Investigating Contingent Adoption of Additive Manufacturing in Supply Chains

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Abstract:

Purpose - The purpose of this research is to investigate the contingent adoption of Additive Manufacturing (AM) and propose a typology to evaluate its adoption viability within a firm's supply chain.

Design/methodology/approach - By conducting semi-structured interviews of practitioners with deep knowledge of AM and supply chains from diverse industries, this research explores the contingent factors influencing AM adoption and their interaction.

Findings - While AM literature is growing, there is a lack of research investigating how contingent factors influence AM adoption. By reviewing the extant literature on the benefits and barriers of AM, we explain the underlying contingencies that enact them. Further, we use an exploratory approach to validate and uncover underexplored contingent factors that influence AM adoption and group them into technological, organizational, and strategic factors. By anchoring to a selected set of contingent factors, a typological framework is developed to explain when and how AM is a viable option.

Originality - This is the first paper in the supply chain management literature to synthesize contingent factors and identify some overlooked factors for AM adoption. The research is also unique in explaining the interaction among selected factors to provide a typological framework for AM adoption. This research provides novel insights for managers to understand when and where to adopt AM and the key contingent factors involved in AM adoption.

Keywords Additive Manufacturing; 3D Printing; Contingent factors; Supply Chain Management; Typology for AM Adoption**.**

Paper type Research paper

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1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, has attracted the attention of practitioners and academicians for decades (Karevska et al., 2019). With continuous evolution, AM is now increasingly used to manufacture end products from merely prototyping. Due to significant improvements in AM performance, thanks to rapid innovation, it is advancing its way into industries such as Aerospace, Defense, Automotive, Consumer Goods, and Medical Devices (Stentoft et al., 2020).

Examples in aerospace include General Electric successfully mass-producing 30,000 jet engine fuel nozzles (GE, 2018) and Boeing developing a critical rotorcraft component of aircraft to achieve design improvements and lower the lead time and machining time (Boeing, 2022), both using AM technology. BAE System's adoption of AM to improve their efficiency in developing combat vehicles due to the technology's design flexibility and quick cycle time is an example from the Aerospace and Defense industries (Niswonger, 2021). In the automotive industry, AM was used to print 60,000 parts for GM in just six weeks to avoid costly delivery delays (Mceachern, 2022). Rolls Royce using AM to manufacture complex and lighter parts that undergo multiple cycles of customization as a part of the design process is another example in the automotive industry (Rolls-Royce, 2018). In consumer goods, Adidas using 3D printing for more innovative and advanced products is an ideal example (Adidas, 2021). AM is being used to produce a wide variety of customized products such as implants and prosthetics in the medical-devices industry (Bromberger et al., 2022).

Existing research highlights the potential impact of AM technology on the operations and supply chains such as (i) enhanced internal flexibility (Eyers et al., 2018), (ii) boost in competitiveness and customer service by enhancing the capacity to produce faster and safer (Giffi et al., 2014), (iii) improved new product development performance and thereby competitive advantage of the firm (Turkcan et al., 2022), (iv) change in supply chain structures focusing on local manufacturing (Durach et al., 2017), (v) better supply chain integration (Delic et al., 2019), and (vi) improved supply chain flexibility and performance (Delic & Eyers, 2020). To extract and deliver these benefits from the AM technology in practice, several mergers and acquisitions in AM domain have occurred representing the growth of the field, such as Midwest Composite Technologies (a 3D-printing company) acquired injection-molding specialist ICOMold LLC (Garcia, 2019), Stratasys acquired a software-centric AM solution company called Origin to accelerate expansion into mass production using AM (Prairie, 2021). Research and practice not only highlight the rising interest in AM but also stress the immense impact AM can make on operations (Fera et al., 2018) and supply chains (Verboeket & Krikke, 2019).

However, despite the current and future potential of this state-of-the-art technology, few studies indicate that AM has not been extensively used across all industries (Koh et al., 2019; Muhammad et al., 2022). Studies by Thomas-Seale et al. (2018), Pinkerton (2016), and Dwivedi et al. (2017) have identified the barriers to adopt AM. According to Oettmeier & Hofmann (2017), businesses are still hesitant to use AM technologies due to a lack of understanding of why, how, when, and where should they be used. While the "why" or "why not" part of this dilemma is addressed by the previous studies that investigate the benefits and barriers of AM (e.g., Delic & Eyers, 2020; Durach et al., 2017; Weller et al., 2015), and 'how' part of the dilemma is clarified by practitioner reports (e.g., Doyle, 2017) and research case studies (Kothman & Faber, 2016; Mellor et al., 2014) explaining the AM implementation process, research that addresses "when" and "where" remains very limited. More specifically, the gap in the literature is the lack of understanding of what are AM barriers and benefits contingent or dependent on ("when" and “where”) in the context of the supply chain. Only a few studies, such as Delic et al. (2019), Delic and Eyers (2020), and Eyers et al. (2018), consider the role of supply chain context when investigating the relationship between AM adoption and performance variables. It is essential to consider the contextual factors because they may affect the practice-performance relationships (Sousa & Voss, 2008). Hence, it is unclear what should be the reasonable expectation in scenarios where technology could be practically and economically viable. For example, an interview participant from the aerospace industry in prior research identifies the ‘lower buy to fly’ ratio as the benefit of looking at AM for their industry (Thomas-Seale et al., 2018). Also, many products in aerospace have intricate and complex design, an ideal environment for AM to thrive (Kunovjanek et al., 2020). However, one must understand that majority of metal products manufactured through AM do not go through a machining process; instead, parts are manufactured using a source of thermal energy to fuse the different layers together (Huang et al., 2013). The thermal energy changes the basic mechanical properties of the material, and the thermal kinetic properties of the resulting product are still uncertain (Huang et al., 2013). Hence, the product made through AM have a difficult time passing inspections and quality checks (Thomas-Seale et al., 2018), it could be several years before a moving part is approved for use. This example emphasizes the need to comprehend the contingent factors for adopting AM.

Furthermore, while extant literature encourages the adoption of AM, it is interesting to note that there appears to be no overarching typology to describe ‘when’ and ‘where’ AM can be adopted. A typology offers representation of the messy aspects of the real world as precisely as possible given the available data collection and enables more profound thought by stakeholders who may be attempting to make decisions in the area of focus (Russell & Swanson, 2019). Thus, developing the typology for AM adoption will enable managers to develop a more nuanced approach to adopt AM in existing manufacturing operations successfully. Therefore, the aim of this paper is to provide systematic support for AM adoption by developing a typology derived from contingences to adopt AM. To achieve the stated aim, we answer the following research questions (RQs):

RQ 1. What are the contingent factors that affect AM adoption?

RQ2. How does the interaction of the contingent factors influence AM adoption?

The study addresses the research question using a systematic approach of inductive research. We use 2 stage approach to achieve the objective of the study. In first stage, we identify the contingent factors from the past literature of AM and in second stage, we validate the identified contingent factors and explore new factors by conducting semi-structured interviews with 13 experts from industrial organizations spanning the aerospace & defense, automotive, and machine manufacturing sectors across the USA, UK, Denmark, and India. This research is relevant for both academics and practitioners. For scholars, it provides a methodologically derived overview of contingent factors that influence AM adoption. For managers, the research brings more clarity to understand conditions under which AM adoption can be more effective.

This paper is structured as follows. Section 2 provides the background of AM technologies and summary of contingent factors in the extant AM literature. Section 3 discusses the methodology focusing on data collection and data analysis. Section 4 presents the findings that emerged from the data, and the discussion section 5 describes the theoretical and managerial implications. Finally, the paper concludes with limitations, and future research directions.

2. Literature Review

2.1 Background of AM

AM technology has been evolving in phases (Berman, 2012) since it was first launched in 1980s (Kruth et al., 1998). In the first phase, AM was used only for prototyping, during the second phase AM technology was starting to see its use extend to creating finished parts, third (current phase) involves the use of 3D printers by end customers (Berman, 2012). However, the technology has not been widely adopted across product categories nor has significantly reduced our dependence on traditional manufacturing. Durach et al. (2017) categorizes the AM technologies powder bed fusion, material jetting, directed energy deposition, material extrusion and photo-polymerization processes to be more important whereas binder jetting and sheet lamination to be least important. Powder bed fusion and material jetting are most likely to lead the market and are applicable in parts production including spare parts, tooling production and prototyping (Durach et al., 2017). Figure 1 provides information on the AM technologies categorized by applicable material.

Insert Figure 1 about here

2.2 Contingent Factors Affecting AM Adoption

For a technology to be successful it is not necessarily sufficient for a company to only adopt (exercising a choice and making a purchase), but also successfully implementing (integrating technology into production) in organizations' processes. For purposes of this research, we define AM adoption as act or process of using AM in the production processes. The benefits and barriers of AM adoption have been studied extensively in the literature. For example, Holmström & Partanen (2014) identified vital role logistics service providers can play in digital manufacturing that will benefit in increasing availability of parts in challenging locations. Wagner and Walton (2016) points out the success factors such as business case that must be managed and control factors such as production efficiency that need to be monitored for AM adoption in the aviation industry. Using a survey of 195 firms, Oettmeier and Hofmann (2017) identify demand side benefits (i.e., customization and production closer to customer) is a key factor that motivates AM adoption. Schniederjans (2017) explore the perceived relative advantages of AM such as speed, quality, productivity, and employees' effectiveness. Jiang at al. (2017) predicted the future development of AM and its economic and social impact. Eyers et al. (2018) examine the flexibility of industrial additive manufacturing systems. Niaki et al. (2019) clarify that even though AM offers economic, environmental, and social sustainability benefits, economic benefits motivate the adoption of AM while social and environmental benefits are given least consideration. Westerweel et al. (2021) show that printing few spare parts on site may help firms manage supply of spare parts in remote geographic locations.

On the other hand, several studies discuss the barriers and challenges to AM adoption. Ford and Despeisse (2016) described the opportunities and challenges of AM based on case studies from company websites, news sources and academic publications. Dwivedi et al. (2017) investigated the relationships between the barriers of AM adoption and ranked them in context of the Indian automotive industry using an interview approach. The study by Thomas-Seale et al. (2018) identified eighteen barriers including cost, machine constraints and validation etc. using case studies conducted with organizations in the UK industries such as aerospace and defense, automotive, heavy machinery, and medical devices. Kunovjanek et al. (2020) provide perceived benefits and challenges of AM across different industry sectors using SCOR framework.

Another category of study focuses on overcoming the barriers of AM adoption. For example, using case study method, Huang et al. (2021) show that combining technological and operational innovation is key for AM to achieve high volume production. Hedenstierna et al., (2019) propose a novel outsourcing scheme called bidirectional partial outsourcing (BPO) to lower the total cost while maintaining responsiveness. Baumers and Holweg (2019) use experiments to analyze role of scale in AM with respect to cost. Baumers Tziantopoulos et al. (2019) offer a framework for evaluating AM enabled supply chain reconfiguration opportunities for decision makers. Knofius et al. (2021) evaluate potential of AM to use as a dual source for spare parts supply.

The main gap in the literature is the lack of understanding on what these barriers and benefits are contingent upon. We believe that not all firms adopting AM will be able to gain all the different benefits or the same set of benefits, extract the same level or magnitude of benefits, be unaffected by all or same set of the barriers, or experience the same level or magnitude of barriers. It is contingent on internal and external factors in the environment to which firm is subjected in their environment. For example, AM provides only certain set of benefits to SMEs such as flexibility and local production of customized products due to factors like lack of investment, limited capacity (internal factors) and dynamic market demand (external factor). Whereas larger companies can gain many more benefits using AM such as accelerated new product launch at marginal cost due to availability of skills and resources (internal factors) and customer demand for highly customized products (external factors). Similarly, firms may face different set of challenges or derive different set of benefits from AM adoption depending on factors such as management support (internal) and geographic location (external). This understanding will also explain why some firms are finding it difficult to use AM for manufacturing final products, limiting the large-scale adoption of AM (Bromberger et al., 2022).

The contingency theory is one of the key lenses employed to analyze organizations. The contingency theory (Thompson, 1967) explains that there is no one unique way to manage an organization because business is dynamic and is influenced by a variety of environmental factors

(Donaldson, 2001). The organizations achieve better performance results when they are able to create a fit between organizational structure and environmental uncertainty (Donaldson, 2001). Thus, many researchers (e.g. Waiganjo, Mukulu, & Kahiri, 2012) advocate that managerial decisions need to be aligned with environmental demands by being aware of contingencies for better performance.

As operations management (OM) and supply chain management (SCM) researchers have moved their focus from identifying best practices to understanding under what conditions certain practices are successful, scholars have become increasingly interested in the role of contextual factors (Sousa and Voss, 2008). This type of study is frequently based in the theory of contingency and seeks to identify relevant contextual factors and investigate their roles and interactions (Sousa and Voss, 2008). Frequently, contextual factors and contingencies are treated as synonyms and utilized interchangeably. In OM field, many studies demonstrate that contingent factors can explain manufacturing firms' adoption of contemporary practices. For example, Flynn et al. (2010) show that contingency factors positively affect the relationship between supply chain integration and firm performance. Wong et al. (2015) suggest that positive effect of supply chain integration on firm’s performance is contingent on the level of market and product complexity.

Extending this analogy to manufacturing firms that have adopted or are on the fence of adopting AM, several contingent factors will influence AM adoption and the value it creates for the firm. Contingency theory is a good fit for our research as it focuses on understanding when AM adoption fits with the firm’s internal and external contexts to deliver enhanced firm performance (Chavez et al., 2013; Wong et al., 2011). Therefore, to achieve desired benefits by adopting AM, managers need to gain significant understanding of the contingent factors involved in AM adoption. Theoretical and practical contributions to contingency theory are made by first identifying contingency variables that distinguish between contexts, then grouping contexts based on these contingency variables (Sousa and Voss, 2008). In order to identify the contingent factors influencing AM adoption, we evaluate the previous studies on benefits and barriers of AM adoption from a contingency perspective. We independently identified contextual factors in each paper and then discussed as a team to reach consensus.

Table I shows contingency factors affecting AM synthesized from literature, such as type of industry (Kunovjanek et al., 2020), firm performance objective (Delic & Eyers, 2020), type of material (Durach et al., 2017), intellectual property rights (Chan et al., 2018), volume variety (Huang et al., 2021), manufacturing modes (Hedenstierna et al., 2019), perceived usefulness and compatibility (Schniederjans, 2017), design of supply chains (Durach et al., 2017), relationship among supply chain partners (Holmström & Partanen, 2014), closeness to consumers' market (Tziantopoulos et al., 2019), intellectual property and data security (Wagner & Walton, 2016). In addition to evaluating extant literature from contingency perspective, we conduct interviews to investigate if there are any other factors that enable or constrain AM adoption in supply chains.

Extant AM literature implicitly state these contingent factors, but in isolation. The studies highlighted above describing benefits and barriers of AM either discuss single case or domain. Due to wide range of contingent variables, previous works are fragmented as they differ in terms of contingencies and research frameworks. Since supply chains are dynamic, multiple factors are likely to interact to drive firm level AM adoption. However, extant research has not captured such interactions. This also represents a problem from managerial point of view because they lack clarity of what contingencies are involved in adoption of AM and how the contingent factors interact. Our study addresses this gap by consolidating product and supply chain level factors in a typology for AM adoption. Although few researchers have developed frameworks for AM implementation focusing on various specific business perspectives, such as Braziotis et al. (2019)

developed a framework based on logistics deployment and Sonar et al. (2020) developed a framework based on firm competitiveness, to our knowledge, no study has developed a typology for AM adoption in generic supply chain context.

Insert Table I about here
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3. Method

As mentioned earlier the purpose of this study is to discover and explore rather than to test hypotheses, thus exploratory qualitative research approach was chosen. The approach is also suitable because the amount of scholarly literature devoted to the issues impeding the widespread use of AM in industry is low (Thomas-Seale et al., 2018). Within exploratory qualitative approach, data was collected through qualitative semi-structured interviews from 13 respondents (Denzin & Lincoln, 2000; Strauss & Corbin, 1998) to study contingencies on which AM adoption depends. Each respondent is an informed employee representing a firm whose geographical heterogeneity includes United States, United Kingdom, India, and Denmark. We employed qualitative data analysis approach advocated by Gioia et al. (2013) for assessing our informative semi-structured interviews. Based on the analysis, we identify the contingent factors influencing adoption of AM. Ultimately, we develop a typology linking AM to supply chains by taking contingent factors into account.

3.1 Research Setting

To capture a range of viewpoints on this phenomenon, we selected a heterogenous sample for interviews in three steps. First, in initial desk research, we selected firms by sifting through our established contacts with industry professionals in order to locate firms meeting our criteria. Second, we attended conferences dedicated to AM to connect with experts in this field. Thirdly, using a snowball sampling technique, we requested recommendations for further interviewers from all experts (Denzin & Lincoln, 1994). We chose firms that operate in a variety of industry sectors, including automotive, machine manufacturing, and aerospace & defense, to ensure our findings are not limited to a single industry sector and to allow for the emergence of alternative explanations (Eisenhardt & Graebner, 2007). Following that, we approached each firm's primary contact via email to decide whether the firm was qualified for and willing to participate in our research. The email included a synopsis of the research objectives, background information on the research team, and an estimated time required from the potential participant. After the primary contact's agreement to participate, we collaborated to identify a key manager who could address our questions. We proceeded to expand our sample of firms by finding new interviewees that fit the criteria above and could shed additional light on the concepts revealed by our analyses. Our interviewees were professionals with an understanding of AM technology as well as its use in the supply chain context.

3.2 Data Collection Process

We conducted interviews per established guidelines to ensure our findings' reliability and validity (Denzin & Lincoln, 2000). Our data collection was driven by a research protocol, which detailed the interview's opening and closing scripts, the request to record the interview, the interview questions, and their structure, and the request to collect supplementary data.

We conducted in-depth, semi-structured interviews with 13 key informants. The interview structure was developed following an extensive review of the literature and the authors' prior knowledge. The interview adopted a semi-structured format, with opening, probing, and closing questions. The interview protocol can be found in Appendix 1. While the interview's fundamental aspects remained similar, we gradually modified and expanded the interview guide (Patton, 2015).

Due to the participants' active participation, we were able to investigate specific contingencies they had observed in practice. The 13 interviews ranged from 42 to 77 minutes, with an approximate average interview length of 60 minutes. Table II provides an overview of the interviewees.

The interviews took place via online communication tools such as Zoom and Microsoft Teams. The interview lengths were limited for two reasons. First, due to each participant's availability, interviews were scheduled for an hour. Second, a participant's knowledge; in identifying a representative sample across the industries and contexts mentioned in Table II, not all participants were able to elaborate on all aspects of the interview. We recorded the interviews, put together notes to preserve our initial impressions following each interview (Miles & Huberman, 1994). Next, we summarized the key takeaways from each interview. Additionally, we obtained secondary data that would be useful for our research from company's website including social media pages, news articles, reports, and white papers. These are also captured in Table II. The secondary data helped us to gain more understanding of AM adoption in the firm and the sector and to triangulate the interview data.

Insert Table II about here

3.3 Data Analysis

We started analyzing the data as it was being collected (Eisenhardt, 1989). Without a specific coding system, the recorded interviews were coded inductively. We analyzed the interview data from each of the specific interviews and also conducted cross-interview comparisons (Eisenhardt, 1989; Miles & Huberman, 1994).

We conducted several steps during this stage to confirm the reliability and validity of our results (Denzin & Lincoln, 2000). As a first step, we started re-reading the transcribed interview data and summarizing each interview (Miles & Huberman, 1994). Second step was to conduct a first-order analysis (i.e., open coding) by compressing the data into words, sentences, and brief paragraphs that were important to answering our research question. In the third step, we coded the data derived from second step using the sub-factors. As a result, we were able to derive second-order categories and overarching dimensions from the literature. As we coded the sub-factors, we observed that the main informants used terms that had not been reported previously in the AM literature (Gioia et al., 2013; Strauss & Corbin, 1990). Next, we started comparing the first-order categories and grouping them into second-order themes (i.e., axial coding) (Gioia et al., 2013; Strauss & Corbin, 1990). Finally, we synthesized analogous second-order themes into all-encompassing dimensions (Gioia et al., 2013).

Based on the set of concepts, themes and aggregate dimensions, a data structure was built (Gioia et al., 2013) as shown in Appendix 2. The initial coding procedure was completed by authors individually, followed by discussion to finalize categories. The different dimensions were then categorized into three broad categories. We iterated between our codes and the AM literature streams during coding in order to compare and ground emerging concepts in the literature (Gioia et al., 2013). In our findings section, we discuss these concepts and themes in further detail. We generated meta-matrices to compare the results from each interview (Miles & Huberman, 1994), compiled evidence for emerging concepts, and ensured that the emerging concepts were replicated across interviews. Findings of the study suggest several contingent factors that influence AM adoption. We develop a typology for AM adoption based on four contingent factors. The exemplar factors that served as the basis for the typology are illustrative but not exhaustive.

4. Findings

A theoretical structure emerged from the analysis, grounded in the data explaining the contingencies for AM adoption. Table III describes the contingent factors that emerged from second order themes in the data structure. Based on the understanding obtained from the review of literature that contextual factors and contingencies are treated as synonyms and utilized interchangeably, we identified those as contingent factors that can have multiple anchor points (shown in brackets in contingent factors columns in Table III), with each of those anchor points potentially defining a different context that can be a fit or a misfit for AM. For example, 'manufacturing location' contingency factor can take anchor points as 'closer to the user' or 'away from the user'. If the requirement on manufacturing location is to be closer to the user, then the context defined is fitting for the adoption of AM. If the requirement on manufacturing location is not necessarily to be closer to the user, then the context defined is less fitting for the adoption of AM. Therefore, depending on the anchor point of different contingent factors that emerged from the data structure, the context defined can be a fit or misfit for the adoption of AM. For each contingent factor, we identified some contextual sub-groups (aggregate dimensions) in order to synthesize the results. We then classify all sub-groups in one of the following groups: "technological", "organizational" and "strategic".

By pulling together the selected contingent factors, we develop a typology for AM adoption that will be useful for managers to understand when and where to adopt AM in their firms. The typology also attempts to capture the interaction of anchor points of four different contingent factors and explains whether the context created by their combination is a fit or misfit for AM adoption. This typology, which can serve as a guide for structuring future studies involving contingencies for AM adoption, is presented in Figure 2. In the following sections, we describe the contingent factors by groups followed by the typology.

Insert Table III about here

4.1 Overview of Contingent Factors

Table III consolidates the contingent factors on which benefits and barriers of AM adoption are dependent and Table IV provides details on how these contingent factors were synthesized from interviews. We further group these contingent factors to several sub-groups and finally classify them into three broad groups: Technology, Organizational and Strategic.

4.1.1 Technological Factors

The most appealing characteristics of AM technologies is the ease with which complex geometry parts can be printed and high level of customization can be achieved. *"The biggest benefit of additive is being able to create geometry that you can't create with traditional manufacturing"* (Participant 5). "*In healthcare, minute customizations can be accomplished that suit to individual customers"* (Participant 3). According to participants, stage of AM adoption is an important factor. AM has been traditionally used at prototyping stage. "*AM can make a prototype needed for a part manufacturing in a few hours to a few days instead of a few months"* (Participant 4). However, adopting AM from design stage itself can be more beneficial. "*But if you implement AM at the beginning of the design process, then the advantages are exponentially more because initially, when aerospace products are designed and being certified on a platform, they are generally made from massive forged blocks that have a 90 to 95% material waste and then are tested for potential design change. So, implementing AM in design will help reduce cost because there's a lot less machining required to achieve final net shape*" (Participant 11). Participants agree that integrating AM in aftermarket for service parts can enhance overall product lifecycle. "*If you think in terms of providing aftermarket service to the customers, AM also enhances product lifecycle since it can* *provide parts that are obsolete and you don't have to rely on external supplier for it*" (Participant 4). Participants from organizations that have implemented AM technology mention that they limit utilizing AM for non-critical parts due to process unreliability for critical components. "*We are using AM for producing tooling that are used for manufacturing less critical components*" (Participant 4). "*We started with the production tools, because no quality checks are needed for non-critical inhouse use*" (Participant 7). "*We use AM for some products that don't need certification because, you know, just it's a non-critical part*" (Participant 2). Participants highlight the need of considering feasibility to produce part using AM including size, weight, cost per part. "*You need to think, does it make sense to 3D print something, because sometimes it doesn't*" (Participant 6). "*Any part that you can think of how to manufacture, we are thinking about AM. That's why we have the whole range of machines, we have the large additive manufacturing and we have the small AM machines to accommodate different sizes*" (Participant 2). "*Size can be a factor too. It depends on the geometry of product then the dimensions. So even if component is larger but need intricate geometry, AM is beneficial to reduce the material waste and cost".* (Participant 10). Even though AM can help reduce overall supply chain costs, it is not cost effective for every type of part particularly in metal products family due to volume constraints. "*AM can't produce every part or can't be cost effective to produce every part but it depends for example Aerospace can live with the more expensive part because they have to save weight and thereby fuel"* (Participant 5). At present, AM is not suitable for mass production of all types of products and is actually industry specific. Hence, production volume becomes a key contingent factor when deciding when to use AM. "*Volumes of specific parts that are dropping down low or if our tool used for production is at the end of its life, it is a trigger point to not buy a new tooling and to switch that over to AM"* (Participant 4). "*Every industry has different volume when it comes to mass production. I mean for an aerospace company; 500 parts can be huge order while for* *automotive such number can be in thousands*" (Participant 1). AM equipment are unable to produce parts as fast as traditional methods leading to low production speed. "*The machines just can't produce parts as fast as traditional methods to support volume* " (Participant 5). However, a few participants indicate the potential of AM technology for mass production in the future. "*I definitely think there's a potential for mass production with additive, especially for parts that small in size mostly made of plastics but metal have potential too"* (Participant 4).

AM enables processing of materials that are hard to process using traditional methods. "*We use AM for materials that are hard to machine like Titanium*" (Participant 5). On the other hand, AM works with limited types of raw materials making it suitable for only a few types of end products. "*Right now, the usage is really limited due to not all materials can be processed on AM equipment*" (Participant 6). Participants mention raw material quality being a concern. Raw material quality is supplier dependent and can pose as an issue since standard specification for powder procurement is not available. "*If we change raw material supplier, you don't necessarily get the powder with same mechanical properties*" (Participant 4). Participants find supply uncertainty as one of the factors that influences AM adoption. "*Yes you have a process to manufacture part but you still have to wait weeks for getting feedstock especially for metals. It is impossible to get the consistent feedstock for bigger machines due to supply delays*" (Participant 6). "*We have to import most powders and there are certain kind of country level restrictions on imports that makes constant supply difficult*" (Participant 1).

Customers still have less trust on AM technology compared to that of traditional manufacturing. The participants who are vendors of AM mentioned "*Customers do not have trust in the AM technology*" (Participant 1). The certifying bodies do not trust the AM process. "There are r*eservations to approve AM parts due to AM process itself*" (Participant 3). AM adopters reveal that AM carries intellectual property (IP) threats since main input of the process is digital design of the product. “*The biggest concern is the print files that contains how we manufacture particular product because everything you need to know about the manufacturing of the part is in the print file that you sent to the printer*” (Participant 4). Absence of part qualification process standards certainly influences the AM adoption decision. “*We are far from standard qualification process*” (Participant 7). “*Part qualification is challenging if you change geometry of the part*” (Participant13). Certification delays can impede AM adoption for certain products that need to be introduced to the market quickly. “*We are holding using AM for certain parts because their certification adds to delay that we can’t afford”* (Participant 12). There is a lack of acceptable specification for AM processes and equipment. “*Standard procedures of AM are still work in process”* (Participant 8). Qualifying raw material powder, that goes as input to AM machines, is a challenge due to unavailability of standard specifications. In most cases, “*customers have to rely on supplier’s own specifications for the raw material”* (Participant 5). AM build unit have a restriction of finite size due to which size of parts cannot be scaled up and to achieve so, entire build unit must be redesigned. The lack of standardization for process and equipment lead to variability in the end products. “*No acceptable standards and specifications are used for AM equipment use. There is no consistency in the end product even if the same machine and same material is used*” (Participant 6).

We synthesize the contingent factors into three sub-groups, namely product, raw material and standardization and certification factors. The contingent factors namely product customization level, geometry of the part, product volume, part feasibility, product application criticality and stage of adoption are consolidated under a sub-group product factors. Raw material quality, material variety, supply uncertainty and raw material properties are consolidated as the raw material factors group that needs to be taken into consideration prior to AM adoption. . Technology trust, IP security, part qualification standards and specifications for process and equipment are consolidated as standardization & certification sub-group. Product factors, material factors and standardization and certification are further grouped as technological factors.

4.1.2 Organizational Factors

Maintenance costs is high due to the uncertainty inherent in new AM technology and the scarcity of service providers, summarized by one of the respondents as "*Pretty high cost associated with configuration, maintenance and calibration of AM systems*" (Participant 11). Additionally, participants suggest that significant investment will be required to revamp the infrastructure to establish end-to-end AM processes and integrate them with existing ones. "*You have to set up a whole factory to make a single AM part including pre and post production process*" (Participant 3). The existing processes are not working interactively with AM, such as material handling processes like conveyor systems, work stations etc. To bridge this gap, additional technologies may be required for smooth integration. Metals, in particular, have a high post-production cost as confirmed by a respondent "*I would say the machine cost is one of significant cost driver for the metals*" (Participant 7).

AM requires skilled labor to achieve the desired attributes, aesthetics, and cost in products. AM processes, particularly with metals and newer technologies, are challenging. Finding a skilled labor to operate an AM machine is difficult. "*There are absolutely challenges with skilled additive technicians. So you need some kind of an expert supervision to keep the process running at this point*" (Participant 8). Firm has to incur expenditure for training and development of AM workforce. "*You have to spend quite a bit time and money on training these new employees and bringing them up to speed so that they can work on these expensive additive manufacturing equipment"* (Participant 1). As several participants noted, in-depth AM knowledge is not uniform across firms and even within firm. "*There is a lack of understanding about Additive technology within departments of organization. I mean R&D employees strongly feel need to adopt AM due to its capabilities but do not understand the complexity involved in procurement of the machines and installation*" (Participant 12). "*Most of the time people over design product that will use AM because they don't know where the upper and lower boundaries are*" (Participant 6). A few participants opined that right now AM process labor relies heavily on experience rather than common documents such as standard work instructions. According to our participants, the problem of skill shortage becomes more severe in developing countries such as India due to unawareness about the technology. There is a need to develop awareness about AM technology across all functions of organization. "*Companies want to put AM machine in house but they also understand that just buying a machine is not the solution. They have to have that amount of learning associated with it"* (Participant 1) and *knowledge and awareness has to be developed beyond design and engineering* (Participant 13).

AM can reduce the production processing cost by providing alternative way to manufacture for metals that are hard to machine. "*If we take an example of a titanium component that needs to be machined out of a billet, right. So, you lose more than 80% of the raw material while machining. So, that is an added cost and the tooling for machining out titanium is quite expensive. So rather than actually machining titanium, why not print it. That will reduce cost*" (Participant 1). Production costs can be lowered for products that use large number of components by eliminating need of subassemblies. "*By reducing number of parts using AM, you've now made simplification that saves cost and labor in subsequent assembly processes*" (Participant 6). AM can also help reducing production costs by either eliminating tooling or producing the tools inhouse. "*We now use AM for producing tool that is at the end of its life instead of purchasing it*" (Participant 4). AM has potential to reduce inventory carrying costs significantly by eliminating need to maintain stock for subassemblies and their raw materials. "*Unlike AM,* in *traditional method, raw material becomes a bit of a complex challenge, because you have to place orders significantly in in in time ahead of when you need it and keep carrying it in your inventory, which can become quite expensive when you're talking about tons of material in order to mitigate the risk of not having material for when you need it*" (Participant 11). Using just in time approach for AM raw material can reduce inventory carrying cost further "*You can have just in time deliveries so that you're not carrying that inventory it's moving from your supplier to you and it's being consumed if you have a known production rate"* (Participant 6). AM can be used to create digital inventory of end products. "*Because it makes no sense to have 50000 sq. m warehouse full of spare parts and there is a part ordered once every 6 months. But customers are compelled to have it due to commitment with consumer. This is where we think Additive manufacturing will play a key role. All of these footprints can then be reduced to digital inventory and printed on demand*" (Participant 12).

The contingent factors are further consolidated into three sub-groups, initial fixed cost investment, training and development, and cost justification. Equipment and its maintenance cost and infrastructure readiness contingent factors are consolidated as initial fixed cost investment sub-group. Skilled labor, knowledge about technology are consolidated to training and development group that need to be taken into consideration prior to AM adoption. Production cost, and inventory carrying cost are consolidated to form cost justification group that need to be taken into consideration prior to AM adoption Initial fixed cost investment, training and development and cost justification are further grouped as organizational factors.

4.1.3 Strategic Factors

According to respondents, decision about to location to install AM equipment is an important factor. "*We've been investigating potential of additive manufacturing closer to user. That way we* *can print part in Europe than in Asia and then ship the part halfway across the world*" (Participant 4). "*AM reduces supply chain length because you are able to produce on demand at a location nearest to consumer*" (Participant 12). Lead time is another factor that influences AM adoption. For example, participant 2 mentions "*The products that take long lead time to manufacture or have longer supplier lead time, we try to manufacture with AM so save the time*" (Participant 2). "*Aerospace organization X that launches rocket takes years to get part from supplier due to complexities involved in the process so they wanted to reduce the lead time for parts and that's when they started using metal additive manufacturing AM can accelerate product's time to market*" (Participant 3). Participants agree time to market is one of the factors that drives AM adoption. "*You can prototype, test, develop in much shorter timeframe*" (Participant 13). "*AM makes product development cycle shorter*" (Participant 2). "*AM allows more time for field testing or accelerated work testing*" (Participant 4).

Our respondents mentioned supplier selection should be given consideration for AM adoption. Qualifying raw material supplier itself is a challenge. For example, "*We did very extensive tour of North American metal powder suppliers to know quality of material , inspection of their equipment, manufacturing processes to qualify suppliers*" (Participant 6). Another aspect is third party supplier selection for outsourcing AM. "*There are many suppliers that will just print part but charge you three times more without quality planning. Getting suppliers that can do that do the quality plans and able to make parts in a production setting instead of a prototype setting is hard*" (Participant 4).

One of the essential factors that need to be considered for AM adoption is production decision i.e. whether to bring the process inhouse or outsource or partially both. "*We started bringing AM in house to focus on process development and process qualification. So the process* *development part focuses on how do you shorten the development cycle. And the second one is qualifying as in how do you rapidly qualifying part*" (Participant 2). "*We have network of partners globally, we would use it for outsource rather than having it inhouse*" (Participant 12). "*Firms generally tend to outsource AM's metal side. I have seen it in automotive, in heavy equipment industries and in O&G*" (Participant 12).

Our participants emphasized factor of using AM as alternative source of manufacturing. "*We had the opportunity to keep lines running with Additive Manufacturing technologies during COVID-19 pandemic shut down*" (Participant 4). "*The other avenue would be use AM as a stopgap. When tool breaks but you want to get product out, better start producing them with additive and then switch over to a traditional once the tooling is ready"* (Participant 5). Several interviewees highlighted suitability of AM for production of legacy parts specifically in defense sector. "*The biggest business what we have actually been encountering in the country or overseas is for legacy components"* (Participant 1). "*We can produce parts that supplier no longer provides or supplier no longer exists"* (Participant 7). In other terms, legacy parts usually do not have substitute products in the market. On demand parts printing is expected to change the aftermarket sales and service operations, specifically for legacy parts. AM adoption can pave proactive and reactive ways to improve resiliency and continuity contingent on practicing AM as an alternative source of manufacturing, and utilizing it for parts that have no substitutes in the market.

The contingent factors identified above are consolidated into three sub-groups. Manufacturing location, lead time, time to market are consolidated as manufacturing competitiveness. Supplier selection, production decision are combined under supply network structure sub-group. Alternative source of manufacturing, legacy parts grouped as resiliency & continuity. The three sub-groups are classified as strategic factors that can influence AM adoption.

Insert Table IV about here

4.2 Synthesis of contingent factors

Based on qualitative research, we derived three groups of contingent factors. The contingent factors present in the environment in which firm operates and their interaction that influence AM adoption explain why firms face different level of benefits or barriers. The results reveal four contingent factors that are not discussed in prior literature. First factor ‘stage of adoption’ indicate that AM can be adopted at different stages of product lifecycle including prototyping, production or service. Depending on what stage AM has been adopted, benefits will differ. Adoption of AM at prototyping stage, which has been the main use of AM (Tziantopoulos 2019), results in benefits such as shorter time to market with marginal cost increase (Khajavi et al. 2014). While adoption of AM in all three stages prototyping, production and aftermarket can significantly reduce the total supply chain cost due to reduced WIP and on hand inventory, less scrap and waste generation and lower production cost. Second factor supply uncertainty will determine the production rate of AM and consequently its benefits. As mentioned by participant 6, it is harder to get consistent supply of titanium metal powder which hampers the production schedule resulting into delivery delays. Third factor findings suggest is supplier selection. Supplier selection for obtaining consistent raw material supply at desired quality specifically for metal products is very hard but critical requirement for AM adoption. Several researches (Heinen and Hoberg, 2019; Chaudhuri, et al., 2020; Frandsen et al., 2020; Knofius et al., 2021; Westerweel et al., 2021) have assessed applications of AM for spare parts. Spare parts can have substitutes and multiple suppliers in the market. However, they do not consider role of AM for legacy parts production. Findings of this research indicate that legacy parts i.e. parts with no substitutes as contingent factor that can reduce obsolescence cost and delivery lead time. It is particularly applicable for military and defense equipment. AM can be used for producing obsolete part at remote location eliminating cost and time associated with procuring or storing such legacy part.

Further, surprisingly, few of the contingent factors are only sparsely discussed in the extant OM and supply chain literature such as: product application criticality, raw material quality, trust in technology, part qualification standards, specification of process and equipment, infrastructure readiness, production decision and alternative source of manufacturing. Holmstrom et al. (2010), Jiang et al. (2017) mention AM's application for non-critical parts. Our findings indicate certification delay depends on the product application criticality. Due to reliability and repeatability concerns of AM, certification of critical parts manufactured using AM takes longer and hence it is mostly being used for non-critical parts such as tooling. Thomas-Seale et al. (2018) mention materials as one of the barriers in terms of variety and quality. Findings suggest that raw material quality as factor that can significantly impact the benefits of AM adoption such as product quality and product development lead time. Dwivedi et al. (2017) mentions lack of trust in technology suppliers as a barrier, while Martinsuo and Luomaranta (2018) find that managers are hesitant to trust AM technologies. Our participants also indicated the lack of trust in the technology, especially in the metal side as being a contingent factor in wide spread adoption of AM within their supply chain. Thomas-Seale et al. (2018) identify machine constraints with respect to part size and scalability as one of the barriers. Our findings indicate that not only size of the machine but also unavailability of specifications for AM equipment can influence AM adoption. Due to lack of specification, AM equipment maintenance and repair takes longer time. It also hamper the repeatability of the parts produced by that machine. Infrastructure readiness which emerged as factor in the analysis can lead to varied level of AM adoption in firms. For example, large firms with more resources can add dedicated AM research center such as GE

Additive, while small and medium enterprise may have to evaluate and select AM machines for particular product. Hedenstierna et al. (2019) suggest partial outsourcing practice for 3D printing firms. The findings of this study suggest production decision i.e. in-house vs outsourced AM as one of the influencing contingent factors. It will affect AM supply chain complexity as well as the associated supply chain cost. For example, outsourcing AM can increase supply chain complexity due to addition of number suppliers and outsourcing vendor related logistics cost. Findings suggest that uninterrupted supply of products is feasible even in disruption but is contingent on using AM as an alternative source of manufacturing. Westerweel et al. (2021) suggest similar approach for printing spare parts at remote locations.

In addition, the other factors that have been discussed in the literature are product customization level (Weller et al., 2015; Dalenogare et al., 2018; Niaki & Nonino, 2019; Tziantopoulos et al., 2019), product volume (Chan et al., 2018; Baumers and Holweg, 2019; Delic & Eyers, 2020; Huang et al., 2021), and material variety (Durach et al., 2017; Holmström et al., 2017; Niaki & Nonino, 2019) among others as reported in Table III.

4.3 Additive Manufacturing Adoption Typology

In this subsection, we develop the relational dynamic among the contingent factors identified in the previous sub-section, which can also be mapped to 2nd order concepts in data structure in Appendix 2. To develop a typology for AM adoption, we select four contingent factors from Table III based on the frequency at which it is mentioned by participants and were also confirmed for critical importance with participants after selection. We follow Gioia et al. (2013) approach in formulating the dynamic relationship among 2nd-order concepts in data structure, in this context contingent factors. The identified factors are product customization level, product volume, criticality of product application, and number of substitutes. We represent factor ‘legacy parts’ as ‘number of substitutes’ since most of the legacy parts usually are unique and do not have substitute products.

Figure 2 presents a typology capturing the interaction between these contingent factors and serve as a guide for selecting either Traditional Manufacturing (TM), Additive Manufacturing (AM) or Hybrid approach (TM & AM) for the product. Before getting into the details of the typological regions seen in Figure 2, a few comments are necessary to set the stage. First, we depict the boundary between two approaches, (i) traditional manufacturing and hybrid approach, (ii) hybrid approach and Additive Manufacturing, as curvilinear since distinction between these approaches differ across industries depending on product type. Second, for many products, the value range of contingent factors may vary over time (e.g. number of substitutes available in the market might change). Third, the exemplar contingent factor combinations of the typological framework are representative but not exhaustive of all possible scenarios in business practice. Finally, the selection of approach may change over time as the capabilities of AM technology advance.

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Insert Figure 2 about here

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First, we explain ‘when’ and ‘where’ TM is a better fit while taking the selected four contingent factors into consideration. Products with low customization level may not demand advanced capabilities of AM and it may not even be economical. TM is the better option when the product has many substitutes in the market. Based on findings of section 4.1, AM is not yet suitable for mass production, especially when it comes to non-polymer parts. AM processes poses a challenge when end-product application is critical because certification and validation process for AM produced parts is not yet standardized and the reliability and repeatability of AM equipment is not yet established. Under aforementioned conditions TM would be most appropriate. For high volume products, TM is suitable to minimize the average cost per unit to achieve economies of scale. Hence, for products that exhibit the combination of contingent factors such as low customization level, many substitutes, critical application and product volume, traditional manufacturing should be retained as a primary method of production. For example, for semiconductors, which typically have critical application, low customization requirement, high volume and many substitutes, TM is most suitable. Standard products such as nut, screws, washer, etc. that have many substitutes, need no or low customization and required in high volume, TM should be retained to reap the economies of scale benefits.

Next, AM is suitable for highly customized or complex geometry products. AM introduces advanced capabilities such as design optimization that can very well tackle high customization requirements of the product. Products that have very low or no substitutes in the market (e.g. legacy components of military equipment), it will be more viable in the long-term for the firm to invest in AM capabilities, either in-house or through collaboration. For product that have low volume, AM can be suitable. Based on findings of section 4.1, AM is currently suitable for non-critical products. Hence, for products that belong to any combination of contingent factors including high customization level, no/less substitutes, non-critical application and low product volume, AM should be chosen as a primary method of production. For example, dental implants, that are highly customized, usually have few or no substitutes, low volume and low to moderate criticality. In this case AM is a suitable choice for production due to its ability to produce such products in a cost-effective way. For the parts that have low volume and non-critical application, such as plastic parts that are used in aircraft interiors, AM can be employed. Similarly, in luxury segment products such as personalized parts for interior of luxury cars, that are highly customized but less critical, AM is an option. For products that have very few or no substitutes, low volume demand and functionally non-critical, such as legacy parts of military equipment, AM is a preferable method of production due to its capability to produce part at remote location. It will also eliminate the need to outsource these parts, saving both cost and time. However, if the legacy part is critical for military and defense application, stringent certification would be needed.

Finally, we explain the region of hybrid approach i.e., utilizing both AM and TM in the manufacturing process. A firm can invest in building AM capabilities, either in-house or through collaboration, but must be aware of its limitation. For example, during pandemic, to avoid costly delays, some automakers switched to additive manufacturing to produce parts in-house (Mceachern, 2022), while some produced dies or molds using AM, which in turn were used in their production floor to produce parts in high volume using TM (Participant 4). The advantage of AM is in producing complex design quickly, but the primary barriers are either criticality of the part being produced or the volume needed to be produced. In the case of GM, the part needed was a plastic seal, and polyurethane based material was sufficient to produce the product with similar usability (Mceachern, 2022). Unlike the nozzle used in airplanes, it didn’t had to go through several stages of certification, hence AM was sufficient for GM to take care of the plastic seal part. Similarly, in the case of Participant 4, the supplier for high demand product went out of business, but they had capacity in their own production floor to produce the product. However, they needed a new tool, i.e. mold/die to do it and AM was used for manufacturing mold/die. Also, in situations when the criticality of the product application is high, AM can still be used either in the prototyping stage or in the tooling stage. A hybrid approach can be selected for maintenance and repair parts as well. For example, worn-out parts of turbine blades in the field can be repaired by depositing new material on the surface and then machining it to achieve the required surface finish (Participant 10). This eliminates the need to produce parts, saving time and cost. Similarly, hybrid approach is suitable for products that have critical applications but low volume requirements. For example, highly precise patient-specific prosthetics can be produced with AM and then machined using TM. The hybrid approach allows to extract the best of both TM and AM and thereby configure supply chain that is faster and flexible.

Since, quality control is still a big concern for industries using metal-based AM process, the actual product is produced using TM to ensure metal's physical properties are intact. According to a recent NIST roadmap, developing a quality control framework and keeping it up to date with the progress of technology will likely remain the focus of metal-based AM (Sames et al., 2016). Till the industry is comfortable with the quality of the end product, for high critical products, a hybrid approach will likely be the near future.

The two factors in the typology namely, product customization level and product volume coincide with dimension called product structure composed of volume and standardization in the Hayes-Wheelwright matrix (Spencer and Cox, 1995). We acknowledge a limitation in this typological framework due to the reduction of four dimensions in a two-dimensional space. This type of classification can be seen in Lawrence et al., (2011) and Narayanan & Altay, (2021) for customer stratification and for humanitarian supply chains. While, the typological framework is a fair representation, it does not capture all possibilities. For example, less critical application products could be produced in high volume, that is not captured in our typology in Figure 2. In this situation, the dominant factor determines the type of manufacturing, i.e., if the high volume is the dominant there, then additive manufacturing cannot be used.

5. Discussion

In this study, we conducted qualitative analysis to investigate the relationship between contingent factors and AM adoption using literature review and interviews. The findings enhance our understanding of on which factors AM benefits are contingent on and stimulate more in-depth investigation of scenarios in which AM adoption is most viable. Extant research provides reasons to adopt AM by investigating benefits of AM adoption (e.g. Kunovjanek et al., 2020) or barriers to adopt (e.g. Thomas-Seale et al., 2018). We advance the extant research by exploring contingent factors and their interaction to explain how and when AM be adopted.

5.1 Theoretical Implications

This study contributes to the literature in the following ways. First, this research generates deeper insights into the importance of contingent factors and their interaction for AM adoption. Second, we evaluate the literature to synthesize the contingent factors using literature and methodological approach, answering to the lack of research in AM adoption considering contingent factors (Niaki and Nonino, 2017). Third, findings of this research suggest four contingent factors that have not yet been discussed in extant AM literature. The findings also indicate several factors that are only sparsely discussed in the literature. Lastly, the study formulates the typology to capture the interaction between the contingent factors. Thus, study brings the research one step further with respect to Wagner and Walton (2016), who discuss several factors for AM implementation in Aviation industry.

The main contribution of the typology reflects the fact that large part of the literature neglects the dynamism of AM adoption process. Firms are still hesitant to adopt AM technologies (Oettmeier & Hofmann, 2017; Bromberger et al., 2022) due to incomplete understanding of influencing factors and their interaction. The comprehensive literature review also revealed this gap. Our typology serves as an aid in explaining how a firm can choose particular manufacturing process at product level. This study contributes to previous research identifying scenarios where AM can be applied leveraging its advantages (Huang et al., 2021). The typology also contributes to the underexplored research domain that investigates selection of parts suitable for AM as stated by Frandsen et al. (2020).

The contingent factors synthesized in this research apply to the focal firm that is adopting AM as well as its supply chain. Specifically, supply related contingent factors are dependent on upstream supply chain partners. For example, contingent factors “supply uncertainty” or “raw material quality” highlight that for AM adoption, it is essential for firms to get steady supply of raw materials (mostly powder) at consistent quality, especially for metals. Similarly, factors under sub-group ‘supply chain network structure’, namely supplier selection and production decision (inhouse vs outsource) directly relate to the upstream supply chain. Adopting AM inhouse or outsourcing will impact total supply chain cost of the firm. On the other hand, few factors are dependent on the downstream supply chain. For example, geometry of the part, level of customizations, lead time, time to market are dependent on customer/market requirement. Thus, our findings largely contribute to the realm of focal firm operations as well as supply chain literature. The findings complement previous operations management research that primarily applies a firm-oriented approach and focuses on firm environment contingencies (Sousa and Voss, 2008; Smith et al., 2012).

Finally, our findings we provide future research avenues. Future researchers may use other statistical method to rank the contingency factors. Scholars may use these contingent factors (e.g. product customization level, production volume) as moderator or mediator to evaluate effect of AM adoption on performance variables (e.g. operational performance, firm performance).

5.2 Managerial Implications

Utilizing the qualitative data analysis approach, this research provides a typology for AM adoption based on contingent factors. Through this study, we advise managers that assuming AM adoption will always provide multiple benefits is a risky oversimplification. Several contingent factors, external and internal to the firm and its supply chain, can hinder or boost AM adoption and affect performance. Hence, it is necessary that managers account for contingent factors involved such as, product application criticality, number of substitutes, product volume and product customization level, when planning AM adoption to make strategic decisions.

The classification of contingent factors is another important contribution to managers. They can use Table III to better understand nature of contingent groups by assessing, for example, which of those are under control of the firm (e.g. infrastructure readiness) and which are not (e.g. product application criticality).

Managers can refer to this typology to identify which manufacturing approach (TM vs AM vs Hybrid) is better suited for any of their products and whether it would be worth to adopt AM. We also describe corresponding benefits. It is possible that not all the products could fit under the typology given the four contingent factors used. Managers would be in best position to assess the major contingent factors applicable for their business and utilize the typology using those factors.

The people/employee dimension has frequently been highlighted in discussions about technology adoption in operations and supply chain management (Kache & Seuring, 2017; Schoenherr & Speier-Pero, 2015). In addition to considering other contingencies, practitioners should focus on organizational contingent factors such as training and development of employees for creating awareness, skill development and cross functional knowledge that influence the AM adoption at very early stage. Additionally, this study provides insights for adopting AM as a primary or alternative means of production. Since, certification process for AM manufactured parts is not yet standardized, it is recommended that firms incorporate rigorous quality checks to avoid product recalls/failures. Documentation such as standard work instructions would help firm implement AM efficiently. Firms need to take measures to increase knowledge sharing between and within organizations. Firms may collaborate with educational institutions to ensure practical knowledge is imparted to future AM technicians, designers and engineers. Since AM uses digital input, challenges related to intellectual property rights need to be tackled to prevent counterfeit products. Of course, to accomplish all these actions, higher management support is critical and plays an important role in AM adoption.

Finally, this research provides managers and practitioners with an overview of the main findings and key contingencies in AM adoption. They can consult the relevant sections of this manuscript to determine which contingent factors are deemed within their significant and how they interact with each other.

6. Conclusion

Through a qualitative study using in depth interview analysis, this paper identified the contingent factors that influence AM adoption and derived typology between major contingent factors. Our research recommends four major contingency factors that influence AM adoption namely, product customization level, product volume, criticality of product application and number of substitutes. The typology based on these factors, though not exhaustive of all possible scenarios, provides insights for when to adopt additive manufacturing or retain traditional manufacturing or utilize hybrid approach.

Despite the methodological rigor used, this study has some limitations that must be considered when conducting future research. First, we acknowledge that our findings reflect respondent's views that might be unrealistically optimistic (e.g. consultants of AM). Second, our proposed factors that formulate typology for AM adoption are more at a general level. While broader scope replicates exploratory type of our research design, we encourage future researchers to explore the contextual factors affecting AM adoption in particular industries to expand our findings. Third, the data gathered is only from organizations adopting AM and does not include its supply chain partners. Further research can be conducted for an entire supply chain to investigate if additional factors exist using case study approach. Lastly, the typological framework developed in this research may be expanded to consider other contingencies for AM adoption that may arise with development of AM technologies. Future researches are suggested to employ in-depth interviews of specific industrial sectors in order to investigate influence of these contingent factors on AM adoption enabled performance variables. Further study may concentrate on quantitatively validating the findings by using survey-based research.

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Table I Review of Benefits and Barriers of AM Adoption from Contingency Perspective

Authors	Research method/design	Benefits of AM adoption	Barriers/Limitations of AM adoption	Major contingency factors
Durach et al., (2017)	Survey	Integration of customers in the supply chain value creation Product development/production lead time reduction, Decentralized, local manufacturing Less or no inventory/ warehouse Reduction of transportation costs (P3b)	Identified 15 barriers including top 5 Limited material variety, Difficulties regarding development of new materials Insufficient quality of parts Stability and reliability of the process Education about AM	Type of industry, Product customization level, Design of the supply chain, Material variety, Product quality, Reliability of process, Production speed, Cost
Hedenstierna et al., (2019)	Case-study	Improved cost efficiency, Delivery performance	NA	Manufacturing modes, Demand level, Outsourcing strategy
Huang et al., (2021)	Case-study	high volume production with AM with a combination of technological and operational innovation	NA	Design for volume, Cost resource deployment, Material flow optimization
Tziantopoulos et al., (2019)	Taxonomy	Improved supply demand matching stabilized, end to end engineered supply networks	NA	Relocating manufacturing operations, Closeness to consumers' market, Collaboration Mass customization
Wagner & Walton (2016)	Focus group research	lower part weight, new design possibilities, part integration, mass customization and the mixing of alloys, tool less, less waste local production less cost of transportation, storage and inventory holding, quicker return of AOG to operational status	NA	Production Efficiency, Intellectual property and data security, Quality assurance and control

Chan et al., (2018)	Delphi	Economic New product development, Low tooling cost	Integration of 3D printing with supply chain, Mass scale implementation, Intellectual property concerns.	Internal integration, Volume variety, IP rights
Niaki & Nonino (2017)	Systematic literature review	Product customization, Less material wastes	Development of new materials for AM, Automation of design and process planning.	Material variety, Product customization level
Delic & Eyers, (2020)	Survey	Deploy design changes in product development, Improves supply chain flexibility Improved supply chain performance	NA	Type of industry, Firm Performance objective, Product design, Production volume, Product variety, Volume variety Order size, Supplier switch cost, Supply chain flexibility
Holmstrom and Partanen (2014)	Systematic literature review	life cycle extension , increased availability of parts in challenging locations, decrease supply chain complexity	product reengineering	Relationship among supply chain partners
Weller et al., (2015)	Literature review	Integration of design and production of complex parts, Reduction in assembly work Low prices for consumers	Quality issues of products, Mass scale production, Raw material costs (metals)	Product customization level
Schniederjans (2017)	Survey	Shorter production lead time Reduction in time-to-market Material savings, Reduced need for tools Localized manufacturing	Regulatory and legal issues, Initial investment cost	Performance expectancy and relative advantage, Perceived usefulness and compatibility, Social influence and coercive pressures

Table II Overview of interviewees

Participant number	Industry sector	Country	Designation	Duration of interviews (in minutes)	Source of secondary data
1	AM startup	India	CEO and Founder	77 mins	Company website
2	Aerospace and Defense	USA	Staff Research Engineer, Control System Autonomous & Intelligent Systems	64 mins	News articles/Press release, Company website
3	Automotive	USA	Project manager	69 mins	News articles/Press release, Company website
4	Machinery Manufacturing	USA	Additive Manufacturing Engineer	57 mins	Company website
5	Research Services	USA	Director of AM Programs	42 mins	Newsletters/Annual Reports, Company website
6	Machinery Manufacturing	USA	Industry Manager: Aerospace & Medical	58 mins	Newsletters/Annual Reports, Company website
7	Industrial Machinery Manufacturing	Denmark	Head of Industry 4.0	68 mins	Whitepapers, Company website
8	Industrial Machinery Manufacturing	USA	Research Engineer - Metals and Ceramics	59 mins	Whitepapers, Company website
9	Business Consulting and Services	Germany	Automotive Research Expert	59 mins	Company website
10	Industrial Machinery Manufacturing	USA	Consultant	47 mins	Company website
11	Aviation and Aerospace Component Manufacturing	USA	VP – Product Development	50 mins	Company website
12	Transportation, Logistics and Storage	UK	Design Engineer	67 mins	News articles/Press release, Company website
13	Machinery Manufacturing	Germany	Additive manufacturing consultant	67 mins	Company website

Table III Overview of contingent factors influencing AM adoption

Group	Subgroup	Contingent factors
Technological factors	Product factors	Product customization level (High; Low) Geometry of the part (Complex; Simple) Product volume (High; Low) Part feasibility (Feasible; Not feasible) Product application criticality (High; Low) Stage of adoption (Prototyping; Production; Aftermarket/Service)
	Raw Material factors	Raw material quality (High; Low) Material variety (High; Low) Supply uncertainty (High; Low) Raw material properties (Easy to handle; Difficult to handle)
	Standardization & certification	Technology trust (Low; High) IP security (High; Low) Part qualification standards (Defined; Undefined) Specifications for process and equipment (Defined; Undefined)
Organizational factors	Initial fixed cost investment	Equipment and its maintenance cost (High; Low) Infrastructure readiness (Ready; Not ready)
	Training and development	Skilled labor (Present; Absent) Knowledge about technology (High; Low)
	Cost justification	Production cost (High; Low) Inventory carrying cost (High; Low)
Strategic factors	Manufacturing competitiveness	Manufacturing location (Closer to the user; Away from the user) Lead time (Long; Short) Time to market (Long; Short)
	Supply network structure	Supplier selection (Hard; Easy) Production decision (Inhouse; Outsource)
	Resiliency & continuity	Alternative source of manufacturing (Absent; Present) Legacy parts production/Number of substitutes (High; Low)

Table IV Contingent factors influencing AM adoption: Interview evidence

Aggregate dimension: Product factors	***Second-order Category***
"We see the benefits of AM in terms of customization" (Participant 6) "In healthcare, minute customizations can be accomplished that suit to individual customer" (Participant 3) "One of AM competence is high degree of customization" (Participant 9)	Product customization level
"The biggest benefit of additive is being able to create geometry that you can't create with traditional manufacturing" (Participant 5) "You can go for more complex geometry" (Participant 7) "You can get neat shape geometry" (Participant 8) "You can achieve good performance gain by printing complicated shapes (Participant 3)	Geometry of the part
"We use for volumes of specific parts that are dropping down" (Participant 4) "The machines just can't produce parts as fast as traditional methods to support volume" (Participant 5) "Every industry has different volume when it comes to mass production. I mean for an aerospace company; 500 parts can be huge order while for automotive such number can be in thousands" (Participant 1)	Product volume
"AM can't be cost effective to produce every type of part" (Participant 5) "Size can be the factor too. It depends on the geometry of product then the dimensions. So even if component is larger but need intricate geometry, AM is beneficial to reduce the material waste and cost " (Participant 10) "Does it make sense to 3D print something, because sometimes it doesn't" (Participant 6) "Any part that you can think of how to manufacture, we are thinking about AM. That's why we have the whole range of machines, we have the large additive manufacturing and we have the small AM machines to accommodate different sizes" (Participant 2).	Part feasibility
"We use AM for some products that don't need certification because, you know, just it's a non-critical part " (Participant 2) "We are using it for tooling that are less critical" (Participant 4) "We use mostly for non-critical parts" (Participant 3)	Product application criticality
"AM can make a prototype needed for a part manufacturing in a few hours to a few days instead of a few months " (Participant 4) "But if you implement AM at the beginning of the design process, then the advantages are exponentially more because initially, when aerospace products are designed and being certified on a platform, they are generally made from massive forged blocks that have a 90 to 95% material waste and then are tested for potential design change. So,	Stage of adoption

implementing AM in design will help reduce cost because there's a lot less machining required to achieve final net shape" (Participant 11) " If you think in terms of providing aftermarket service to the customers, AM also enhances product lifecycle since it can provide parts that are obsolete and you don't have to rely on external supplier for it " (Participant 4)	
Aggregate dimension: Material factors	**Second-order Category**
"If we change material suppliers, you don't necessarily get the powder with same mechanical properties" (Participant 4) "You get a ton of variation between powders" (Participant 5) "One of the biggest barriers is that not having a procurement specification in place" (Participant 11)	Raw material quality
"Right now, the usage is really limited due to not all materials can be processed on AM equipment" (Participant 6) "It doesn't fit to every industry or every product" (Participant 13) "The real challenges is AM can't produce parts with all the materials" (Participant 5)	Material variety
"Yes you have a process to manufacture part but you still have to wait weeks for getting feedstock especially for metals. It is impossible to get the consistent feedstock for bigger machines due to supply delays" (Participant 6) "We have to import most powders and there are certain kind of country level restrictions on imports that makes constant supply difficult" (Participant 1) "There are absolutely challenges with getting materials" (Participant 8)	Supply uncertainty
"Used for materials that are hard to machine like Titanium" (Participant 5) "Produce tools (like dies, stamps) that can in turn be used for difficult to machine parts" (Participant 13)	Material properties
Aggregate dimension: Standardization & certification	**Second-order category**
"Customers do not have the trust in the technology" (Participant 1) "There are reservations to approve AM parts due to AM process itself" (Participant 3) "On an industrial scale, the number of success stories are still probably rather limited" (Participant 9)	Technology trust
"Intellectual property security is a concern" (Participant 8) "Everything you need to know the manufacturer of the part is in the print file that you sent to the printer" (Participant 4)	IP security

"Part qualification is challenging if you change geometry a lot for additive" (Participant 13) "We are holding using AM for certain parts because their certification adds to delay that we can't afford" (Participant 12) "Part of the supply chain challenge is qualification of process" (Participant 5) "We are far from standard qualification process (Participant 7)	Part qualification process standards
"Standard procedure for AM is still a work in progress" (Participant 8) "We don't have process standards yet on how to qualify the powder" (Participant 5) "No acceptable standards and specifications for AM equipment use" (Participant 6) "There's no consistency in the end product even if the same machine and same material is used" (Participant 6)	Specifications for process and equipment
Aggregate dimension: Initial fixed cost investment	**Second-order Category**
"Equipment cost has been a huge concern" (Participant 8) "Maintenance of equipment cost is the prohibitive factor" (Participant 12) "I would say the machine cost one of significant cost driver for the metals" (Participant 7) "Pretty high cost associated with configuration, maintenance and calibration of AM systems" (Participant 11)	Equipment and its maintenance cost
"A significant amount of infrastructure revamp is necessary to introduce additive manufacturing onto the shop" (Participant 2) "You have to set up a whole factory to make a single AM part including pre and post production process" (Participant 3) "The existing processes are not working interactively with AM" (Participant 2) "Most of the aerospace companies and some of the oil and gas companies they have a small tech center of additive manufacturing in house because they really want to learn as much as possible about the technology, but most of their production is from outside because they don't want to invest that much in their infrastructure" (Participant 1)	Infrastructure readiness
Aggregate dimension: Training and development	**Second-order Category**
"You have to spend quite a bit time and money on training these new employees and bringing them up to speed so that they can work on these expensive additive manufacturing equipment" (Participant 1) "There are absolutely challenges with skilled additive technicians. So you need some kind of an expert supervision to keep the process running at this point" (Participant 8)	Skilled labor
"Knowledge and awareness have to be developed beyond design and engineering" (Participant 13) "There is a lack of understanding about Additive technology within	Knowledge about technology

departments of organization. I mean R&D employees strongly feel need to adopt AM due to its capabilities but do not understand the complexity involved in procurement of the machines and installation" (Participant 12) "Problem right now is AM has been more experience-based technology rather than a scientific" (Participant 1) "Companies want to put AM machine in house but they also understand that just buying a machine is not the solution. They have to have that amount of learning associated with it" (Participant 1)	
Aggregate Dimension: Cost justification	***Second-order Category***
"By reducing number of parts using AM, you've now made simplification that saves cost and labor in subsequent assembly processes" (Participant 6) "We now use AM for producing tool that is at the end of its life instead of purchasing it" (Participant 4) "Post processing costs is one of the cost drivers for the metals" (Participant 7) "Speed and cost are advantages for using prototyping" (Participant 4) "If we take an example of a titanium component that needs to be machined out of a billet, right. So, you lose more than 80% of the raw material while machining. So, that is an added cost and the tooling for machining out titanium is quite expensive. So rather than actually machining titanium, why not print it. That will reduce cost." (Participant 1)	Production cost
"Unlike AM, in traditional method, raw material becomes a bit of a complex challenge, because you have to place orders significantly in in in time ahead of when you need it and keep carrying it in your inventory, which can become quite expensive when you're talking about tons of material in order to mitigate the risk of not having material for when you need it" (Participant 11) "Because it makes no sense to have 50000 sq. m warehouse full of spare parts and there is a part ordered once every 6 months. But customers are compelled to have it due to commitment with consumer. This is where we think Additive manufacturing will play a key role. All of these footprints can then be reduced to digital inventory and printed on demand" (Participant 12) "O&G customers have this huge machinery installed and they pay a lot of money in AMC to OEMs for keeping all the components on the shelf. Due to AM, now they're thinking on a digital inventory. They're thinking about digital inventory" (Participant 1) " You can have just in time deliveries so that you're not carrying that inventory it's moving from your supplier to you and it's being consumed if you have a known production rate " (Participant 6)	Inventory carrying cost

Aggregate dimension: Manufacturing competitiveness	***Second-order Category***
"We've been investigating potential of additive manufacturing closer to user. That way we can print part in Europe than in Asia and then ship the part halfway across the world" (Participant 4) "AM reduces supply chain length because you are able to produce on demand at a location nearest to consumer" (Participant 12)	Manufacturing location
"Aerospace organization X that launches rocket takes years to get part from supplier due to complexities involved in the process so they wanted to reduce the lead time for parts and that's when they started using metal additive manufacturing" (Participant 3) "The products that take long lead time to manufacture or have longer supplier lead time, we try to manufacture with AM" (Participant 2) "AM production lead times are fairly short" (Participant 12)	Lead time
"You can prototype, test, develop in much shorter timeframe" (Participant 13) "AM makes product development cycle shorter" (Participant 2) "AM allows more time for field testing or accelerated work testing" (Participant 4)	Time to market
Aggregate Dimension: Supply network structure	***Second-order Category***
"We did very extensive tour of North American metal powder suppliers to know quality of material , inspection of their equipment, manufacturing processes to qualify suppliers" (Participant 6) "There are many suppliers that will just print part but charge you three times more without quality planning. Getting suppliers that can do the quality plans and able to make parts in a production setting instead of a prototype setting is hard" (Participant 4)	Supplier selection
"We started bringing AM in house to focus on process development and process qualification. So the process development part focuses on how do you shorten the development cycle. And the second one is qualifying as in how do you rapidly qualifying part" (Participant 2) "Firms generally tend to outsource of AM's metal side. I have seen it in Automotive, in heavy equipment industries and in O&G" (Participant 12)	Production decision (Inhouse vs outsource)
Aggregate Dimension: Resiliency & continuity	***Second-order Category***
"We had the opportunity to keep lines running with additive technologies during pandemic shut down" (Participant 4) "During the covid time, some countries were closed leading to using AM for production" (Participant 1) "The other avenue would be use AM as a stopgap. When tool breaks but you want to get product out, better start producing them with additive and then switch over to a traditional once the tooling is ready" (Participant 5).	Alternative source of manufacturing

"The biggest business what we have actually been encountering in the country or overseas also is for legacy components" (Participant 1) "We can produce parts that supplier no longer provides or supplier no longer exists " (Participant 7) "Long tail part manufacturing, there is a huge potential to use AM" (Participant 7) "It makes sense for us to do repair on site, this is where we see additive mfg. playing role" (Participant 12)	Legacy parts production/Number of substitutes

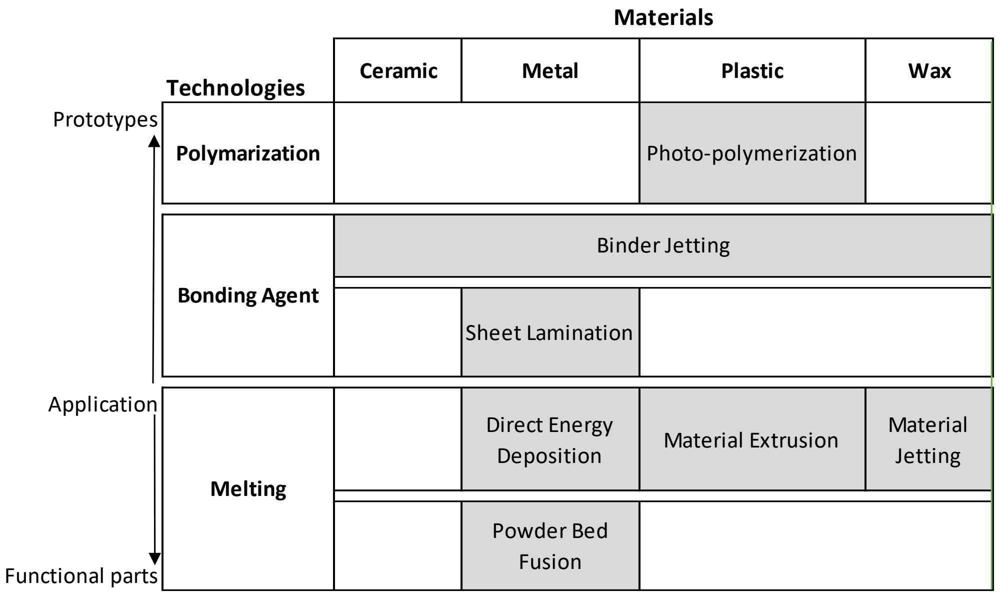


Figure 1. Additive Manufacturing Technologies

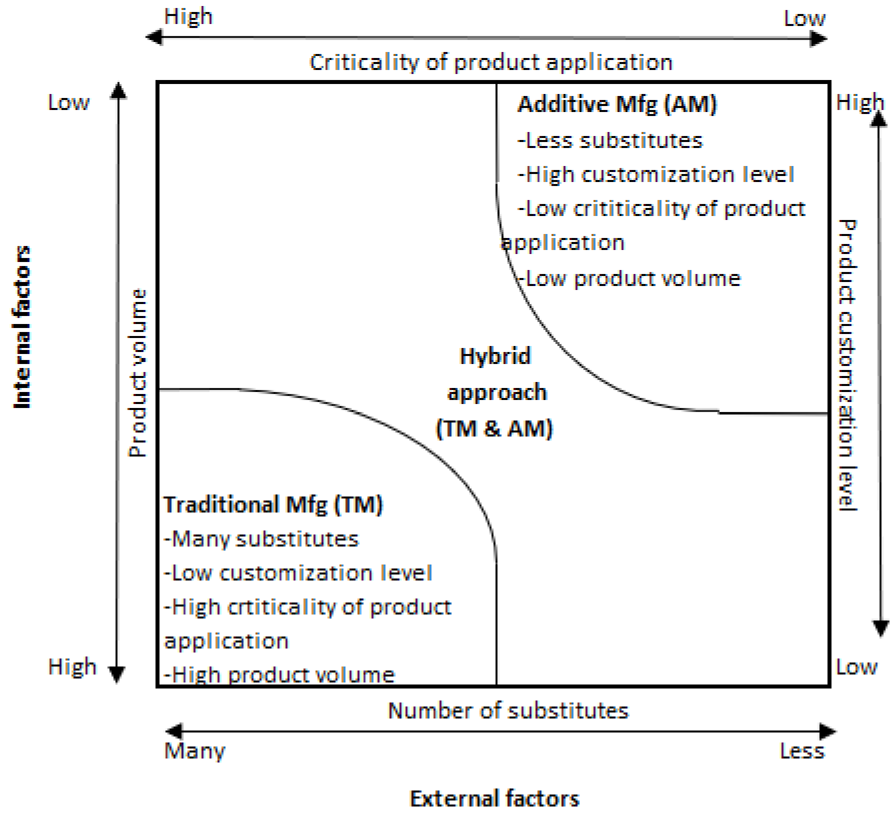


Figure 2. Typology for AM adoption

Appendix 1. Interview Protocol

Company Information

- Your company is best categorized as which industry sector (Aerospace and Defense, Healthcare, Medical Devices, Automotive, other?)
- What are some of the main products/product lines that your company manufactures?
- If it's appropriate to share, what is your approximate sales revenue for last financial year?
  - If the answer is NO, then we state the following: If this information cannot be disclosed, we totally understand.
- How many employees do you have working across all locations of your organization? (size of the organization)
- How many years/months of experience do you have directly working in Additive Manufacturing?
  - Have you operated/experienced the AM equipment first-hand? If yes:
    - How difficult has it been operating, any specific challenges that you have faced?
    - Did you need specialized employees to operate AM equipment, has it been difficult to find qualified people to operate AM equipment.

Manufacturing Process Related Questions

- Are majority of products in your company built to stock or custom order (assemble/manufacture/build to order)?
- Could you please shed some light on the transition process from traditional manufacturing to AM?

AM Implementation

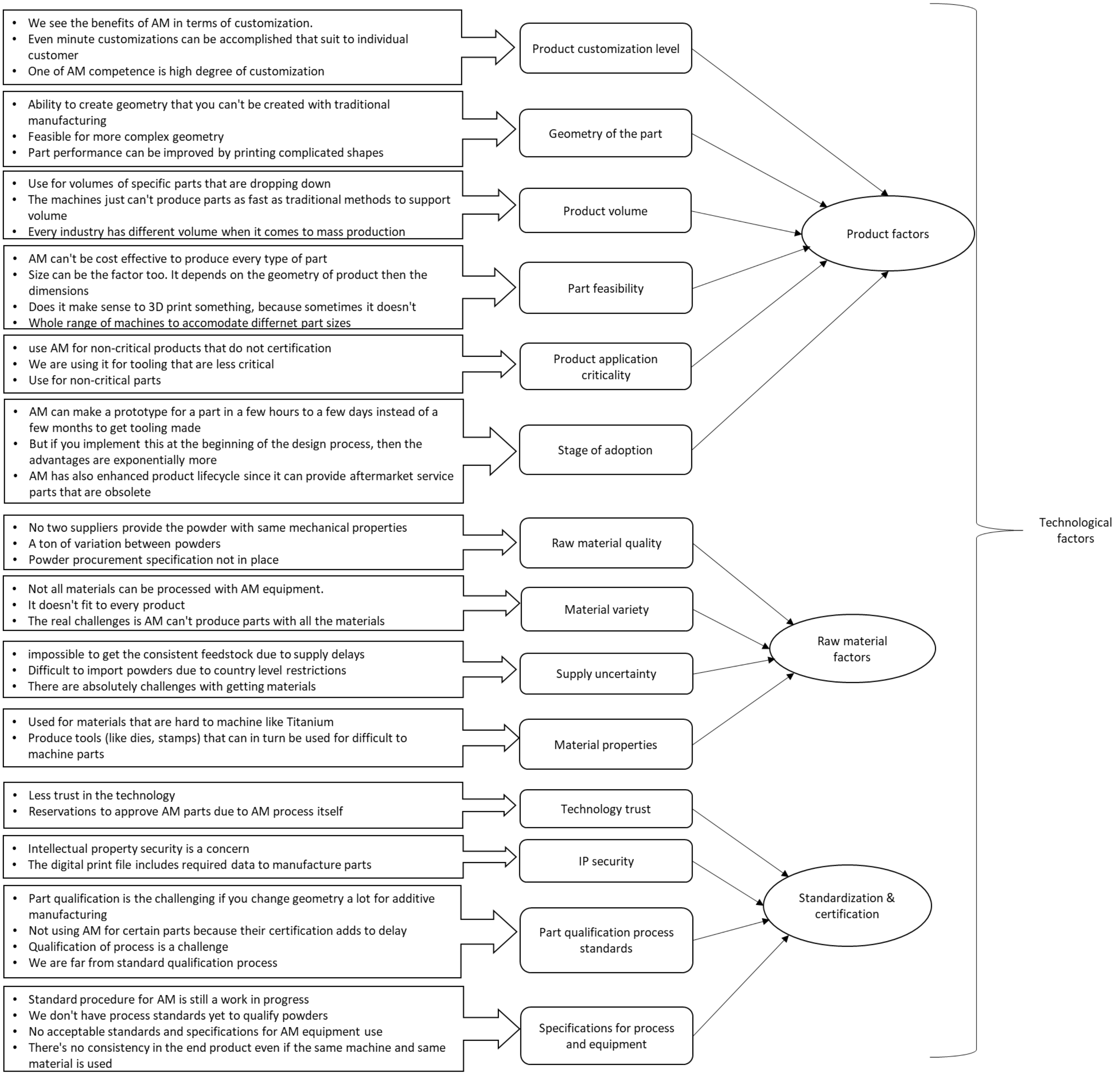
- When did you start using AM in your manufacturing process?
- What was the main reason for AM implementation?
- What is the level of AM implementation (one/multiple production line)?
- Has AM fully replaced conventional manufacturing in your organization?
- Do you use or foresee AM for Mass production (or) majority of your products? If not, why?
- Which AM technologies do you use in your organization
(Powder bed fusion, directed energy deposition, material jetting, material extrusion, photo-polymerization, binder jetting, sheet lamination, other?)
- What are the AM equipment models that are used in your organization?
- Do you happen to know the approximate investment your company made for AM (or) what is the approximate cost of the AM equipment?
- Did employees go through detailed maintenance/repair parts and training?
- What raw materials do you use for AM?
- What issues do you face with procuring raw materials for AM?
- For which processes do you use AM (prototype/production)?
- In your opinion what are some of the advantages or positive effects that your organization experienced implementing AM when compared to conventional manufacturing?

- In your opinion what are some of the disadvantages or negative effects that your organization experienced implementing AM when compared to conventional manufacturing?

Following Additional Prompts Employed as Required:

- How?
- Please Describe.
- Can you elaborate on that?
- Will you explain that in more detail?
- Can you give me examples or tell a story of an experience about that?
- How does that work?

Appendix 2. Data Structure



- We see the benefits of AM in terms of customization.
- Even minute customizations can be accomplished that suit to individual customer
- One of AM competence is high degree of customization

- Ability to create geometry that you can't be created with traditional manufacturing
- Feasible for more complex geometry
- Part performance can be improved by printing complicated shapes

- Use for volumes of specific parts that are dropping down
- The machines just can't produce parts as fast as traditional methods to support volume
- Every industry has different volume when it comes to mass production

- AM can't be cost effective to produce every type of part
- Size can be the factor too. It depends on the geometry of product then the dimensions
- Does it make sense to 3D print something, because sometimes it doesn't
- Whole range of machines to accomodate differnet part sizes

- use AM for non-critical products that do not certification
- We are using it for tooling that are less critical
- Use for non-critical parts

- AM can make a prototype for a part in a few hours to a few days instead of a few months to get tooling made
- But if you implement this at the beginning of the design process, then the advantages are exponentially more
- AM has also enhanced product lifecycle since it can provide aftermarket service parts that are obsolete

- No two suppliers provide the powder with same mechanical properties
- A ton of variation between powders
- Powder procurement specification not in place

- Not all materials can be processed with AM equipment.
- It doesn't fit to every product
- The real challenges is AM can't produce parts with all the materials

- impossible to get the consistent feedstock due to supply delays
- Difficult to import powders due to country level restrictions
- There are absolutely challenges with getting materials

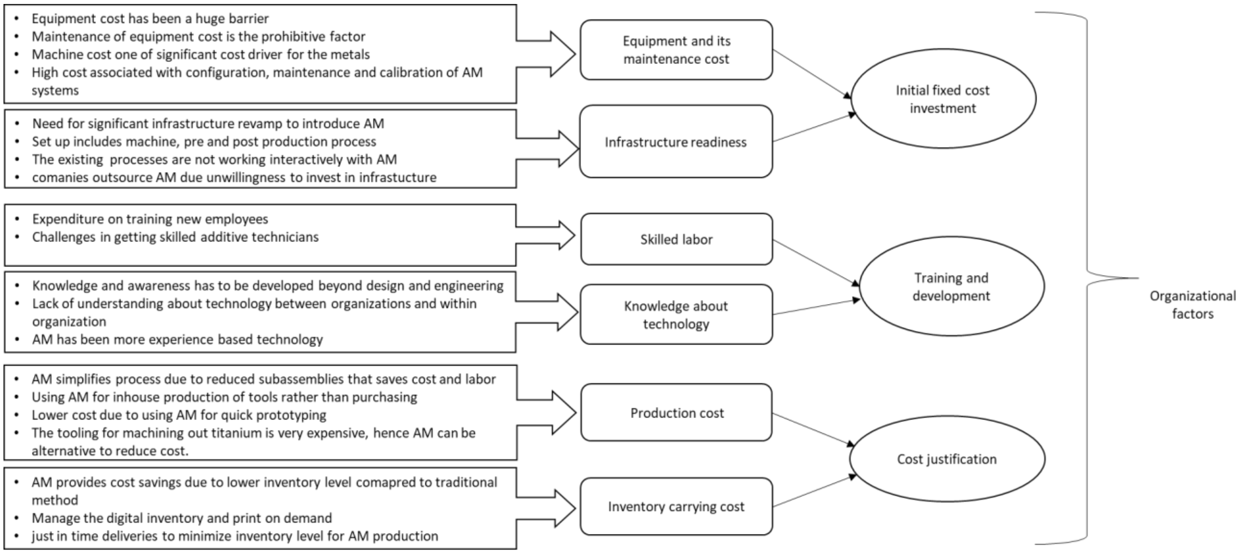
- Used for materials that are hard to machine like Titanium
- Produce tools (like dies, stamps) that can in turn be used for difficult to machine parts

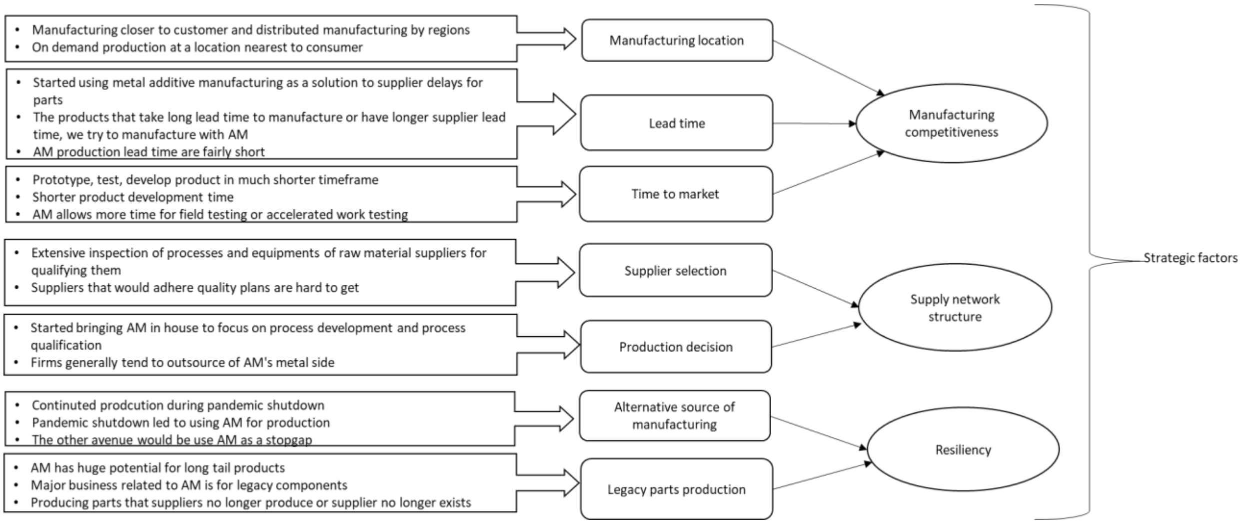
- Less trust in the technology
- Reservations to approve AM parts due to AM process itself

- Intellectual property security is a concern
- The digital print file includes required data to manufacture parts

- Part qualification is the challenging if you change geometry a lot for additive manufacturing
- Not using AM for certain parts because their certification adds to delay
- Qualification of process is a challenge
- We are far from standard qualification process

- Standard procedure for AM is still a work in progress
- We don't have process standards yet to qualify powders
- No acceptable standards and specifications for AM equipment use
- There's no consistency in the end product even if the same machine and same material is used


Equipment cost has been a huge barrier
Maintenance of equipment cost is the prohibitive factor
Machine cost one of significant cost driver for the metals
High cost associated with configuration, maintenance and calibration of AM systems
Equipment and its maintenance cost
Need for significant infrastructure revamp to introduce AM
Set up includes machine, pre and post production process
The existing processes are not working interactively with AM
comanies outsource AM due unwillingness to invest in infrastucture
Infrastructure readiness
Initial fixed cost investment
Expenditure on training new employees
Challenges in getting skilled additive technicians
Skilled labor
Knowledge and awareness has to be developed beyond design and engineering
Lack of understanding about technology between organizations and within organization
AM has been more experience based technology
Knowledge about technology
Training and development
AM simplifies process due to reduced subassemblies that saves cost and labor
Using AM for inhouse production of tools rather than purchasing
Lower cost due to using AM for quick prototyping
The tooling for machining out titanium is very expensive, hence AM can be alternative to reduce cost.
Production cost
AM provides cost savings due to lower inventory level comapred to traditional method
Manage the digital inventory and print on demand
just in time deliveries to minimize inventory level for AM production
Inventory carrying cost
Cost justification
Organizational factors


Manufacturing closer to customer and distributed manufacturing by regions
On demand production at a location nearest to consumer
Manufacturing location
Started using metal additive manufacturing as a solution to supplier delays for parts
The products that take long lead time to manufacture or have longer supplier lead time, we try to manufacture with AM
AM production lead time are fairly short
Lead time
Prototype, test, develop product in much shorter timeframe
Shorter product development time
AM allows more time for field testing or accelerated work testing
Time to market
Manufacturing competitiveness
Extensive inspection of processes and equipments of raw material suppliers for qualifying them
Suppliers that would adhere quality plans are hard to get
Supplier selection
Started bringing AM in house to focus on process development and process qualification
Firms generally tend to outsource of AM's metal side
Production decision
Supply network structure
Continuted prodcution during pandemic shutdown
Pandemic shutdown led to using AM for production
The other avenue would be use AM as a stopgap
Alternative source of manufacturing
AM has huge potential for long tail products
Major business related to AM is for legacy components
Producing parts that suppliers no longer produce or supplier no longer exists
Legacy parts production
Resiliency
Strategic factors