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Assessing Adoption Factors for Additive Manufacturing: Insights from Case Studies

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Abstract: *Background:* Research on Additive Manufacturing [AM] provides few guidelines for successful adoption of the technology in different market environments. This paper seeks to address this gap by developing a framework that suggests market attributes for which the technology will successfully meet a need. We rely on classical technology adoption theory to evaluate the challenges and opportunities proffered by AM. *Methods:* We apply a framework of technology adoption and assess these parameters using seven case studies of businesses that have successfully adopted AM technology. *Results:* We find that successful business adoption is highly associated with the relative advantage of AM to rapidly deliver customized products targeted to niche market opportunities. *Conclusions:* Our findings provide a decision framework for AM equipment manufacturers to employ when evaluating AM technology across various market environments. All five adoption characteristics were found to be important however, the primary decision criterion is based on the relative advantage of AM over other, traditional, technologies. From a practitioner perspective, our research highlights the importance of AM in attaining a competitive advantage through responsive, customized production which can address the needs of niche markets.

Keywords: additive manufacturing; adoption of innovation; case study research

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1. Introduction

De Treville et al. [1] recently posed a provocative question: "It is not whether manufacturing has a future in the high-cost environment, but rather, what kind of manufacturing has a future?" Manufacturing is linked to an improved quality of life and more recently has been adopted as an essential lifeblood that supports our global economies. This has led to renewed investment on the part of developed countries to bring back domestic manufacturing, reversing the outsourcing to low-cost countries and localizing manufacturing closer to end consumers [2]. However, to effectively overcome the lack of traditional, labor-intensive processes in developed countries, proponents of domestic sourcing suggest that the adoption of high-tech and emerging technologies such as additive manufacturing (AM) can enable domestic production activities [3]. This forms the basis of our inquiry, which seeks insight into two research questions:

- How can AM be deployed in domestic production environments to provide significant market advantages that justify its adoption?
- What is the general set of market archetypes for which AM will prove to be successful?

In this context, we seek insights into the key advantages that render AM an effective means of domestic production in Western countries. The technology has been deployed in many sectors including aerospace, automotive, engineering and healthcare, to name but a few. In 2015, the global market for AM reached 5.31 billion Dollars, which is expected to exceed 21.50 billion Dollars by 2025 [4]. Despite the broad spectrum of industries employing AM, there exist a paucity of tools or frameworks available to directly support the decision-making process for adoption. For instance, prior research cites the direct manufacturing costs (material, machine time, energy consumption) of various additive technologies and compares these direct costs against traditional manufacturing approaches [5]. Although labor costs associated with AM are less of a factor, recent research suggests that new forms of labor costs have grown in importance during AM adoption. Early research suggested that labor costs associated were viewed as marginal relative to the investment costs [6], however, this perspective has been superseded by the recognition that learning curve effects and post-production activities can significantly add to labor costs [7].

We recognize that investment in AM is a unique type of business investment and, as such, must consider the relevant market characteristics in which it will be deployed. The second research question considered is thus: *What are the general set of market archetypes for which AM will prove to be successful?* Our research into AM contributes to both theory and practice through the development of a framework that matches the likelihood of successful AM performance outcomes based on strategic market advantages that are unique when adopting this technology.

At the heart of our analysis is the debate regarding whether AM can truly provide an advantage over standard manufacturing process technologies [8,9]. Some researchers argue that the technology provides capabilities that are not yet well-understood or well-defined, such as niche production capabilities for spare parts manufacturing [10–12]. Given that AM is a 30-year-old technology, the obvious question that remains unanswered is why the technology has not been adopted more widely and rapidly? Through case study analysis of different rationales that lay behind successful adoptions of AM, we sought a better understanding of the patterns for application of the technology to business problems and market requirements.

We chose to evaluate AM technology using a "tried and true" technology adoption model that has been reliably applied in the past, (but not yet applied to AM). Specifically, the five attributes of successful innovations developed by Rogers and Shoemaker [13] provide a useful lens for the evaluation of AM technology. Adoption is defined as the process by which an organization migrates from considering the innovation to final implementation [14] across the members of a social system. Briefly, Rogers and Shoemaker propose five attributes that affect the rate of technology adoption: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability and (5) observability. We use these criteria in the context of business outcomes, to assess a set of seven AM adoption cases and establish the primary use cases that define business archetypes for successful AM adoption.

The paper begins by providing an overview of prior AM research delineating the primary reasons for business adoption rates, followed by the methodology employed in the research. Through the use of a structured interview protocol tied to the five adoption attributes, we investigated the measures being used by companies to evaluate the effectiveness of AM. In doing so we sought to create insights into the reasons for the erratic adoption of AM as a technology. We conclude with a set of propositions that establish a set of business archetypes that delineate instances when AM adoption is likely to be successful. These archetypes represent an initial set of environments that will require further empirical validations in future studies.

2. Literature Review

2.1. Additive Manufacturing

Recent research highlights how the terminology of AM has arisen from the earlier term, prevalent in the 1980s, of 'rapid prototyping' [15–18]. The ability to prototype a new product rapidly remains the strongest application for AM [19]. Limited examples of manufacturers who employ AM for volume production are beginning to surface [20]. Emerging applications are also considering AM as a platform for rethinking product design, allowing firms to efficiently produce and customize products using digitized manufacturing for unique demand requirements without a cost penalty [12,21], thereby establishing a new value proposition for businesses [11,22–26].

The AM industry continues to evolve with manufacturers offering an array of new products leveraging AM's design freedom and process innovation, which increases competitiveness and flexibility while reducing waste [27–29]. The interdependence of the 3D printing process, the type of material used, the nature of the product design and the physical dimensions of the part to be manufactured all influence the selection of machinery. The myriad of options creates its own challenges and complexity as there are few industry standards that can guide businesses on the best selection of equipment for different business environments [30].

The broad range of materials and the versatility of the technology to produce complex and unique designs have led to the adoption of the technology across a variety of sectors, including aerospace [31], sports equipment manufacturers and personal healthcare products such as prosthetics, dental implants and hearing aids [9]. In fact, the use of AM in the hearing aid sector has become the predominant technology revolutionizing how manufacturing operates in customizing patients' products [28]. AM's perceived advantages include speed of product design prototypes, manufacturing cycle time and low customization costs [12,19]. However, the technology is not without its difficulties as the costs of operating the equipment can be significantly higher than conventional processes. In addition, quality control issues have arisen in certain sectors, as has a lack of data on long-term material properties and increasing concerns about the security of AM against counterfeiting [30,32,33].

The full extent of the technology on market-related business outcomes is still emerging [18]. AM technology has the potential to disrupt and affect organizations beyond their internal operations and may shift the role of the customer, the structure of the supply chain and the market-facing strategy deployed to manage and operate the supply chain in significant ways [25]. Some authors [34] consider AM as the "transformation of organizations to digitalize their entire manufacturing process", with effort expended on how to optimize their implementation. The possibilities for AM are expanding; however, relatively few manufacturers appear to have a clear picture of exactly how the technology will create market value in a domestic setting [3,35]. In practice, the adoption of new technologies is always challenging, as the investment payback and implementation issues are perceived as major risks for managers who lack effective decision frameworks.

Mellor et al. [16] proposed a model that considers external forces, AM strategy, the AM supply chain, systems of operations, organizational change and AM technology. This single case study, based on an interview with the CEO, examined the incorporation of AM into a traditional manufacturing company specializing in rapid prototypes. The framework provides interesting insights into potential pathways for adopting AM, however, it reflects a single business with a core capability based on rapid prototyping. Roscoe et al. [3] examined an implementation of AM within an aerospace business, a sector that adopted AM early and suggest that the reconfiguring of micro-foundational procedures and processes is needed to enhance operational capability in the exploitation of the technology. These studies highlight the organizational challenges with implementing AM, at both a micro and macro level. However, their usefulness as a guide to support managers in assessing the business outcomes of technology, relative to the appropriate needs of the business and customer requirements, is limited. Wholesale organizational change given the early stage of the developing technology is a major step, and, in practice, adoption appears to be relatively cautious.

This paper explores how the adoption of the technology impacts market strategies within different business ecosystems and determines the characteristics of AM adoption that yield the best "fit" with the market-facing requirements. In this manner, we seek to create a managerial framework for the adoption of AM technology and increase the likelihood that it will be successfully integrated into the broader business requirements [36].

This is in line with other studies that have looked at new technology adoption, for example, mobile banking [37], Uber [38] and Blockchain [39]. We develop this framework through a series of targeted case studies developed across a range of different industry settings.

2.2. Theoretical Framework

AM adoption and Business Outcomes

Though industry is investing a substantial amount of time and resources in AM adoption there is significant scope for further expansion [32]. Researchers have examined and recorded a multitude of factors that are important in considering the adoption of AM technologies for businesses and consumers [8,40].

Research on the adoption of technology has relied on several frameworks to explain the different patterns of events for a variety of innovations. Over the last three decades, authors have repeatedly highlighted Rogers and Shoemaker's [13] five attributes of innovation adoption as a framework that offers greater insights into the complex phenomenon of innovation adoption. Briefly, Rogers and Shoemaker [13] propose five attributes of innovations that affect their rate of adoption: (1) relative advantage—the benefits of the innovation over the technology/processes it replaces, (2) compatibility—fit of an innovation with current work practices, processes and values, (3) complexity—relative ease of an organization to understand and use an innovation, (4) trialability—ability of an organization to adopt and experiment with an innovation on a limited basis and (5) observability—visibility and evidence of an innovation and its success within the community. We chose to adopt the Rogers model as it focuses specifically on the adoption of innovations and not so much on their diffusion. The focus of the paper is directed primarily on the rationale that firms utilize for adopting AM technology, although we recognize measuring industry adoption is difficult to assess. The adoption decision is linked to the broader decision of how the technology relates to the specific market requirements. In assessing AM against each of these attributes, a more unified approach to AM technology adoption can be derived. Drawing from existing research on AM, we identify the unique attributes of AM within each of these categories. The specific characteristics (cost, time to delivery, customization, etc.) that are specific to each attribute (relative advantage, etc.) are linked with prior research that alludes to these relationships.

Relative advantage is the perceived benefits of an innovation over current practices it supersedes. Economies of scale form a central tenet of traditional mass manufacturing providing the basis for low unit costs through increasing output. With AM the unit cost is almost immune to volume within the supply chain, and this is a key consideration [5,19,41,42]. Historically, tooling costs have been amortized over the life of the product. However, AM reuses platforms and tools for multiple components providing greater flexibility and speed of response without the burden of fixed capital costs per product [43]. The ability to forego the tooling stage and develop physical products potentially in a matter of hours is a particular advantage [15,16]. The versatility of AM also provides the basis for customization for "free" and the opportunity to develop complex and niche products that would have not been commercially viable with traditional manufacturing approaches [44–46], and supply niche markets that would otherwise be hard to serve [3,12,47].

Adoption Attributes (Relative Advantage): cost implications (*COST*, e.g., relative to alternative forms of production), time to deliver (*TIME*), customization for customer needs (*CUSTOM*), fills a specific market niche that is not currently served (*NICHE*).

Compatibility—the degree to which an innovation is perceived as consistent with existing values, processes, standard working practices, experiences and needs of potential adopters of technology. AM, through its innovative technological approach, can provide the opportunity to meet market needs that may not have been possible with traditional operations. However, fit with existing systems or production processes may lead to potentially different and higher costs [7], requiring investment in training for innovative materials, design and changes to data storage, flow and structures [48,49]. Though AM has been shown to reduce time and quality problems resulting from assembly operations compared to traditional approaches, it still requires consideration of its compatibility with current work practices and organizational structure to avoid functional silos.

Adoption Attributes (Compatibility): consistency of innovation with existing organizational structures (*ORGSTRUC*), meets a clear market need (*MARKET*), fit with existing production processes and information systems (*FIT*), compatibility with the flow volume of data required for production (*DATA*).

Complexity—the degree to which an innovation is viewed as relatively difficult to comprehend and use. Traditional manufacturing through its "Taylor-istic" standardized approach has developed discrete and repetitive tasks clearly defined and supported by standard operating procedures across the supply chain. AM production has the potential to disrupt supply chains through decentralization of manufacturing, enabling production to shift to the point of consumption, leading to ill-defined roles and responsibilities and challenging industry norms. Comprehending the impact of these changes on ill-structured cost changes can challenge organizations to justify and implement AM [16]. Adopting AM requires new skills across the supply chain as procurement moves from buying componentry from many suppliers to raw materials from a few, and design directly interfaces with manufacturing, by-passing production engineering [43].

Adoption Attributes (Complexity): difficulty to implement (*IMPL*), technical skills required to adopt (*SKILLS*), lack of industry standards (*STD*).

Trialability—the perceived degree to which an innovation may be experimented with by potential adopters. Compared to the known processes and procedures of traditional manufacturing, where designs are dictated by production and component constraints, AM supports an organization's ability to co-create with the customer new and previously undefined processes [6]. The additive technology provides the opportunity to pilot innovative and intricate products without the costs of investing in capitally intensive tooling and equipment [50]. Supporting the piloting and trialing of AM requires training on the design and manufacturing techniques to enable organizations to develop and create specialized skills and abilities [34].

Adoption Attributes (Trialability): degree to which innovation can be piloted (*PILOT*), support services for training (*SERV*), ability to create specialized competencies (*ABILITY*).

Observability—visibility of technology within the community in which it is used. Many existing examples of traditional manufacturing approaches exist across multiple industries however, relatively fewer AM installations provide less visibility of the benefits of the technology in use [6,51]. The lack of evidence in a specific industry sector can hinder adoption as organizations become concerned about investment costs and uncertainties of AM technology operational costs [52]. However, the promotion of AM success is beginning to grow and become more apparent as sectors as diverse as universities, healthcare, sportswear and the food sector, as well as the aerospace and automotive sectors, highlighting the successful application of the technology [31].

Adoption Attributes (Observability): visibility of AM to potential adopters (*VISIBLE*), evidence of use in sector (*EVID*), success stories to support adoption (*SUCC*).

Each of these five categories, when combined in a unified framework, can help managers evaluate the opportunities and risks of AM relative to traditional production approaches. We seek to validate this methodology and derive a framework for developing an understanding of the potential costs, risks and performance benefits expected from adopting the technology within manufacturing organizations and the supply chains in which they operate. We use a series of seven case studies, that together help define a unique set of business archetypes that provide a robust approach for evaluating the relative benefits of adopting AM technologies. We begin by describing the research methods used to establish this validation.

3. Research Methods

Research design: We purposively selected case study firms from diverse industries and sizes that were identified a priori as having a successful adoption of AM technology [53].

Interviews were conducted in conjunction with a subjective approach that supported the collection of information on the 'lived experience' of managers who were able to overcome the challenges of AM adoption and the characteristics of this adoption that rendered it successful [54,55]. As shown in Appendix B, we selected organizations that had a minimum of 3 years of experience working with AM technology and thus had an established success record with adoption of the technology. This enabled a detailed analysis of the outcomes and performance characteristics that supported successful AM adoption.

The sample design was based on the fact that most organizations are in the evaluation, adoption or initial implementation stage of AM [30]. The rather limited success of AM within the wider manufacturing community led us to explore the business rationale that justifies its adoption in circumstances when it has in fact been successful. Our exploratory approach allowed us to study AM in its context as there has been comparatively little empirical research that explores the practical implications arising from the technology [9,56]. Deloitte [57] similarly highlight that research, and the AM debate needs to move into a study on what is actually happening rather than the development of further theories on what might be possible.

We identified seven organizations in different markets to understand their approaches and spoke to the individuals who were the most knowledgeable within each firm. These individuals were also involved in the key decision-making process that considered the opportunities and risks associated with the AM choices they made. We included organizations that not only developed prototypes but also manufactured AM-produced finished products. We focused predominantly on smaller organizations, (some of which were embedded within a larger organization) for several reasons: (1) smaller organizations are often more nimble when it comes to the adoption of new technologies, and (2) the management structure was such that we were able to speak with C-suite level individuals (subject matter experts), who were able to articulate in their own words the details and benefits of AM [30] and (3) smaller organizations were often able to articulate the risks and investment goals of AM relative to their business outcomes. The case studies were screened through initial inquiries to determine whether the users believed the use of AM was successful within their organization. This purposive case selection allowed us to extract specific attributes of the technology, yielding more significant and more meaningful results [58]. Note that we did not include cases in our sample where executives informed us that they had tried to use the technology but had failed.

Data Collection: An interview protocol was developed to ask the case study businesses about their AM use (including their products and customers), benefits and drawbacks, cost analyses and impacts and the effects on product design and manufacturing. The interview protocol covered how the organizations were using AM, the rationale of why they chose to do so and the nature of how they used it. The questions contained within the protocol were derived from the five adoption attributes to explain technology adoption [56,59]. Each attribute provides indications about determinants to support adoption and offers a basis for comparing traditional manufacturing approaches to AM [51,60]. The protocol was piloted by the research team to assess its suitability and was modified to provide clarity on the questions posed. Five researchers conducted a qualitative investigation into the adoption of the technology adding to the richness of the data interpretation [61]. Further details of the interviews are given in Appendix B. Each interview was accompanied by a detailed discussion explaining how the technology was being used, followed up by detailed questions on the market forces that drove the innovation adoption.

Data Analysis: Interviews were transcribed and coded by the researchers. Included within each case were quotes and accounts from interviewees describing and illuminating the points being made. After completing the case studies, the results were written up and reviewed by the authors. Data reliability was ensured by using a common case study interview protocol and having all reviewers access to the case notes database to allow easy retrieval of information [62], as well as ensure repeatability of our study. Internal validity was ensured through case pattern matching by multiple authors, documenting the chain of evidence for each of the cases in a set of tables [62,63]. The authors then coded each case relative to the different adoption attributes, operating in isolation from each other, to ensure reliability [64]. The researchers looked for patterns involving a priori determined codes [56] from the adoption attributes outlined previously and used these to provide "a comparison of a pattern of observed outcomes with some pattern of expected values derived from a given theory" [65]. These patterns supported the development of a more robust theoretical picture of the adoption and performance attributes that supported AM. An overview of the a priori codes used to map the interviews to attributes of the Rogers and Shoemaker [13] framework is shown in Figure 1.

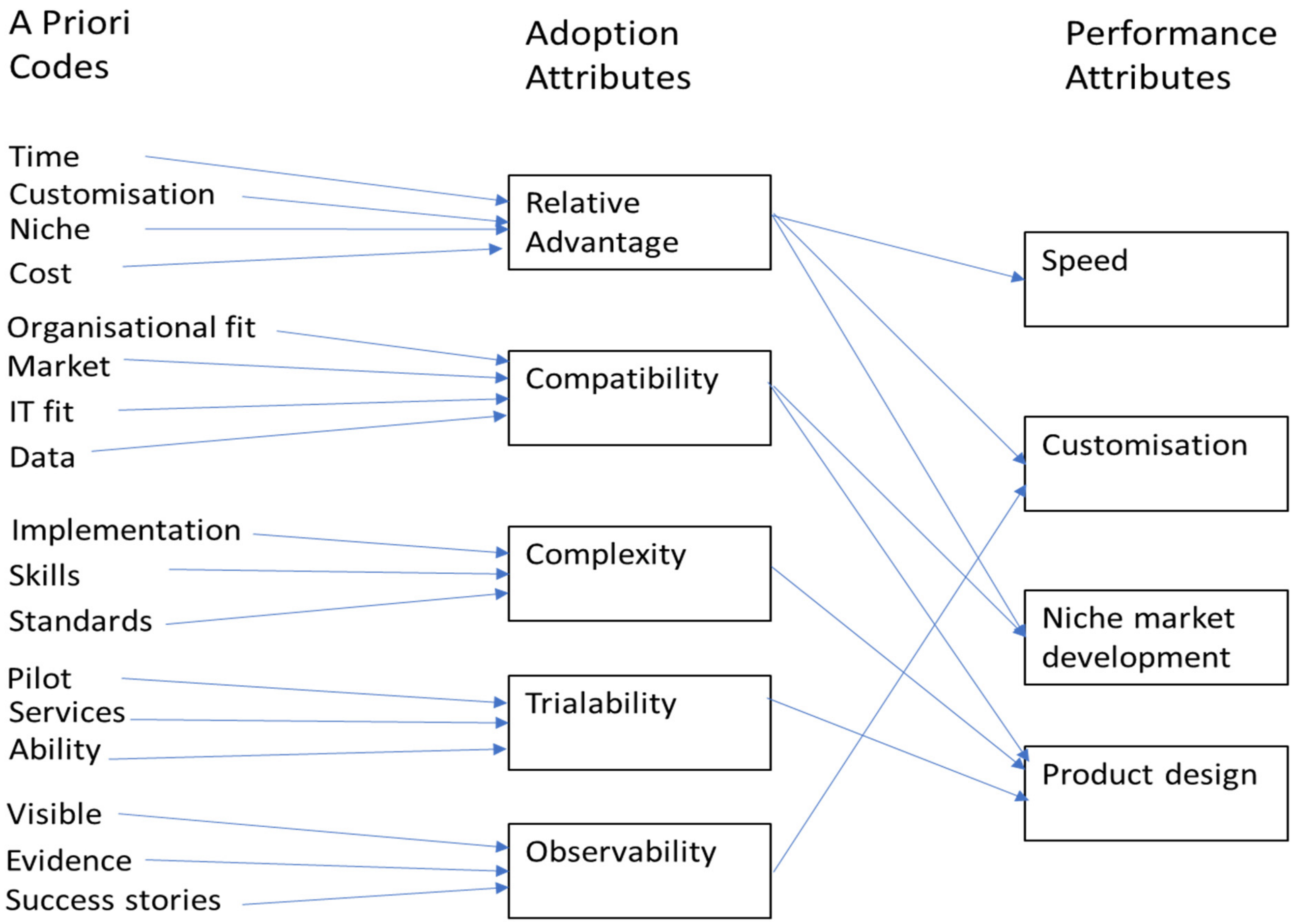

Figure 1. Overview of AM data structure.

In this manner, specific comments and quotes from interviews were coded and assigned to different adoption attributes. For each case, the relative performance advantages that followed the adoption of AM were likewise assessed and mapped as shown in Figure 1. Patterns emerged that dictated the unique sets of adoption attributes for each case, and these were then used to create a corresponding "business archetype". The business archetypes emerged as the coded cases were found to validate the performance characteristics shown above, but that also demonstrated emergent themes for each business that characterized the more granular elements of these outcomes to the specific business environment (as shown in Figure 2). These archetypes are described in the form of a set of propositions that link the attributes of AM that benefit specific types of business ecosystems, which are then translated into theoretical and managerial implications. The results of the cases are described in the Results section that follows, and the emergent archetypes are subsequently described in the Discussion.

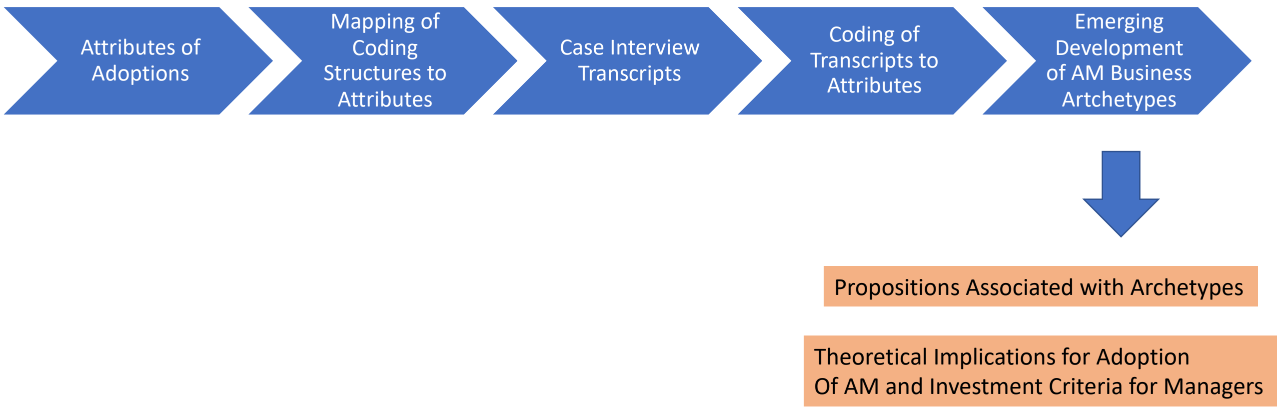

Figure 2. Research Methodology.

4. Discussion of Cases Examined

We conducted in-depth interviews with a range of organizations involved with AM, to understand their operations, decisions, experiences and challenges. In doing so, we positioned them relative to the five attributes of adoption likelihood, to better document the performance attributes that highlighted how AM was being adopted. The case study business characteristics are noted below and are summarized in Appendix A.

1. **Light Co.** is an established manufacturer of lighting products for the industrial and commercial sectors exporting across the globe. With the advent of Light Emitting Diode (LED) technology, the organization has had to re-engineer its product range to incorporate the changes in lighting technology as well as introduce new items that can satisfy customers' demands for longer-life offerings. The sector is actively using AM that supports the promotion of the technology to customers. Light Co. utilizes two printers that are managed by designers and operated by production to develop prototypes and samples that support the salesforce and minimize lost time in designing hard tools. The benefit of AM was highlighted by the Finance Director "If you don't need inventory, make to customer demand, but that is very much around the bespoke model or customization. That would allow us to evaluate a whole cost model to restructure the supply chain"
2. **Filters Co.** is an established manufacturer of industrial filters predominantly applied in the liquid and gas industry. The company is headquartered in the UK with global reach and employs about 25 people. The company is under increasing pressure from Asian competitors and developed an innovation agenda focusing on AM using Stainless Steel Metal Printers. AM allows Filters Co. a clear distinction in the market by offering highly customized filter solutions. The company invested in one large commercial metal printer. Filters Co. was the first owner-operator of a commercial metal printer in the region. The observability of the technology was extremely low. Filters Co. was able to trial the technology in collaboration with the local University and build capacity through hiring graduates. Compatibility was extremely low due to the highly traditional manufacturing workshop layout and processes. The information flow was predominantly manual and the complexity of this particular technology from a Filters Co. perspective was rather high. The AM machine helped to disrupt the traditional mindset and had a positive impact on the innovative culture in the organization. The technology is viewed as the future of the business by the M.D. "We are not profitable with our AM machine, but we know it is the future".
3. **Toys Co.** is an Australian-based provider of highly customized electrical components for remote-controlled aircraft employing 5 people. The company provides standard and customized solutions to a global niche market. The end-users are predominantly hobbyists and amateur remote-control aircraft owners requiring customized housing solutions for their model aircraft. Initially, AM was applied for rapid prototyping. It

allowed the company to significantly lower the cost of its electrical housing solutions. Recently, the company deployed the printers for low-volume electrical housing manufacturing. AM was a natural evolution for Toys Co. being a niche provider to a highly innovative hobbyist market. According to the operations manager "It is a no brainer. I can test and feel a new design within days costing me a fraction of the traditional plastic molding process. No ROI model required". AM aligned well with company values and had a strong fit with existing design technology. Product lifecycles are short and new product innovations are rapidly prototyped. The co-owner was introduced to the technology at their local university. The investment into a polymer printer was minor and the use was predominantly self-taught using online media. AM adoption had significant cost benefits by avoiding an elongated molding process, advanced functionality and freedom of design for end-users that desire high levels of customization.

4. **University Hospital** is a Canadian medical research facility with more than 600 people, working to investigate many diseases. The facility seeks to accelerate medical discovery and has key strengths in advanced medical imaging, cellular and molecular biology, genomics, immunology and stem cell biology. The facility employs an interdisciplinary approach with physicians and physicists, biologists and biomedical engineers, all working under one roof. The facility has produced more than 80 patents, 15 licensing agreements and eight spinoff companies that have raised more than $45 M in investment capital. The engineers developed a process where radiology data files are imported and used to produce custom metal components for a closed-loop pipeline for image-based design and additive manufacturing in orthopedics. These are generally in the form of custom-made metal components to guide surgeries, as "cutting guides", which serve to reduce bloom loss and reduce the time to make accurate cuts during surgery. In addition, the center produces implants for surgery. The AM lab has become a low-volume customized manufacturing facility and is entirely dedicated to the production of parts for its physician and patient community. The opportunity of AM was highlighted in a remark by the Head of the 3D printing lab "Radiology is used to produce images, not plastic or metal models. Surgeons don't know how to ask for a model. There are very few jurisdictions for a revenue stream. We combined all of these needs and do it in a closed-loop facility where we take the image, build the model, and work with the physician and the patient." This is a new form of specialized manufacturing adopted by a service provider.
5. **Life Sciences Inc.** is a large global life sciences company that created a 3D Printing Centre of Excellence. They view AM technology as a collection of a broad family of technologies ranging from metals to polymers to biomaterials—materials that mimic living tissue—in order to create objects. The Centre employs technologies to deliver AM printing solutions to different operating companies across the organization. The technology can have transformative applications across all businesses, including surgical tools for surgeons, medical implants for patients and even medicine tablets for consumers. For example, a surgeon treating a person going into trauma surgery might need multiple cases of instruments, which creates a lot of inefficiencies. With AM the goal is to customize these instruments specifically for each patient, eliminating the need to bring multiple-sized instruments into surgery. AM can also speed up the production of tools, producing the entire tool in one sitting. Finally, AM can be used to develop solutions for older patients to remind them to take their pills using AM-printed sensors that send a signal to a cell phone. There are multiple other applications being explored as intimated by the Senior Vice President (SVP) "Our CEO asked the question—why do we have 353 printers around the world, and what are we doing with them? He made it a priority, and we now have a rich set of roadmaps. We will be using it for mass personalization, localized manufacturing, and partially high-volume manufacturing".

6. **Electro Co.** is a small UK-based company designing and producing specialist power supply, radio and fiber optic products for a range of customers worldwide. The electronics typically need to be housed in shielded metalwork and often need to function in adverse environments. Their products are cost-sensitive and low volume, but time to market is important. AM allows initial physical designs to be evaluated and shared with the customer and final metalwork manufacturer. It is used in the prototyping phase as a straightforward way of establishing the viability of design options in terms of practicality (e.g., cable routing) manufacturability and to show the end customer a physical representation of the unit. For the engineering manager AM has "been invaluable for the company ... it gives us that supreme confidence when we get parts cut". The advantage is primarily that a final design can be agreed upon far more rapidly than if AM were not used. Other internal production support uses (e.g., assembly jigs, component test beds and cable support devices) have been identified once the AM machine was available in their facility.
7. **Plastic Co.** is an Australian-based small enterprise. The company invested in AM technology offering services to existing clients with the objective of growing its client base beyond the local region. It offers services such as reverse engineering of components using handheld scanning devices, CAD design for AM and scale prototypes of next-generation products. This leads to the opportunity for new market entry, and the General Manager commented "one of the most exciting projects was the spare part production of a 1952 Ford Customline. The owner could not identify a suitable spare dashboard for the car, so we scanned the old one and 3D printed a new dashboard in two components due to the large size. We have seen a steady increase in demand for this kind of stuff". Plastic Co. had strong compatibility with respect to information required in the production area and fit with existing processes and information systems in particular during the design stages. The company had great support from the local University until new AM-specific resources were hired. Additionally, the company observed international evidence of other plastic molding businesses adopting AM technology. Plastic Co. invested in more sophisticated polymer machines, so complexity was judged high. The key advantage is centered around freedom of design for one-off highly customized polymer parts. However, customers also benefitted from a cheaper and faster prototyping process prior to investing in plastic mold.

Using the coding structures associated with the five attributes of adoption, the codes shown in Figure 1 were used to identify the specific elements of each business that were aligned with each attribute. The results are shown in Appendix A. Note that the coding scheme figured prominently in the discussions that emerged in each interview, but also demonstrates the unique business ecosystem characteristics that emerged in each organization. These unique attributes were then developed into business archetypes and described in propositions as illustrated in Figure 2.

5. Tying Cases to Defined Archetypes

To understand the patterns of adoption for AM, we sought to map the attributes of business applications and performance attributes. We denoted these as "archetypes", which represent different applications and performance attributes of the AM technology, and therefore different strategic and operational characteristics. Archetypes are expected to demonstrate underlying mechanisms of AM application however, they are not anticipated to be overly prescriptive [66]. These archetypes emerged as we sought to understand and classify how AM was adopted in each of the different business environments. These archetypes suggest certain relationships that exist between the attributes (relative advantage, compatibility, complexity, trialability and observability) and the core factors mentioned by the managers in our case studies. These relationships were specified in a set of propositions that established the linkage of each archetype to the attributes of AM that were meaningful in the investment decision. These relationships helped to establish the relative level of "fit" between the business environment and the attributes of the AM technology. The resulting propositions begin to establish the managerial criteria that are important in the AM adoption decision; the design, sourcing, manufacturing and delivery activities associated with each archetype can begin to provide important clues for AM manufacturers and adopters alike for marketing and investing in AM technology. We begin by describing the characteristics of the archetypes in Table 1, and then map the case studies to each archetype.

Experimental

The organization is engaged in some AM activities, but the goal in this environment is to begin to experiment and understand the strengths and weaknesses of the technology, to keep abreast of changes in the technology and to signal to the market the cutting-edge, innovative nature of the firm's business strategy [51]. For small organizations, the use of 'fab-spaces' is an advantage in the initial stages before the final product is stable, and these are available to entrepreneurs both as physical sites and via web-based ordering [45]. In most deployments, there are currently no plans to use AM for prototyping regular or spare parts production. Capital investments are minimal and considered more part of R&D/market-signalling than regular production costs. Pilots may often be run with universities or research labs to explore and become familiar with the technology. In this sense, the experimental approach may be exploratory with a view to exploiting opportunities that these relatively low-risk 'vanguard' projects offer [67,68]. However, deciding to invest in new technology within a complex and uncertain market is necessarily challenging (e.g., [69]), and such (often multi-stage) investments involve learning and knowledge transfer around the organization [70]. As such, clarity on the benefits may be elusive for some time [68], which will likely delay major investments in the technology. This was also recognized in the Light Co. case, where AM was primarily a marketing tool to demonstrate the art of the possible.

Proposition 1. *Experimental AM adopters recognize no significant customer value attributes from AM but view it as helpful in shaping market strategies for target market niches through mapping and defining the limits of AM capabilities.*

Rapid Prototyping

AM can be deliberately implemented as a solution to speed up the prototyping process. This offers the opportunity to bypass the expense and time incurred in a formal tooling stage [15,16]. Crucially, it also delays a financial commitment to the tooling, allowing more options in the development phase. In the language of Klein and Meckling [71], a 'skeptical' approach can be taken, delaying the final decision until as late as possible and incorporating knowledge gained during the process (such as technical improvements, and customer feedback). An early decision on the final product (the 'optimizer' approach) depends on design certainty. This can indeed be superior if clarity is available, but it is well-established that in the cases where multiple iterations and testing are valuable, techniques that support knowledge-generation as part of the work are beneficial (e.g., [72,73]) and that this flexibility supports customer satisfaction [17]. Key performance metrics for justifying AM in this environment are development speed and design flexibility. A good example is the Toys case, in which AM was used for a targeted niche market (hobbyists) that was a very small, defined set of customers. In this case, the strategy, to realize this new market opportunity, is not to deploy AM as a substitute for regular production but as an important component of sales and marketing interactions with purchasing to define the feasibility of different product designs and attributes.

Proposition 2. *Value for rapid prototypes is primarily in the form of marketing to customers, involving the use of AM in specific applications such as envisioning the final product prior to production in a rapid manner.*

Spare parts production

Spare parts can be characterized by large variety, intermittent demand and a high shortage cost [42]. There is limited empirical research on spare part selection for AM [74,75], but recent studies have identified that it can be financially superior if the higher costs of AM make it worthwhile [76]. This can include selective deployment of AM machines in key distribution centers [77], and early investment in AM has been shown to generate benefits sooner [78]. However, issues have arisen around post-processing and supplier quality parity [79], so a total cost perspective should be maintained [78]. The application of AM in this context works well for a subset of spare parts defined by low volumes, complex design/tooling and significant ECs [45,46]. For example, a significant efficiency improvement in the aircraft industry is identified by Ghadge et al. [47] as AM helps balance inventory levels, increase responsiveness and decrease disruptions (see also [80]). This was also the case at Plastic Co., where customer needs for spare parts and reverse engineering was a perfect application for AM technologies.

There are two distinct operational sub-strategies within this group:

1. Speed of replenishment is seen as significantly more critical than costs (for example, in aviation applications).
2. AM is seen as a way to drive down inventory costs associated with traditional methods of holding spare parts for small demand requirements. For example, spare parts may be used for old cars, but AM can be used to produce such parts on-demand as they are very infrequent.

Proposition 3. *For spare parts providers, replenishment speed of spare parts, especially difficult to obtain parts, is a defined market niche valued by many customers that justifies the adoption of AM.*

Low-volume primary manufacturing of standard designs

At this stage, AM is seen as a viable alternative to traditional manufacturing process choices for specific sets of low-volume products [25,81]. Organizations have not moved beyond prototyping at this stage but rather they are using AM to develop rapid designs together with a view to increasing sales and volumes, enabling the production of standard designs [64]. Katic and Agarwal [82] suggest that small-to-medium enterprises that produce a high variety of customized products at low volumes (HVLV) need to balance the need for operational efficiency with the requirement for innovation and novelty to satisfy their customers. It is not yet competitive at medium- and high-volume production, but for low volumes it can offer shorter lead times and sometimes decreased total production costs [83], and this is beneficial for some clients. Sasson and Johnson [84] also highlight the benefit of the technology in terms of an ability to isolate and control low-volume production from scalable mass production. AM thus offers the opportunity for a business strategy based on rapid, well-controlled, production, at competitive prices. This was the case at Life Sciences, where customized products for patient operations required in a short time, at premium prices, made AM a good fit for the market need.

Proposition 4. *Low volume producers are targeting customers that want small-batch products in a shorter lead-time, and are willing to pay a premium for them, with a view to expanding sales and production volumes.*

Production of non-standard design

AM potentially offers the capability to manufacture non-standard design items that may be difficult or impossible to produce through subtractive techniques [15,25]. Some authors highlight the transformational changes it offers to manufacturing, with rapid customization of complex parts to suit customers' needs (e.g., [44]), and the attendant benefits this offers for new product functionality. Others, though, are more cautious.

Colosimo et al. [85] highlight the challenges in ensuring quality, and Shukla, Todorov and Kapletia [86] identify some of the current barriers to mass customization, including limited object size, the slow speed of printing and a lack of expert designers. These difficulties notwithstanding, successes such as the GE LEAP fuel nozzle offer advantages over more traditional manufacturing techniques. Another example of success was the Filters Co. case, which produced non-standard designs for niche markets and combined these with traditional job shop capabilities, demonstrating the ability of manufacturers to develop focused demand chains that deliver increased levels of customer value [87].

There are three operational sub-strategies in this archetype:

1. Optimized design providing better product performance and conformance quality.
2. Combined functionality leading to fewer parts and lower inventory costs associated with traditional subtractive and assembly methods.
3. Creation of customized make-to-order products expanding product range flexibility.

Proposition 5. *Non-standard production using AM is targeted at customer niches that require significant customization of standard products and are not willing to wait.*

To summarize, Archetype 1 uses AM as a vehicle for market positioning, Archetype 2 uses it to allow customers to view new products in marketing and Archetype 3 uses it for spare parts production. However, Archetype 4 is the first instance where AM is used as a viable alternative to traditional manufacturing, to produce rapid designs with a view to increasing sales and production volumes, leading to the production of standard designs on standard manufacturing equipment. Finally, Archetype 5 firms view AM as a means for the production of non-standard designs that are not prototypes but are actively marketed as unique products. The difference between 4 and 5 is that 4 is still producing small volumes but never views these volumes as their core business; 5 uses AM as part of its core business strategy for producing one-off products only for unique customer needs. We note from our case data that organizations do not necessarily correspond to one archetype only but can be associated with several (see Table 1), reflecting the strategic options open to manufacturers when developing customer value.

Table 1. Archetypes 1–5 represent very different adaptations of AM in support of end products.

Archetype (and Case Examples)	Strengths	Limiting Factors	Performance Attributes
1. Experimental [Light]	R&D/Market Signaling	AM not justifiable based on a cost, quality, delivery or flexibility basis	Pilots to understand technology and skills
2. Rapid prototyping e.g., [15,16,88] [Light, Toys, Electro, Plastic]	Faster prototyping, especially for complex designs Good for marketing to demonstrate products Can provide quicker speed to market	Item size constraint by build tray Minimum mfg. time Material choices/high material costs 3D printing Capex & personnel costs	To meet specific customer needs to view products and market, speed to market
3. Spare part production (existing traditional design) e.g., [45,89] [Life, Toys]	Inventory cost savings Tooling cost savings Higher material yields Improved operations performance through AM production of tooling, changeover devices and selected MRO speed to market (outbound logistics)	Same as above, plus: Potentially higher per-unit transportation costs due to shipping quantities of one. Item size constraints Minimum mfg. time Material choices/high material costs 3D printing Capex & personnel cost, Quality constraints due to higher tolerance levels	Can meet customer needs for spare parts

Table 1. *Cont.*

Archetype (and Case Examples)	Strengths	Limiting Factors	Performance Attributes
4. Low-volume primary mfg. (traditional design) e.g., [56,81] [Life]	Same as above, plus: Reduced outsourcing costs Enhanced supply chain resilience due to localized manufacturing, more cost-effective for very low volume production runs (e.g., avoid molding costs)	Same as above	Meet market niche for low volume products in shorter time
5. Production of non-standard design [15,90] [Filters, Toys, Uni Hosp, Life]	Optimized design—better product performance Combined functionality—fewer parts, fewer suppliers, lower upstream SCM costs Customization	Same as above, plus: Product designers/engineers capable of exploiting/ maximizing AM technology product performance	Customization of products for specific customer needs in shorter time period

Our research into AM sought to contribute to both theory and practice through the development of a framework and recommendations for evaluating the impact of additive manufacturing on performance attributes. We developed an archetype framework based on our AM literature review and outlined five research propositions that suggest that successful AM deployment is associated with attaining specific business objectives. These objectives include the following: (1) to gain knowledge of the technology through initial pilots and explore niche market opportunities, (2) as a marketing and demonstration tool for new product concepts, (3) to manufacture spare parts at speed, reducing the requirements for finished goods stock, (4) to exploit the speed of AM for low-volume parts at a price premium and (5) for the manufacturing of customized niche products with short-lead times and higher prices. Our seven case studies provide empirical data that support the development of five propositions and archetypes and demonstrated that the descriptive framework in Table 1 can be used to develop deeper insights into the options that managers are faced with when deploying AM.

The findings from the case studies, however, do not suggest that there is a "correct" way for managers to engage with AM, but two important trends were observed. The relative advantage of AM was shown to be important in terms of speed, customization and development of niche applications/markets. The managers in each case focused on AM as a "game changer" that required "minimal" investment, highlighting unique and specific performance outcomes as the primary business motivation. AM was viewed as a versatile tool providing platforms and tools for multiple components without the burden of fixed capital costs per product [43]. Substantial information gaps regarding the true cost of the AM technology adoption was not an important factor in any cases for justifying the business benefits though it was recognized in the medical cases that the direct manufacturing costs were lower.

The explanation for adopting the technology, without substantive costs, appears in the second trend identified in the findings. Namely, AM provides the opportunity to respond quickly to the need for three types of market opportunities: (1) quick response for prototypes or spare parts, (2) niche market, customized products, or (3) a range of new life-enhancing products produced for unique customer needs. In each of these types of markets, the successful organization was focused on creating new forms of value that had nothing to do with being the lowest cost product on the market. Customers in these markets were willing to pay a premium for velocity capabilities, associated with the deployment of new one-off products, prototypes and customized non-standard designs. All case studies deployed the technology to improve their customer experience through rapid prototyping and/or manufacturing of customized products. The opportunity to develop bespoke products and co-create and develop niche markets proffered by AM was a reoccurring theme within the approach of organizations to engage with the technology. The centricity of customers and their role within the operations was evident in the findings as organizations actively engaged their customers/patients earlier in the design and development processes. While AM may not be suitable for high volume, low-cost products, this may change as the technology evolves and is able to be deployed for mass-customized approaches. The primary benefits of additive manufacturing capabilities for the case study organizations were tied to speed of response to customer needs for spare parts, prototypes, low volume customized production and non-standard product designs.

The relative advantage of AM over traditional manufacturing is strongly reflected in the responsiveness of the technology (Time), as well as the ability of businesses to customize products and the development of unfilled niche market needs. However, the cost of employing AM is likely to be greater than traditional production methods, reflecting the importance of response speed as being more important than cost in the mind of the customer. AM provides the platform for the movement from a manufacturing to a consumer-centric business model by involving the customer in co-creation resulting in closer ties across the length of the elongated design process [25]. For AM production of non-standard designs, innovations are reliant on the customer as a major source of innovation.

In terms of the adoption of innovation compatibility, the primary attribute is the ability of the technology to be compatible with specific market needs. The speed of converting a concept into a new product has opened up new markets and value streams for customization that fit with markets' needs that were not previously accessible. Data compatibility was important for most of the organizations due to the volume of data and its application in the design process. Populating the equipment with data to produce parts was viewed as a design/engineering task outside the remit of traditional manufacturing. Digitization and shared data are an essential foundation of the technology that will remain important going forward. The ability to transfer large volumes of data, through the support of cloud computing, has made AM much more appealing for deployment and facilitates interfaces between different functional areas, particularly engineering, operations and physicians. The issues of organizational and production fit were found to be less important but should be a consideration [3].

Complexity with adopting AM was highlighted in terms of a lack of industry standards for material and equipment that was challenging businesses in determining the way forward. For organizations with design skills, the implementation of AM was not viewed as a major obstacle. The deployment of the technology was found to enhance the ability of organizations to strategically offer a greater variety of services and products, and an ability to offer a more complex portfolio to gain a competitive advantage [67,91]. The dichotomous challenge of minimizing the negative consequences of increased product range complexity while supporting strategically important growth in their offerings needs to be considered. When investing in AM, organizations need to comprehend the impact of the technology on the complexity within their operations in terms of increases in processes, data and markets, as well as products.

For organizations considering the adoption of AM, the ability to trial the technology was viewed as important, though not as critical as its relative advantage in the decision to invest. The acquisition of support services and specialist knowledge and training, by suppliers, in piloting the new technology was pivotal in progressing from the consideration to the investment stage. However, which form of AM to invest in was unclear due to a lack of standards. Observing what the sector was embracing was viewed as significant in determining the direction of travel as institutional pressures are important in many sectors, particularly medical, to provide social legitimacy [92]. Lack of visibility can also limit the promotion of AM due to customer concerns over quality and lack of trust in the technology.

6. Practical Implications and Recommendations

AM literature abounds with studies on prototyping and the business benefit of rapidly producing samples and supporting designers in modeling new products. However, most of these prototyping examples indicate that the designers are using AM to develop products for traditional manufacturing. Our case studies move beyond this boundary to include and investigate organizations that are deploying AM to manufacture final products. Our research into AM contributes to both theory and practice through the development of a framework and a set of recommendations for assessing different performance attributes associated with AM based on the type of application, as well as the likelihood of adoption of the technology in the future. All five adoption characteristics were found to be important however, the primary decision criterion is based on the relative advantage of AM over other, traditional, technologies. From a practitioner perspective, our research highlights the importance of AM in attaining a competitive advantage through responsive, customized production that can address the needs of niche markets. Nevertheless, when it comes to how businesses adopt and justify AM, we identified three primary issues that arise from this research, that provide important guidelines for practitioners.

First, the primary rationale for adopting AM should be focused on creating customer value in the marketplace, to meet a specific need. Adopting the technology should be driven by a desire to offer new services and products to customers in a timely manner. The case study organizations expected that cost reductions would be achieved in time, as their understanding of the technology and financial measures developed, but this was not a significant element in the adoption decision. Meanwhile, AM will need to be justified by a higher cost to the customer, to facilitate the adoption of the technology across a wider array of sectors and businesses. Our archetype framework could serve as a useful foundation to research the development of measures that can assist practitioners assessing the adoption decision.

Second, AM provides a platform for organizations to alter their customer value proposition through migrating from a conversion of resources into commodities perspective to a high value, high customization focus. However, the lack of industry standards, visibility and benchmarking opportunities challenge organizations in determining the future direction of AM deployment to deliver the relative advantage of the technology. As AM moves more into the mainstream, there are increasing opportunities to observe and test the technology, especially in the context of universities and research centers. It is recommended that organizations explore partnering arrangements with universities to aid them in overcoming obstacles related to standards and gaining insights into best practice in their sectors. This was indeed the case in four of the organizations we looked at (Plastic, Toy, Hospital, Filters).

Finally, the adoption of AM has implications for the management of complexity. New AM services and products are operating alongside traditional methods that are increasing complexity in terms of data management, product range, organizational fit and process compatibility. The ability to simultaneously explore new value streams derived from AM while continuing to exploit the benefits of traditional manufacturing approaches will necessitate the development of an ambidextrous approach in operations management. Strategically, AM proffers the opportunity to combine standardized production with customization in the creation of customer value.

7. Conclusions and Limitations

Our research study established some important conclusions for the field of advanced technology and in particular the growth and deployment of additive manufacturing. We sought to understand the key market drivers that led to the successful adoption of AM technology and their linkage to specific attributes of the technology using a framework first put forth by Rogers and Shoemaker [13]. Our empirical case analysis produced several important insights. First, the case studies confirm the requirement for a strong market focus; AM should be adopted primarily as a "pull" requirement from well-defined customer needs. Second, there are many different types of customer "gaps" that can be filled with AM technology. In particular, as customers increasingly want to visualize products before making large investments, the use of prototyping is a particularly important application. Others include the growth of customized medical implants and surgical aids to support safer and quicker surgeries for an aging population that needs back, hip and knee replacements. Third, AM has a high potential to reduce complexity in supply chains and to also support more domestic manufacturing of critical healthcare products in a crisis. These and many other important applications have been identified. The framework around trialability, observability, relative advantage, complexity reduction and trialability is still very relevant.

From a research perspective, the case studies provide some empirical support for our archetype framework. However, future research, qualitative and quantitative, will be required to address and strengthen the cost aspects of the model and provide insights into the non-cost performance attributes that are driving the various levels of activity and the adoption characteristics that are supporting the deployment of AM. The emphasis on exploiting niche market and product customization options to deliver customer value without the underpinning of pay-back models is contrary to traditional operations and finance positions requiring further research on justifications and sustainability of the stance.

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Appendix A. Case Study Characteristics

Adoption Attribute / Business Application	Relative Advantage	Compatibility	Complexity	Trialability	Observability	Performance Attributes
Light Co. (prototyping and experimentation)	Improved product development and prototyping speed. Used for quick production of jigs and machine parts Manufacturing of special, one-off, products without having to cost in a tool	Quick customer approval due to AM, which is better than 3D drawings and visualizations. Outsourcing of AM used for items too large for own printer, material is not suitable for in-house equipment.	Used by designers as technology is similar to CAD Looking to replace sand-casted components with AM items as a traditional supply route	Printers are relatively cheap to purchase providing a low barrier to entry Supports evaluation stage of new products with customers' input	AM used to showcase technology to customers. AM currently a design and marketing tool more than a manufacturing instrument, though industry use is widespread.	Speed, product design viability, product demonstrations Experiments to try and develop alternative machine parts
Filters Co. (production of non-standard designs)	Improved product design not feasible to manufacture using traditional methods. Improved liquids and gas throughputs (efficiency gains) for company customers Growing new market segment	AM is used for manufacturing using a hybrid system; filter elements are printed to stock and then welded together in the workshop. Only recently was AM used to make components for final assembly	Supply chain complexity is transferred into product design. Certain metal meshes are hard to come by; a lot of supply problems and complexities have been removed.	The company started trialing the technology at University. Only then was investment in a large metal printer undertaken.	Customers often do not want to know if their part is AM or not. Customers expect lower quality of an AM part, so process origin is not declared to the customer. Customers are reserved in terms of change.	Customized products for niche market

Adoption Attribute / Business Application	Relative Advantage	Compatibility	Complexity	Trialability	Observability	Performance Attributes
Toys (rapid prototyping and production of non-standard designs)	Improved product development and prototyping speeds at a fraction of the traditional cost for molding and reshaping. Highly customized designs required for electrical housings due to space constraints. Speed to market for existing customer segment	Enabled the company to gain market share in a very niche market segment through high levels of customization and speed. AM is contributing components to small batch production. All designs are developed using 3D modeling software; therefore integrates seamlessly into the in-house manufacturing process.	Little systems complexity. AM brought new improved functionality and speed	Printers are relatively cheap to purchase providing a low barrier to entry. Handling and operation of the printer was self-taught using YouTube.	AM is heavily used for rapid prototyping in the hobbyist niche market. Printers often run small batch production of customized electrical housing solutions due to size constraints in the application (model planes)	Customized products for niche market Meet market niche for low volume products in shorter time
University Hospital (production of non-standard designs)	Uses high-quality images to produce cutting guides for orthotic surgeries, using metal or plastic. Reduces cost of the component by in-house production. Reduces Operating Room (OR) time ($80/minute) and reduces time for patient to recover. One day of hospital recovery time pays for 3D printing cost.	Needed to develop a robust procedure for biomedical engineers and physicians to collaborate well. Cloud computing allowed rapid exchange of information that was fundamental to this. Need imaging equipment that can produce a robust 3D Printing data set that can be used for printing on AM equipment.	Required investment in the right imaging equipment. Keeping the AM center in-house allowed the hospital to service its own patients, without being subject to international audit requirements. More complicated if required to use in US and Canada.	Plastic technology was well-developed and group could run cheap trials. Once surgeons saw the success of the technology, they started eagerly requesting AM to create components to put in humans.	Marketed to patients as customized implants; surgeons saw immediate benefits of cutting OR time during surgery using jigs. Increased visibility of the hospital in the community.	Customized product for patient operations and implants in short period of time Meet market niche for low volume products in shorter time
Life Sciences Inc. (Low volume primary manufacturing, spare instruments and production of non-standard designs)	A custom-produced tri-flange cuff with flanges used in a hip replacement can cost $60 K to produce today. With 3D printing, it costs as little as $5 K and is much faster (weeks vs. months) Cost of materials is the primary disadvantage today, but this will get less expensive as volumes go up.	One of the biggest barriers is the slow reaction of the FDA to approve 3D printed parts and allow them on the market. Once approved, it will bring the cost down further by 90%, and will continue to drop. Cloud computing is an essential component of the development of AM. Computing power in the last five years has sped up the growth of 3D printing.	Up until recently, the size of the data file and the complexity of the information was the biggest barrier. With cloud computing, that is no longer an issue. The complexity of valuation and qualification is not well understood, and there is a need to work on how to monitor the process, predict the outcome and measure and prove it on a one-off basis. Not validated to full potential.	Company has been very open about its progress and has been showcasing the technology at trade shows. Have developed global partnerships with major manufacturers to develop processes with them, including pharmaceuticals, medical devices and others.	Demonstrations allow patients to envision what is possible and allow surgeons the ability to introduce new methods that are more efficient.	Customized product for patient operations and implants in short period of time Meet market niche for low volume products in shorter time
Electro Co. (rapid prototyping)	Ability to ensure products are brought to market quickly by de-risking new designs. Example: metal housing, £1200- and 4–5-week delivery vs. plastic AM model £300 made overnight.	Predominantly used for prototyping parts before they are cut in metal in a standard manufacturing facility. Rapid, low-cost, evaluation of new housings and structures before committing to new, long lead-time, metalwork	Able to test structures to make sure they function and are acceptable to the customer.	Allows a physical representation to be made quickly and easily before discussion with the metalwork supplier. Superior options in terms of manufacturability or cost may then be identified as a result.	Ability to evaluate the assembly of a complex multi-element structure to develop market position	Speed, product design viability, product demonstrations

Business Application \ Adoption Attribute	Relative Advantage	Compatibility	Complexity	Trialability	Observability	Performance Attributes
Plastic Co. (rapid prototyping and reverse engineering of spare parts)	Improved product development and prototyping speeds for rapid prototyping customersManufacturing of special spare parts, which are no longer available or highly customized to end-user needs—predominantly private automotive enthusiasts Increased service offering to existing market segment and growth of new B2C segment	Highly compatible with existing business. Extension of old polymer molding business and creation of new value stream Lack of compatibility with existing IT infrastructure, processes, practices and knowledge due to traditional manufacturing background. High upfront investment cost in capacity and capability. Establishment of a new, separate value stream. No financial modeling conducted.	The workforce had major difficulty in comprehending innovation, as well as the sales team, which was reluctant to sell new AM capabilities offered. High investment cost in staff (AM expert hired) and training cost of existing sales force	At the time of investment into AM, polymer technology trialability was limited. Small trials run with local University improved perception of risk. High financial risk due to limited trialability in remote Australia	Visibility in the community is high due to the nature of the parent company. Visibility beyond the region is marginal. Visibility allowed the establishment of strong local market reputation with increase in demand for existing and new AM value stream over the past 5 years. AM had a spillover effect.	Deliver customer needs for spares through reverse engineering Speed, product design viability, product demonstrations

Appendix B. Details of Interviews

Organization	Interview Duration	No. of Researchers Present	Years of Adoption	Respondents
Light Co.	1.5 h	2	3	Finance Director, Operations Director, Production Manager
Filters Co.	1.5 h	3	7	Managing Director
Toys Co.	1.5 h	1	3	Operations Manager, Director
Hospital	1 h	1	4	Head of 3D Printing Lab
Life Sciences	1 h	1	5	SVP of 3D Print Division
Electro Co.	2 h	1	3	Engineering Manager, Mechanical Engineer, 2. Electrical Engineers
Plastic Co.	2 h	2	8	AM Manager, AM Engineer, Director

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