaboration with suppliers and customers. Vendor support during the implementation process has long been recognised as a critical factor of implementation success. It has been shown that the level of complexity of the technology innovation is directly related to the level of intensity of the user-supplier interaction processes [44]. Therefore vendor support is proposed to be a key factor in AM implementation.

A characteristic of current AM industry worthy of note is the tendency for machine suppliers to be material suppliers (such as the powders used) 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. There will also be decisions on where to locate manufacturing as the removal of tooling requirement may results in the possibility of distributing manufacturing according to demand locations as in theory the only inputs required for production are CAD data and raw material.

4.0 Research methodology

Due to the exploratory nature of this research area, case studies are used to investigate the AM implementation process and test the research framework. Implementation research provides guidance for identify the most suitable interviewee for this research area, indentifying the four most critical constituencies as: technology vendors, upper management, project engineers and plant operating and maintenance personnel [45–49]. A single case was chosen for this study in order to get an in-depth view of AM implementation. The case company was selected as it represents a rare case of a successful RM implementation (in terms of business success), as it is a national leader in supplying both plastic and metal RM parts.

4.1 Company background

Company A is a leading supplier of SLS and Direct Metal Laser Sintering (DMLS) products in Europe specialising in the production of complex and functional metal rapid prototypes, aesthetic models and low volume production components to industries including Aerospace, Automotive, Dental, Medical, FMCG, Marine, Defence and Pharmaceutical. The company began the first steps in developing a DMLS capability four years ago. The informant at Company A was the company Chief Executive Officer (CEO) the enquiry was also supported through interviews with the machine vendor. The company was started as a specialist in polymer AM processes and focusing on producing prototypes for external customers. Following implementation of metal-based processes the focus has been on production applications due to the process costs and the reduction in overhead costs for higher volumes. The focus on the implementation of the DMLS systems was made for 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.

5.0 Results and discussion

5.1 AM Strategy

The company has a clear mission of becoming Europe's leading supplier of SLS and DMLS parts. A number of factors have led to the implementation of DMLS at Company A. One of the main contributing factors to implementation may be viewed as the CEOs perception of technology benefits, at a stage where the technology was very much in its infancy, the CEO recognised the potential for competitive advantage through innovation and technology 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, another factor contributing to the decision to invest in DMLS at Company A may be viewed as the changes in the RP sector. As the systems have matured, many companies have taken this capability in-house which has reduced the amount companies request from specialist suppliers, such as Company A. Though this change has had drastic effects in certain markets for the company, in many it has been less severe and although demand may have decreased it has not disappeared.

Though the company has achieved significant success the challenge for case company is that in order to maintain the business benefits of the technology it needs 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*."

The strategy at Company A is 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 which influence the approach to AM implementation at Company A, including, the culture within RP (discussed in section 5.3), the company not having an established customer base (as discussed in section 5.5) and lacking production capability (particularly regarding the post-processing requirements in DMLS, discussed in section 5.4). Their response to this apparent inefficiency has been to become experts in *"design and application development in a particular way"*. Though the company has built up a workshop facility to support the DMLS system, through deliberately finding and designing parts to suit the process they have been 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"*.

Therefore, this represents the company's main in-house capability. However, an important implication of this is that this does require a lot more design thought, therefore regarding productivity, downstream process may be reduced, but upstream process is increased. Regarding the current market for DMLS products, the informant suggests that it is difficult to know where the next job will come from and how the market for DMLS products will change over time. Therefore it remains a particularly turbulent environment, where both the technologies and the markets are relatively new. The informant also states that with a few exceptions, industry knowledge of the process has significantly lagged behind that of the users. Among these exceptions is the aerospace industry, with requirements for lighter aircraft and more efficient processes often influenced by environmental legislation. Company A are targeting these manufacturers as they require less education on process benefits and the components are more suited to AM production.

5.2 AM Technology

The CEOs perception of AM benefit is that they must be considered over the lifecycle of the product, which itself presents a challenge when attempting to educate customers on these potential opportunities. This is reflected in the company's focus on Aerospace applications. In aircraft component manufacturer, the potential to reduce part weight through the design freedom unlocked when using AM processes can create mass savings over the product life cycle. This is also reflected in the company 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 the potential for increasing in-house DMLS capacity. Other tradeoffs identified by the CEO include high process costs, largely due to the slow speed at which parts are produced, resulting in high product costs reducing the potential market size of DMLS. However, as the informant states 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..."

Though the company focuses much of its activity on aerospace applications development, the certification periods for this sector has meant the company has been forced to look to other sectors over this period of certification. This is in part due to the fact there are few technical standards for AM processes, resulting in long certification periods for safety critical parts in commercial aircraft applications.

5.3 Organisational Change

The company is an SME and is purely self funded which results in a lack of capital for technological investment and R&D activities, creating a barrier to increasing capacity and developing production applications. One approach to solving these issues is using RP to fund RM R&D activities. For Company A the experience and skill shortage is in conventional metal working and aerospace process flow. The role of the production manager for the DMLS implementation was identified as an area where this is most visible, with the CEO describing the role as being much more specialized than that of the SLS side of the company. Therefore this may be viewed as an organisational characteristic of RP companies moving to RM, with experience and skill gap in production applications.

The company's experience in RP has also affected the organisational culture, as the knowledge structures which organisation members use to perform tasks and generate social behaviour will have been invented, discovered or developed in an RP environment. The CEO suggests that in an RP environment the focus is "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. Whereas in the manufacture it is likely that cost and quality control become critical for success. The company has a centralized organic structure with the CEO being the key decision maker which has benefits in this turbulent environment for speed of response however they are vulnerable to individual misjudgement. The workforce structure is composed of design engineers and engineers, with a production manager. The structure has changed significantly, starting as a replication of the original plastic RP side structure. The CEO suggests the organisational structure is something they "*will likely work out as they go along*", as there are no precedents to work from.

5.4 Systems of Operations

The company spends a huge percentage of customer facing time educating customers. This education is likely to be around process capabilities and constraints, where design for process considerations must be taken into account in order to capture the technology benefits. From this case study the quoting process is identified to be a time and resource consuming operation.

Whereas in RP, quotation is less complex as the process chain itself is significantly less complex (discussed below). Furthermore in RP there is no need for part re-design and cost is not necessarily an order winner at one-offs and small batch volumes, where delivery speed may be more important. For RM, process chain complexity, design for process and cost reduction must all be considered at the quotation stage.

The process chain in RM applications was also highlighted as an area of significant change during the case study. The length and complexity of the process chain in RM applications is drastically increased (when compared to RP) as heat treatment, finishing and measuring processes are required for quality production parts. In this environment the CEO suggests it becomes "*a whole workshop coordination".* This increase in complexity is partly due to the characteristics of the DMLS process, requiring support removal and other post processing activities. Secondly, this is due to the quality control requirements for production parts when compared to prototypes. As previously stated, these downstream processes may be reduced through quality design for process and optimised process planning strategies.

5.5 The AM Supply Chain

The case company's background in Rapid Prototyping means that they do not have an established customer base for production metallic components. Compared to a machining company who is trusted as a parts supplier, the company must therefore spend significant amount of resources on attracting new customers. On the subject of machine suppliers vendor restrictive practices including machine suppliers controlling the powders which can be processed and locking down machine parameters were discussed. These practices reduce the material range available to the organisation, likely reducing the potential products therefore markets the company can serve. Powder control by the supplier also means that material cost remains high, as there is a lack of competition. Secondly, restrictive practices by suppliers include locking down process parameters creating "annoyance" for high end users. This is likely to hinder the R&D practices of the company as the company is unable to experiment with process parameters optimisation tasks. This issue also creates a reliance on the machine suppliers R&D activity, as the systems become closed to operator adjustment. The CEO suggests it is surprising how little the machine vendors look to learn from the experience of Company A regarding machine development. In particular, he points out how some vendors are more responsive to making them production capable than others.

In this case location of manufacture remains 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.) restrict the flexibility of the manufacturing system in terms of location. This is likely to be the case for some time until further machine improvements are in place which reduce the requirements for post-processing of components and AM moves closer to net-shape manufacture.

6.0 Conclusions and Future Work

The case company has shown to provide 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. It is important to acknowledge the nature of the case study presented in this paper and the specific scenario under study. The scenario investigated in this paper is 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 case, 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 additive manufacture constraints and changing a traditional production culture would likely have greater influence on implementation success. Therefore, future work may look to compare the approaches in these different scenarios, and potentially map these approaches using the factors presented in this framework.

Limitations of the study include the fact the framework was tested using a single case study. Yin [50] suggests single-case designs may be viewed as vulnerable and Voss et al. [51] 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 may be focused on further case studies of AM implementation in different organisational contexts and supply chain scenarios. As the number of implementers increases the variety of cases will be open to researchers. Though there is unlikely to be one correct approach to implementing AM processes, this study has provided an insight into the challenges with AM implementation and has proposed a framework to assist managers in implementing this potentially disruptive technology class.

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