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The Impact of Additive Manufacturing on the Flexibility of a Manufacturing Supply Chain

Ageel Abdulaziz Alogla [1,2,*], Martin Baumers [1], Christopher Tuck [1] and Waiel Elmadih [1]

1 Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK; martin.baumers@nottingham.ac.uk (M.B.); christopher.tuck@nottingham.ac.uk (C.T.); waiel.elmadih1@nottingham.ac.uk (W.E.)
2 College of Engineering, Umm Al-Qura University, Mecca 21961, Saudi Arabia
* Correspondence: ageel.alogla@nottingham.ac.uk or aaogla@uqu.edu.sa

Abstract: There is an increasing need for supply chains that can rapidly respond to fluctuating demands and can provide customised products. This supply chain design requires the development of flexibility as a critical capability. To this end, firms are considering Additive Manufacturing (AM) as one strategic option that could enable such a capability. This paper develops a conceptual model that maps AM characteristics relevant to flexibility against key market disruption scenarios. Following the development of this model, a case study is undertaken to indicate the impact of adopting AM on supply chain flexibility from four major flexibility-related aspects: volume, mix, delivery, and new product introduction. An inter-process comparison is implemented in this case study using data collected from a manufacturing company that produces pipe fittings using Injection Moulding (IM). The supply chain employing IM in this case study shows greater volume and delivery flexibility levels (i.e., 65.68% and 92.8% for IM compared to 58.70% and 75.35% for AM, respectively) while the AM supply chain shows greater mix and new product introduction flexibility, indicated by the lower changeover time and cost of new product introduction to the system (i.e., 0.33 h and €0 for AM compared to 4.91 h and €30,000 for IM, respectively). This work will allow decision-makers to take timely decisions by providing useful information on the effect of AM adoption on supply chain flexibility in different sudden disruption scenarios such as demand uncertainty, demand variability, lead-time compression and product variety.

Keywords: additive manufacturing; 3D printing; manufacturing flexibility; supply chain management; injection moulding; smart factory

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1. Introduction

Supply chain management plays a critical role in organizations, particularly in ensuring smooth and efficient production runs with changing patterns in demand [1]. Recently, fluctuations in demand have been caused by factors such as product customization, which has become more commonplace, which in turn lead to shorter product life cycles. Other factors such as increased competition and the rise of globalisation have also played a part in demand fluctuation. All of these factors have made it imperative for organisations to be flexible in order to survive in the long-term, whether that means adjusting production to meet higher or lower levels of demand, or in having the ability to adapt and produce customized products or services that can effectively meet customer needs [2,3]. Where flexibility is well-developed and becomes the modus operandi for a business, this can help manufacturing firms respond to changes in customer requests that may come in the form of increasing, decreasing, cancelling, or changing the timing of orders [4]. Naturally, all of these changes in the marketplace have made it difficult for manufacturing firms to operate in isolation and prosper; therefore, collaboration has become a necessity, as has the need to redefine flexibility, by increasingly viewing flexibility from the lens of the supply chain e.g., [5,6].

In pursuit of developing such capability, firms are considering Additive Manufacturing (AM) [7], commonly known as 3D Printing, as a technology that is capable of fabricating products directly from digital files without the need of tooling or moulds [8,9]. Unique characteristics of this technology such as lack of tooling, on-demand production, freedom of geometry and the consolidation of assemblies into single components have led recent studies to suggest AM as a technology that could improve flexibility e.g., [3,8,10]. What has not been studied however are the consequences that might occur when adopting AM to improve flexibility, mainly due to essential trade-offs that must be made during the process of adoption.

The first aspect of these trade-offs concerns the relationship between flexibility and cost. While adopting AM technology may increase supply chain flexibility in some aspects such as volume, it can, at the same time, lead to a decrease in other competing aspects such as cost. This potential trade-off is critical because, in reality, manufacturing firms operate in different environments and under different market conditions and some companies may find it more beneficial to prioritize efficiency over flexibility [11]. Relying on dedicated manufacturing technologies (i.e., to manufacture core products with high volumes), as opposed to flexible ones, may therefore be appropriate for these manufacturing firms. For instance, standard products with predictable demands, such as water bottles, would not require as much supply chain flexibility as products in the fashion industry. The significance of this distinction cannot be underestimated because adopting AM for industries that do not require many product variants or do not have uncertain demand may lead to unnecessary higher unit costs. This view has been highlighted by Pujawan [12], who stresses the importance of carefully assessing the target flexibility level to avoid unnecessary costs. In fact, it has been demonstrated that enhancing supply chain flexibility in certain contexts can be counterproductive [13–15]. The second trade-off issue to consider in terms of using AM to improve flexibility is that flexibility itself is not a standardised capability; rather, it is a competency with many layers and aspects that must be customised for a given context [16].

Responding to the disparate changes in demand may require a different type of flexibility on each occasion. For instance, changes in volume demand require volume flexibility, while the ability to respond to different customer preferences and choices may require mix or process flexibility. A delicate balance exists and must be achieved between each of these flexibility trade-off aspects as an increase in one can lead to a decrease in another. Understanding this precise balance is emphasised by Vokurka and O'Leary-Kelly [17] who highlight the need to examine the interrelationships between these flexibility aspects in order to ensure the successful development of flexibility. This highlights the importance of not only recognizing the different elements that can impact AM adoption, but also in having the requisite skills, knowledge and systems in place to increase supply chain flexibility, as neglecting to do so will most likely lead to failure.

The important issue of examining the impact of AM on supply chain flexibility has recently begun to attract the attention of AM and supply chain researchers. For instance, Eyers and Potter [18] show how AM improved flexibility through the dynamic allocation of labour. Eyers, et al. [19] also provided a detailed study examining different flexibility aspects that can be achieved through AM. By conducting a structured literature review, Verboeket and Krikke [20] suggest that AM can improve supply chain flexibility in terms of both volume and variety of products. Delic and Eyers [21] investigated the relationships among AM adoption, supply chain flexibility and supply chain performance in the automotive industry, finding that AM can positively impact flexibility and performance. Mohd Yusuf, et al. [22] discuss the design flexibility that AM offers in the aerospace industry. Chung, Kim and Lee [7] also suggest that AM, if incorporated within a smart supply chain, could increase the flexibility needed to respond to changing demand. Verboeket and Krikke [20] also predicted an increase in supply chain flexibility with the adoption of AM. These studies are valuable in studying distinct flexibility aspects in AM, yet their varying perspectives reflect the remaining gap of understanding whether AM can increase various supply chain flexibility aspects considering their interrelationships and the corresponding cost penalty. Moreover, the relationships between the various supply chain flexibility aspects (i.e., volume, mix, delivery and new product introduction) and the characteristics of AM have not yet been clarified, so it is not clear how AM can impact supply chain flexibility and to what extent. It is also important to address this gap by considering the impact of AM on flexibility in comparison with other established manufacturing technologies, to allow for more realistic assessment of AM.

The aim of this paper is to elucidate for decision-makers and managers what distinct supply chain flexibility aspects are needed for different scenarios in the context of AM adoption. To address this aim, this paper contributes to the knowledge base of AM adoption in two ways. The first contribution is conceptual, and maps AM characteristics against critical disruption scenarios based on distinct supply chain flexibility aspects. The second contribution is an empirical indication in the form of a case study, providing practical insights to the developed framework.

This paper is organised as follows: Section 2 describes the developed model that maps certain AM characteristics relevant to flexibility against distinct market disruption scenarios. Section 3 describes the case study undertaken and reveals the findings obtained from this case study. Section 4 discusses these findings in relation to the developed conceptual model. Section 5 summarises and concludes this study.

2. Development of a Conceptual Model of Flexibility in AM

The research methodology of this work is divided into two major parts: the first is the construction of a conceptual model that identifies the relevant variables in this study and how they interact with each other, followed by the second part where a case study is undertaken to gain insight into the developed conceptual model. This section discusses the first part of the methodology of the conceptual model that links certain AM characteristics with key market requirements faced by managers and decision-makers.

Firms need to be flexible in different ways to successfully respond to market volatility. Previous research has recognised several types of flexibilities and perceived flexibility as an enabler to a higher level of firm responsiveness that lines up supply competencies with demand fluctuations [23–27]. While researchers are not in agreement as to what flexibility types are correlated with an overall higher level of supply chain responsiveness, several researchers agree on four external flexibilities [26,27]: new product (i.e., launch) flexibility, mix flexibility, volume flexibility and delivery (i.e., distribution) flexibility. For consistency, this paper perceives supply chain flexibility as a mix of external flexibility types identified in the existing research. The need for external flexibility is dictated by external market requirements. The key external market requirements are demand uncertainty, demand variability, product variety and lead-time compression [26]. Figure 1 shows how these external market conditions such as demand uncertainty or demand variability give rise to the need for external flexibility (i.e., perceived by the customer viewpoint) which in turn requires the development of internal competencies by the firm.

Technology-minded supply chain scholars are interested in AM since it exhibits various characteristics that can affect certain aspects of flexibility. The first of these characteristics is freedom of geometry, which explains the freedom product designers have when designing complex AM products [28]. This AM characteristic helps managers facing market trends that necessitate adopting a product proliferation strategy or continuously introducing new products to the market to achieve higher levels of mix and new product flexibilities. These two flexibility aspects are also achieved via part consolidation, the second of these AM characteristics, which describes the AM capability to produce multiple discrete components fabricated as one final part [29]. The third AM characteristic relevant to flexibility is the absence of tooling (such as jigs, moulds or dies) in this technology. Through this feature, higher levels of mix flexibility, new product flexibility and volume flexibility can be achieved. The last of these AM characteristics is on-demand production, where products can be produced when and as needed [30,31]. Figure 2 presents the conceptual model that links these AM characteristics with the key market conditions faced by managers and clarifies what supply chain flexibility aspects can be achieved with each link.

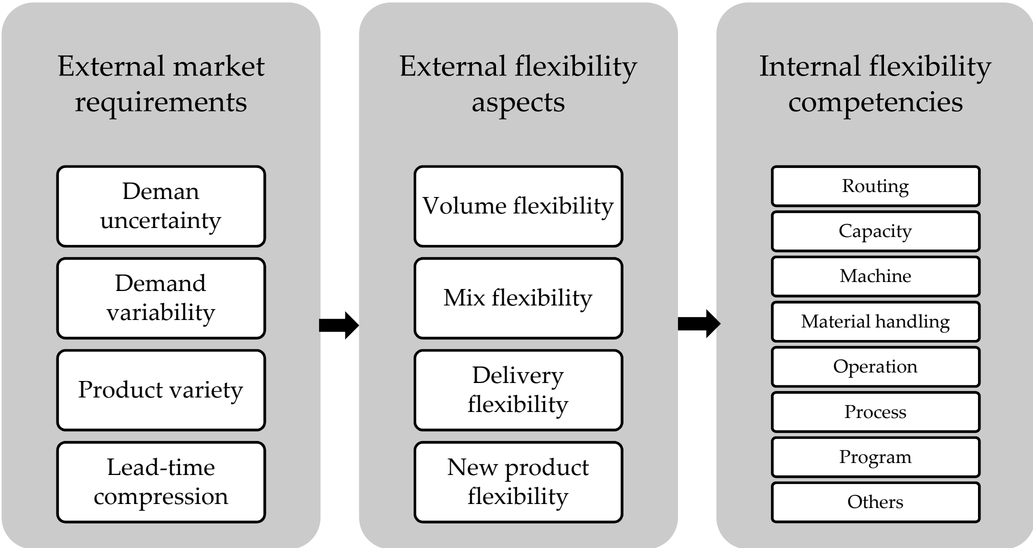

Figure 1. The link between external market requirements, external flexibility and internal flexibility (inspired by Reichhart and Holweg [26]).

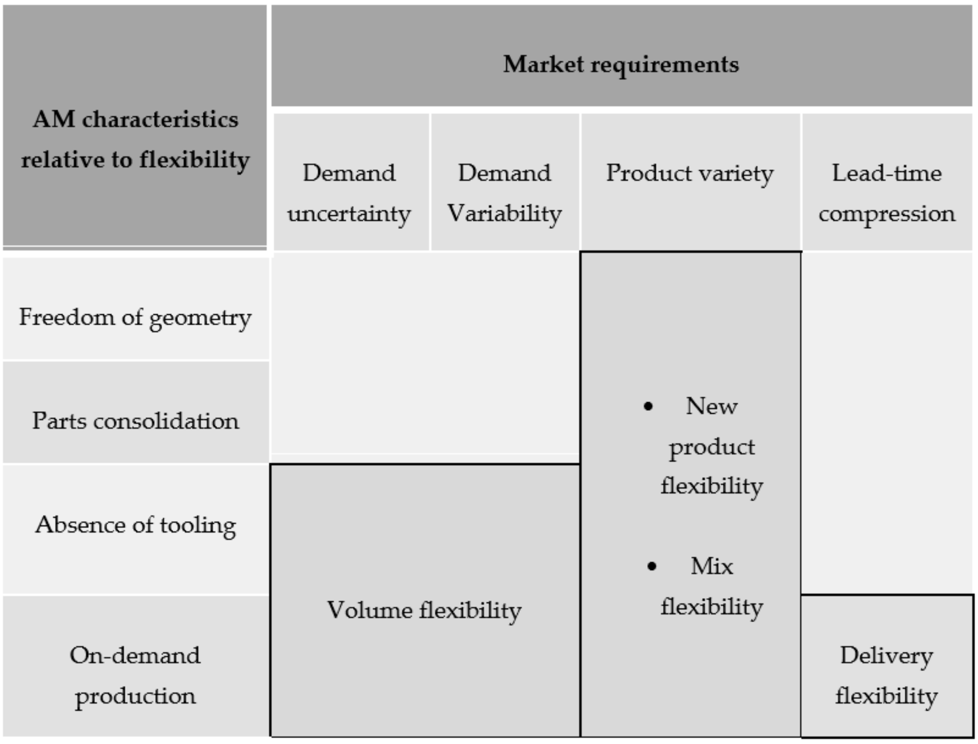

Figure 2. A conceptual model that maps AM characteristics relevant to supply chain flexibility against key market scenarios faced by managers.

The main aim of the conceptual model, presented in Figure 2, is to highlight the managerial problems faced by managers and decision makers, which will also encourage future research. This framework facilitates an understanding of the flexibility aspects that can be achieved with the adoption of AM; thus, allowing the comparison with other manufacturing technologies for each one of the flexibility aspects. It also helps managers and decision-makers to assess the costs and benefits of adopting AM to better respond to each one of the market requirements. For instance, when a decision-maker faces market demand that is uncertain or variable, then volume flexibility is needed. The absence of tooling and the capability to produce products on-demand make AM a suitable technology for providing this volume flexibility. In addition, a high level of engineering skills during manufacturing would not be needed to utilise the AM features of freedom of geometry and parts consolidation; this is mainly because these features are not required to achieve volume flexibility. This absence of direct correlation between the AM features and production flexibility is reflected by the empty boxes in the conceptual model of Figure 2.

3. Case Study

This section describes the case study undertaken to gain insight into the developed conceptual model discussed in Section 2. Taking into account the three levels of supply chain management—namely: operational (i.e., specific function unit), tactical (i.e., plant) and strategic (i.e., network) [32]—this case study considers a tactical perspective so that an appropriate reflection of the external flexibility aspects is achieved. This section is divided into four main sections. The first of these describes the context in which this case study has been undertaken and the data collection procedures followed to conduct the study. The second section describes the manufacturing cost parameters collected and utilized for this study following the proposed cost model [33]. The third section illustrates the flexibility metrics adopted to measure the performance of AM in comparison with the current manufacturing technology investigated in the case study. The fourth section shows the results obtained following the execution of the case study.

3.1. Description and Data Collection

A case study has been undertaken in stages of retrospective data collection. The case was studied in a plastic product manufacturing company that produces pipe fittings. Since flexibility is needed in the presence of demand volatility [4], all company products were first evaluated and data on the historical demand for each product was collected to select a product with a demand that is attributed by both uncertainty and variability. The selection of the product was approached using the Coefficient of Variation (CV), which is a measure utilised to establish the level of volatility (i.e., uncertainty and variability) in demand for a product, and was estimated using the method proposed by Olhager [34]. Following this assessment, a PVC Pipe tee joint 3/4″ (shown in Figure 4) was chosen for the study for its high level of demand volatility (233%), far exceeding the 40% threshold recommended by Halawa, et al. [35]. Figure 3 shows the historical demand of this product for the 48 months, reflecting its high volatility level throughout this period.

The company fabricates the product using Injection Moulding (IM), which is one of the most widely dedicated technologies adopted in mass production settings. The IM machine used by the company is Haitian MA 5300. Pertaining to the chosen product, additional process time and cost data were collected, including changeover durations and lead-times. The solid volume of the product shown in Figure 4 is 14.83 cm^3. While the company continuously reviews the inventory level of each production line and sets a production schedule once reorder points are reached, initiating this production line requires a two-week pre-notice due to a normal level of capacity utilisation of the available IM equipment.

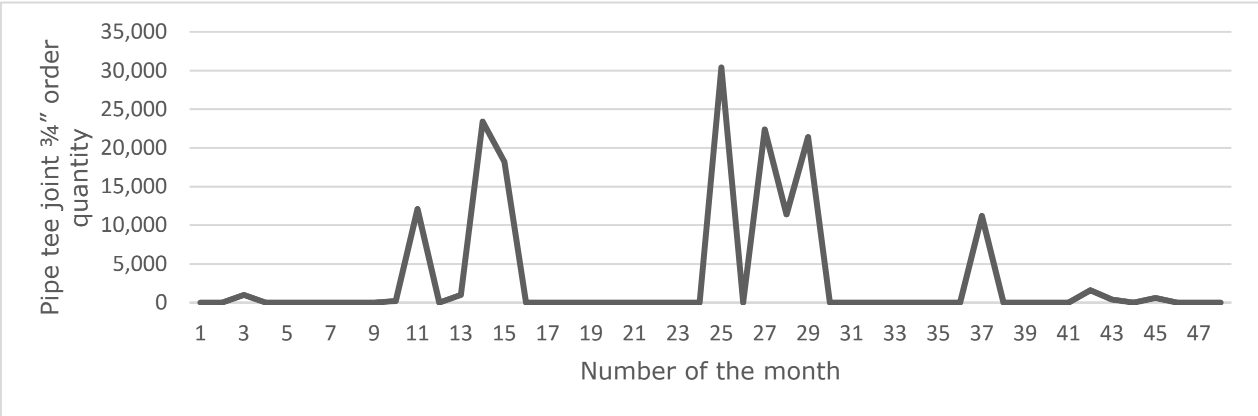

Figure 3. The historical demand of the Pipe Tee joint fitting 3/4″ for 48 months.

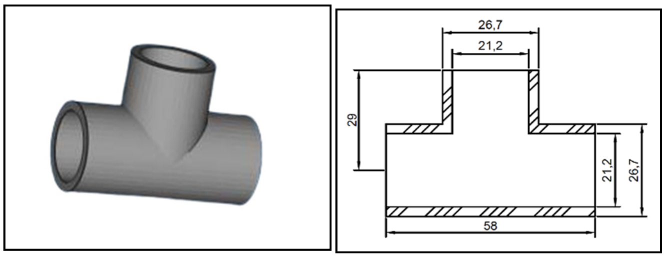

Figure 4. CAD drawing of the part selected for the case study: Pipe tee joint 3/4″ (dimensions in mm).

Figure 5 represents the current supply chain configuration of the company. Through its continuous review inventory model [36], the company implicitly takes into account demand and market characteristics. Where a quantity over the currently available inventory level is requested by the customer, and hence cannot be served out of existing stock, the customer will usually contact competing companies motivated by the long lead-time needed to fulfil the order. Due to a normal level of capacity utilisation of the available IM equipment, resulting from the manufacture of products featuring predictable and continuous demand, the lead time for the production for other products exceeds two weeks in most cases, which is deemed too long for a reactive Make-to-Order approach.

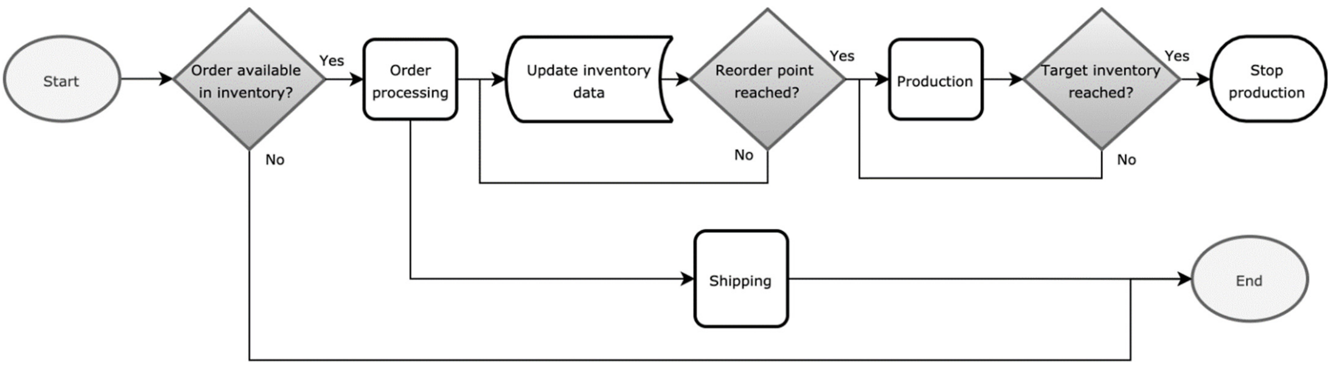

Figure 5. Flowchart of the current supply chain configuration of the pipe tee joint manufacturing company.

The following step in the investigation was to construct a corresponding process model for AM. As shown in Figure 6, the replacement of the conventional IM process by AM technology significantly altered the structure of the model. The AM system chosen for this study is the EOS P770 system, which is a polymeric laser sintering system with a relatively sizeable nominal build volume of 700 mm × 580 mm × 380 mm [37]. Allowing for a clearance of 5 mm from every dimension for each part, a raster-type model of build volume packing was applied to approximate that each AM build could contain a batch of 1584 units of the chosen part.

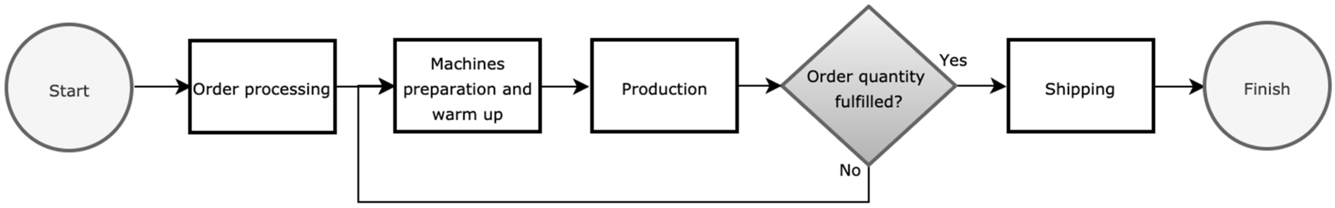

Figure 6. Flowchart of the supply chain configuration with AM only.

To estimate the total time to produce each AM batch, the volume of the bounding box (see Ruffo, et al. [38] for further information) first was estimated at 149,787.2 cm^3. Applying a typical building rate of 32 mm/h for a layer thickness of 0.12 mm provided by the supplier [37], a total build time of 51.35 h was estimated for this bounding box. This time, however, overestimates the total sum volumes of the contained parts. Hence, a revised total time of 23.87 h was obtained using a parameter that was derived experimentally by Ruffo, Tuck and Hague [38] to estimate the reduction in time needed to account for this overestimation. Following Baumers and Holweg [39], additional 59 h were also added to account for the post and pre-processing steps resulting in a final total time of 82.87 h. We assume that the product performance of both technologies (IM and AM) is functionally equivalent.

3.2. Manufacturing Cost Parameters

As pointed out by Upton [40], firms must flexibly respond to sudden market changes with little or no penalty in cost or performance. In this case study, one important cost factor is the scale of production size or quantity. It is anticipated, based on the economies of scale phenomenon, that higher production volumes lead to lower unit costs (i.e., cost per part) [2]. In IM in particular, economies of scale exist as the cost of tooling (i.e., cost of producing the mould) is spread over production quantity. This phenomenon, however, does not relatively manifest itself in parts fabricated by AM due to the lack of tooling [41]. Unit cost models, therefore, are developed for both manufacturing technologies based on the general model structure for inter-process comparisons proposed by Atzeni, Iuliano, Minetola and Salmi [33], described in Appendix A.

The material used to produce the part using IM is PVC procured as a feedstock at €16/kg. Since PVC cannot be processed with the investigated variant of AM technology, laser sintering, the corresponding material employed in the AM supply chain is a Nylon 12 type material (PA2200) procured at the cost of €54/kg. Due to the characteristics of proposed AM technology, sacrificial support structures are not needed in the AM route and the degraded raw material is the only form of waste. Labour costs entered the AM pathway in the form of the direct cost of €0.23/part. The purchase price for each AM system (EOS P770) is estimated at €668,475, based on Hasan [42], with assumed useful life of five years. A depreciation cost of €133,695 per year therefore has been estimated in this study following a straight-line depreciation technique. These cost parameters have resulted in a constant unit cost for AM with a value of €2.72. We note that the observed AM cost level is broadly in line with the cost performance reported by Atzeni, et al. [42].

For the IM route, the most significant cost element is the tooling expense, estimated by the company at €30,000; this cost was amortised over the manufactured quantity. This cost is incurred only once since the tooling can be re-used to produce the same part repeatedly, but cannot be exchanged with other toolings in the production line as it is part-specific. The tooling features four mould cavities, allowing the concurrent processing of four units in the moulding cycle, with each moulding cycle taking 74 s to complete. The operator cost per part for IM, arising as a direct cost, is €0.009/part. The IM machine (Haitian MA 5300) price is estimated at €110,000 with an assumed service life of five years. This results in a depreciation cost of €22,000 per year.

3.3. Flexibility Metrics

This case study utilises the four flexibility aspects discussed in Section 2 (i.e., volume, mix, delivery and new product) as a measurement of the firm responsiveness. These external flexibilities together exhibit the overall responsiveness of a supply chain to sudden changes in customer needs and requests. Next subsections briefly discuss each one of these flexibility aspects [43].

3.3.1. Volume Flexibility

Volume flexibility can be defined as the range of possible manufacturing volumes a company can produce in response to demand. Based on this, Beamon [43] characterises volume flexibility, Fv, as the probability of the quantity demanded being within a certain interval:

$$F_v = P\left(\frac{O_{min} - \overline{D}}{\sigma} \leq D \leq \frac{O_{max} - \overline{D}}{\sigma}\right) \quad (1)$$

where D represents the instantaneous market demand as a random variable with an approximately normal distribution with mean $\overline{D}$ and standard deviation σ. O_{min} denotes the minimum profitable production volume a company can produce in a specific period and O_{max} refers to the maximum profitable production volume within the same period. For both supply chain models, it is assumed that profitability is constrained by the maximum time a customer can wait, which is estimated at two weeks based on the information provided by the company. Using this metric, a high value for Fv represents a high degree of volume flexibility and vice versa. In both supply chain scenarios, $\overline{D}$ was set to 3240 parts with a standard deviation of 7530 parts, based on the collected historical sales data. Additionally, O_{max} for IM was estimated at 134,400 parts and at 78,400 parts for AM. O_{min} was estimated at 200 parts for the IM route (based on the minimum possible quantity a customer can order from the inventory) while a quantity of 1584 parts was assumed to be the minimum order for the AM route to ensure adequate capacity utilisation.

3.3.2. Mix Flexibility

The concept of mix flexibility, Fm, represents the range of different product types that can be produced throughout a specific period of time. This aspect can be captured by considering the changeover time as a metric. The mix flexibility, hence, was calculated for each supply chain model by linking it to the changeover time T_{ij} from product family i to product family j, which represents the set-up time in this study. Mix flexibility therefore is estimated as follows [43]:

$$F_m = T_{ij} \quad (2)$$

3.3.3. Delivery Flexibility

The primary purpose of the delivery flexibility metric, F_D, is to reflect the ability to shorten a production lead-time to accommodate rush orders. Therefore, delivery flexibility is expressed as the share of slack time in lead-time. The delivery flexibility metric proposed by Beamon [43] is based on the assumption that the supply chain produces more than one product, which is not the case in the model presented in this work. Therefore, an adapted delivery flexibility equation is used:

$$F_D = \frac{L - E}{L} \quad (3)$$

where L is the due time (or last possible time to deliver the product) and E is the earliest time the product can be delivered. As specified in Section 3.1, a two-week maximum lead-time window is assumed.

3.3.4. New Product Flexibility

The flexibility of new product introduction, F_n, measures the ability to add new products to the current manufacturing processes. This flexibility aspect can be reflected using Beamon's (1999) model, in which C refers to the cost required to add a new product to the system:

$$F_n = C \quad (4)$$

3.4. Results

Interesting insights into the performance of both technologies are obtained from comparing the estimation of the four supply chain flexibility metrics: (i) volume flexibility, (ii) mix flexibility, (iii) delivery flexibility and (iv) new product flexibility. As evident from Table 1, the supply chain employing IM shows greater volume and delivery flexibility with 65.68% and 92.8% compared to 58.70% and 75.35% for AM, respectively. This is primarily due to the existence of buffer inventory in the IM supply chain, which gives the ability to fulfil orders with volume as low as 200 and instant shipping of parts from the warehouse. This is unlike the AM route, which requires at least 82 h of production to process any order. AM, however, in this case study shows lower changeover time and cost of new product introduction to the system, which is indicated by the higher level of mix and new product introduction flexibility compared to IM (i.e., 0.33 h and €0 for AM compared to 4.91 h and €30,000 for IM, respectively).

Table 1. Comparison of the flexibility metrics.

Flexibility Metric	Unit	AM	IM
Volume flexibility	%	58.70	65.68
Mix flexibility	hr	0.33	4.91
Delivery flexibility	%	75.35	92.85
New product flexibility	€	0	30,000

To analyse the relationship between volume flexibility and unit cost in this case study, the unit cost of different production volumes has been estimated for both manufacturing technologies. Then, the unit cost curve is plotted against the volume flexibility level at each production quantity scenario as in Figure 7A,B.

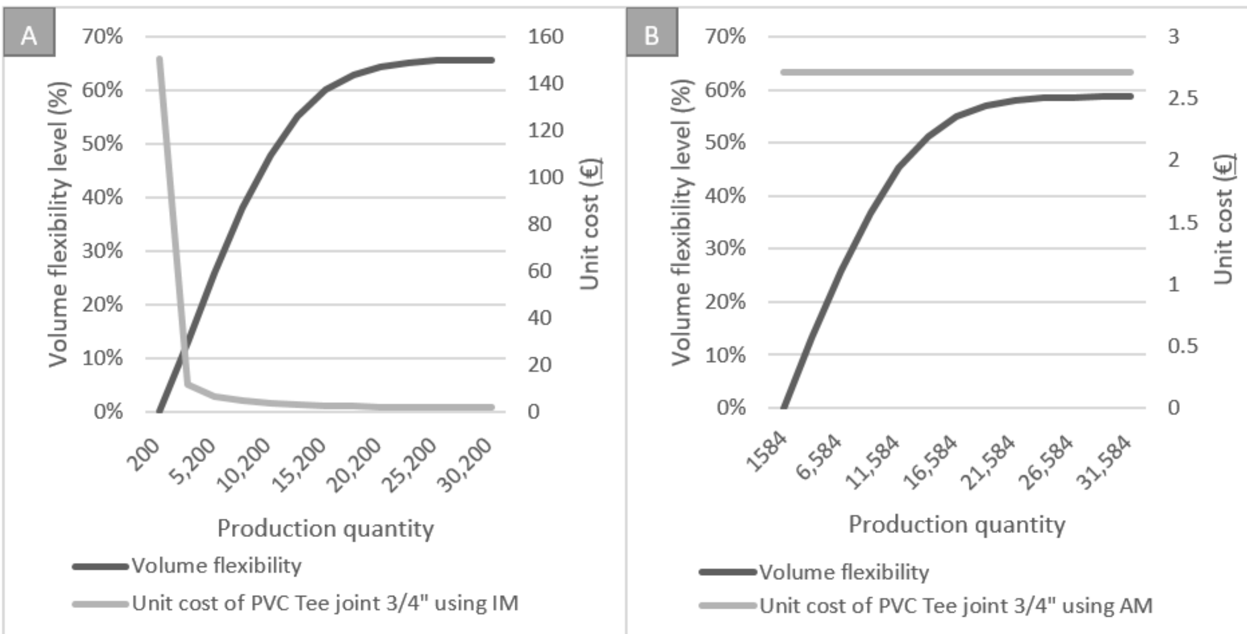

Figure 7. Relationship between volume flexibility and unit cost of the studied part for (**A**) IM and (**B**) AM.

As can be seen in Figure 7, the unit cost of AM is not reduced with each increase in production quantity compared to IM (see also Hopkinson and Dicknes [44]). In both supply chains, volume flexibility shows the same pattern of sharp increase at the beginning before it starts to plateau once reaching a certain production quantity. This is because the volume flexibility is estimated, as shown in Section 3.3.1, based on a minimum production quantity O_{min} and a maximum production quantity O_{max} in relation to the mean $\overline{D}$ of the historical demand, which is 3240 parts a month in our study. Therefore, such diminishing of increase in the volume flexibility is expected since the increase in production quantity is rendered useless relative to the market demand. A supply chain that utilises IM, thus, would be more attractive when aiming at increasing volume flexibility due to the inverse proportion between the unit cost of its products and its volume flexibility.

4. Discussion

Interesting insights are gained from the case study on the conceptual model shown in Section 2. Neither the absence of tooling nor the on-demand production in AM seem to play a critical role in improving volume flexibility, especially in comparison with an established manufacturing system. The lower volume flexibility level shown by the proposed AM route in the case study contradicts the proposition advocated by Verboeket and Krikke [45] that AM increases volume flexibility from a supply chain perspective. While this might be accurate from a manufacturing perspective, a supply chain perspective necessitates the inclusion of inventory as one crucial input in measuring flexibility, as pointed out by Lau [46] who emphasised the need to incorporate other functions in the company when targeting higher flexibility level. The lower level of volume flexibility in the AM supply chain is in alignment with the results presented by Eyers, Potter, Gosling and Naim [19] who found moderate evidence of the capability of industrial AM system to vary the production volume flexibly.

It should be noted, however, that while these flexibility aspects are required from a supply chain perspective, they are still caused by internally developed competencies such as machine, material handling, routing and labour flexibilities. As indicated by Zhang, et al. [47], these competencies are strongly and positively correlated with two external capabilities: mix flexibility and volume flexibility. The existence of the labour flexibility in the AM systems was evident in recent research [18,19] which should correlate with high volume flexibility level. Nonetheless, when compared with a supply chain that relies on dedicated manufacturing technology, as in the case of IM in our case study, the AM supply chain is not commensurate to the same flexibility level as that of IM. This shows the significance of holding a buffer stock to flexibly respond to rapid changes in volume and delivery, a point that has been repeatedly emphasised in the literature [26,48,49].

As observed in the high rate of AM adoption in industries that entail the need for either mass customisation or economically low production volumes [50], this study provides insights into possible aspects that led to such adoption. From a flexibility perspective, the critical aspect of lack of tooling in the AM technology fosters: (i) easier introduction of new products into the system and (ii) achievable product proliferation strategies. Whilst the latter has great benefits associated with preserving and acquiring additional market share [51], it leads to substantial operational problems linked with less responsive delivery performance [52]. This trade-off might explain the lower delivery flexibility level for the AM supply chain in this case study (i.e., 75.35% compared to 92.85% for IM) as it was impacted by the lack of instant shipment using buffer stocks.

Features like the absence of tooling and freedom of geometry in AM can also address a challenge that has emerged in the manufacturing realm recently. Moreover, the development of industrial new technologies in connection with the Internet of Things (IoT) has driven the fourth industrial revolution, collectively known as Industry 4.0. One important concept that has emerged from this revolution is the smart factory, an interlinked and flexible manufacturing system that utilises constant feedback from linked processes and production methods to adapt and cope with new market and environment conditions [53]. Sjödin, et al. [54] have reported several challenges that hinder the successful implementation of the smart factory. One major challenge was the need for adopting contemporary approaches that support more agile and rapid products to the marketplace. In addressing this challenge, Sjödin, Parida, Leksell and Petrovic [54] urged the introduction of agile product development approaches as opposed to the traditional Stage-Gate one. One implication of adopting an Agile product development approach is the production of a Minimum-Viable-Product (MVP) for faster launch to the market [55,56]. The unique characteristic of the lack of tooling in AM facilitates the successful production of MVPs and, hence, flexible iterative product development processes in the smart factory. The utilisation of AM for creating MVPs has been recently validated by Storbacka [57] and described in details by Reichwein, et al. [58].

Based on the overall results of this study, a model that captures the fitness of the different flexibility aspects with major supply and demand characteristics is proposed in Figure 8. Based on this model, a supply chain can be either in a strategic fit or lack thereof. A flexible manufacturing technology such as AM would be most appropriate for market environments with low demand volumes as widely suggested in the AM literature e.g., [59,60]. This, in turn, can result in attaining higher mix and new product flexibility levels. On the other hand, a dedicated manufacturing technology such as IM would require higher demand levels to ensure the proper realisation of economies of scale [61]. Hence, greater volume and delivery flexibility levels can be achieved in response to sudden changes in market requirements.

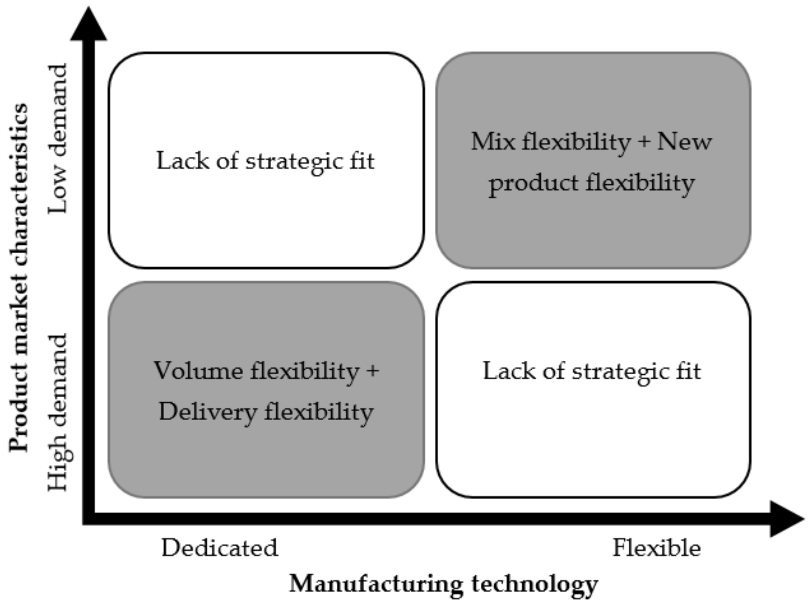

Figure 8. The relationship between the external flexibility capabilities, manufacturing technology and demand volume level.

This study, however, is not inclusive of all possible aspects and some limitations should be noted. First, the chosen product is standardised and usually ordered by wholesalers and stockiest in high volumes. Had different product with complex geometry and relatively low demand volumes been chosen, different flexibility metrics would have been observed. This option, however, could not be realised due to lack of industrial access and time constraints and should be left for future studies. Second, this study also did not consider other forms of responsive supply chains (i.e., supply chains that require flexibility). For instance, other production lines utilise postponement strategies that allow for certain elements of a modular product to be produced in batches, whereas the production of the remaining elements is deferred to the latest point near to the customer request. In these cases, certain features of the manufactured product will be customised based on customer preference, which requires various degrees of customisation. This will examine the capability of AM to increase certain flexibility aspects (i.e., internal ones such as process, program and labour or external ones such as delivery or postponement). Studying such cases and examining the effect AM would yield on flexibility will permit more comprehensive exploration. Future studies should consider different product types within the same range of demand volatility to allow for more generalisable conclusions related to the effect of AM on flexibility.

5. Conclusions

In the supply chain management literature, it has been emphasised that managing manufacturing systems should incorporate flexibility as a core objective along with cost, quality and dependability. There were no studies, however, that examined how adopting AM affects these flexibility aspects in response to certain market disruptions. This paper addressed this gap by developing a conceptual model that maps AM characteristics relevant to flexibility against key market disruption scenarios. This work offers novel insights into the relationship between AM and supply chain responsiveness that will inform future research and practitioners.

To gain further insight into the developed conceptual model, a case study was undertaken that examined the effect of AM adoption on supply chain flexibility in comparison with other conventional manufacturing technologies. By conducting an inter-process comparison between AM and IM using data collected from a manufacturing company, the study provided some tentative quantification of these aspects. The AM supply chain without inventory in this case study was relatively ineffective in responding rapidly to different demand volumes (i.e., 58.70% for AM compared to 65.68% for IM) and delivery times (75.35% for AM compared to 92.8% for IM). Also, the supply chain that utilised IM would be more attractive when aiming at increasing volume flexibility due to the inverse proportion between the unit cost of its products and its volume flexibility. However, due to the lack of tooling, the AM route provided more flexibility in producing a wide range of products with less time (i.e., 0.33 h for AM compared to 4.91 h for IM) and at a lower cost when introducing new products to the system (€0 for AM compared to €30,000 for IM).

AM might seem an attractive option when aiming at improving flexibility. However, it can also be less attractive relative to other manufacturing technologies and for certain supply chain flexibility aspects. These results particularly demonstrate the feasibility of adopting AM in production environments with demand volatility. When considering AM as a choice to increase supply chain flexibility in volatile environments that entails potentially high production volumes, AM might be ineffective compared to other dedicated manufacturing technologies. Furthermore, this study suggests that lead-time compression enabled by the on-demand production of AM technology will not be sufficient to outweigh the lead-time compression attained by a supply chain employing a buffer stock strategy produced by IM. On the other side, AM can significantly increase supply chain flexibility in production settings where customised products or low production volumes are demanded, attributed mainly to the lack of tooling in AM. The new product flexibility offered by AM can also play a key role in facilitating the application of agile product development that requires constant production of MVPs, a challenge that hinders the successful implementation of the smart factory. These results will inform both practitioners and scholars to predict the effects of AM adoption on distinct supply chain flexibility aspects.

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Appendix A

The unit cost models developed for this study are based on the general model structure for inter-process comparisons proposed by Atzeni, Iuliano, Minetola and Salmi [33]. The cost model of parts produced by IM consists of four elements. The first element is the material cost, MC, and is estimated as follows:

$$MC_{IM} = W \times M_{IM} \tag{A1}$$

where W denotes the part weight and M_{IM} represents the material cost per kg. The second element of the IM cost model is the machine cost per part IC_{IM}, which is estimated as follows:

$$IC_{IM} = CH_{IM} \times T_{IM}/N_{IM} \tag{A2}$$

where CH_{IM} denotes the IM machine cost per hour which is estimated based on the machine price and the depreciation technique, T_{IM} refers to the cycle time and N_{IM} represents the number of cavities in each mould. The third element is the mould cost per part KC_{IM}, and it is estimated as follows:

$$KC_{IM} = K/V_{IM} \tag{A3}$$

where K is the mould cost and V is the production volume. The fourth element of the IM cost model is the operator cost per part OC_{IM}, which is computed as follows:

$$OC_{IM} = O_{IM} \times T_{IM}/N_{IM} \tag{A4}$$

where O_{IM} is the operator cost per hour. Finally, these four elements are added together to form the unit cost of parts produced by IM, UC_{IM}, as follows:

$$UC_{IM} = MC_{IM} + IC_{IM} + KC_{IM} + OC_{IM} \tag{A5}$$

On the other side, the cost model of parts produced by AM consists of three cost elements. The first one is the material cost per part, MC_{AM}, and it is computed as follows:

$$MC_{AM} = \frac{0.5 \times M_{AM} \times V_{AM}}{N_{AM}} \tag{A6}$$

where M_{AM} denotes the AM material cost per kg, V_{AM} represents the build volume in cm^3 of the selected AM machine and N_{AM} represents the number of parts produced in one job. The second element is machine cost per part, AC_{AM}, and it is estimated using the following equation:

$$AC_{AM} = CH_{AM} \times \frac{T_{AM}}{N_{AM}} \tag{A7}$$

where CH_{AM} denotes the AM machine cost per hour which is estimated based on the machine price and the depreciation technique, T_{AM} represents the build time in hours. The third and last element is the operator cost per part, OC_{AM}, and it is computed as follows:

$$OC_{AM} = \frac{O_{AM} \times A}{N_{AM}} \tag{A8}$$

where O_{AM} represents the machine operator hourly rate whereas A denotes the pre- and post-processing hours needed for each build. The unit cost of parts produced by AM, UC_{AM}, then is estimated as follows:

$$UC_{AM} = MC_{AM} + IC_{AM} + OC_{AM} \tag{A9}$$

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