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Impact of Additive Manufacturing on Supply Chain Complexity

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Abstract

This paper aims to determine whether additive manufacturing (AM) always simplifies the supply chain. The advent of AM as a final-parts production method can radically impact supply chains. Due to AM's inherent characteristics that suit customised production and complex geometries, utilization of this technology continues to expand into various industries (e.g. aviation, defence, automobile, medicine). Some of the crucial areas that AM can contribute to are cost reduction and simplification of organizations' supply chains. An objective examination of the entire supply chain rather than merely focusing on production cost is important when studying the impact of switch-over from conventional to additive manufacturing. Supply chain complexity is caused by the proliferation of products, processes, suppliers, and markets, resulting in additional costs and decreased company profit. Therefore, to clearly illustrate the benefits and shortcomings of a switch-over to AM, it is necessary to investigate this transition in depth. In this paper, we analysed supply chain complexity before and after the implementation of AM in three case companies from distinct industries by conducting interviews or utilizing publicly available information. Our findings underline the simplification of supply chain in one of the cases, after the switch to AM, while it resulted in slightly higher complexity in another case. In the third case, the impact of switching to AM on the supply chain complexity is dependent on several variables. We contribute to the literature by elucidating on the common belief that AM simplifies the supply chain. We found that the implementation of AM is not a silver bullet to reduce the complexity of every supply chain.

1. Introduction

The term additive manufacturing (AM) comprises of a set of manufacturing techniques that are capable of generating physical components layer by layer. It is substantially different from subtractive and formative techniques, which require high up-front investment for tooling cost. On the contrary, AM allows the production of geometrically complex components and entire assemblies without the need of tools through design data in a digitally streamlined process. In fact, AM technology enables the digitalization of manufacturing that facilitates high variety of products without significant cost penalties related to tool production [9]. However, one question remains with regard to the implementation of AM in the supply chain – its impact on the complexity of the chain. For this reason, the current research aims to determine the impact of AM on supply chain complexity by conducting three case studies.

Supply chain complexity is defined as the interconnectedness and interdependencies across a network where a change in one element can have an effect on other elements [17]. It is referred to as the core challenge of a business: 'If you are in supply chain management today, then complexity is a cancer you have to fight.' This statement by the supply chain operations vice president of Coca-Cola Company [3] underlines the seriousness of supply chain complexity in today's global economy.

Increased supply chain complexity introduces various challenges and difficulties [4]. Factors such as the push from investors for higher profits and market competition have led to a trend towards broader product portfolios (i.e. more products, more models,

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more variations) in different industries (e.g. automobile models and options from each brand, handsets from cell phone makers), which mean more complexity as they require more personnel, processes (i.e. production technology), facilities, suppliers, markets and customers [17], [4]. In many cases (e.g. General Motors Company, Apple Computers before 1999), this added supply chain complexity and its corresponding costs pushed companies towards bankruptcy.

Ford and Despeisse [7] suggest that AM can simplify supply chains through the reduction of subcomponents. Huang et al. [12] also state AM has a supply chain simplification impact. However, the current body of knowledge has a holistic view and does not delve into various applications and cases to investigate if AM does simplify supply chains in actual practice.

Therefore, supply chain managers need to gain awareness of potential outcomes of AM implementation in their supply chains to be able to benefit from them. The AM's capability in producing nearly unlimited designs and complex geometries without tooling enables the combination of multiple parts into one. It also makes possible production postponement, economic product customization, and very small batch manufacturing. These possibilities are significant because multi-tier supply chains with dozens of suppliers providing hundreds of parts can be simplified into controlling a few raw materials near the production line.

This article takes into account the importance of AM for future supply chains and aims to answer the following research questions:

1. *Does AM always simplify the supply chain?*
2. *What are the implications of AM on supply chains complexity?*

This paper is divided in six sections. After the introduction, a literature review on the research subject is presented. The section on methodology explains how we reached the outcomes. The next section describes the results of this study. Finally, this paper ends with the discussion of future case studies and the conclusions, where we suggest future research directions.

2. Literature review

2.1. Supply chain complexity

Lambert et al. [15], conceptualised the supply chain as 'the alignment of firms that bring products or services to market'. Chopra and Meindl [19] identified the various components of supply chains; they stated, 'a supply chain consists of all stages involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves'. In this article, the last definition is used to study supply chain complexity and simplification methods.

Bozarth et al. [4] distinguished three types of supply chain complexity drivers: downstream, upstream, and internal manufacturing (Table 1). In addition to the main classification, this approach further explains the causes of each type of complexity in detail.

The complexities mentioned in Table 1 arise from various sections of supply chains. Any solution or strategy designed to solve these complexities (i.e. simplify the supply chain) therefore needs to affect the corresponding section. Our review of the literature resulted in a number of simplification strategies, which are presented in this section.

Table 1. Drivers of supply chain complexity. [4]

Item	Complexity driver
1	***Downstream***
1-1	Number of customers
1-2	Heterogeneity in customer needs
1-3	Shorter product life cycles (i.e. frequency of various product introduction) and long product lifecycle (i.e. logistics of supporting activities)
1-4	Demand variability
2	***Internal manufacturing***
2-1	Number of products
2-2	Number of parts
2-3	One-of-a-kind or low volume batch production
2-4	Manufacturing schedule instability
3	***Upstream***
3-1	Number of suppliers
3-2	Long and/or unreliable supplier lead times
3-3	Globalization of the supply base

Postponement and speculation are two closely related concepts. While postponement is due to the uncertainty of demand and high products variety, speculation is used to take advantage of the economies of scale when product diversity is not a concern. In a postponement strategy, the producer delays product finalization until the exact demand from the customer is determined. With this method, supply chain complexity due to heterogeneity in customer needs [24] and demand variability [23] can be reduced. Conversely, when a product has high consumer demand, few varieties, and sells in a competitive market, speculation is used, to take advantage of economies of scale and reduce the supply chain complexity caused by the high number of customers [20].

Standardization is another strategy that impacts supply chain complexity by reducing the variety of products produced. Modularization is also a complementary strategy used to simplify the product customization in supply chain. Modularization can alleviate the supply chain complexity by reducing the number of suppliers and shortening the final assembly time [22].

Design for function, as explained by Holmström et al. [10], is a new concept that evolved from novel digital production methods. It removes the constraint of design for manufacturing and enables the designer to manufacture the performance optimised form of a part or product. This concept has the potential to reduce the number of parts in supply chains [11].

Moreover, in-house production, which is implemented by a number of industrial companies (i.e. SpaceX and Tesla, Inc.), has been shown to have positive results regarding cost and reliability [1]. According to [2], companies with in-house capabilities are more likely to encourage a supplier to be innovative and reliable, and this can positively affect the upstream complexity of the supply chain.

2.2. Additive manufacturing

Additive manufacturing is also known as three-dimensional (3D) printing, a method of producing objects directly from a three-dimensional computer-aided design (CAD) file. This method works opposite to conventional production methods, which subtract excess material from a raw shape to achieve the intended geometry. AM produces parts by adding a thin cross section of the part's 3D geometry on top of each other to construct the intended design. The computer software produces these thin two-dimensional cross sections and sends them to the AM machine to be laid out on raw material [9], [11]. This technology, which emerged in the 1980s as a method of producing prototypes, is nowadays adopted for final parts manufacturing [26]. This change can be attributed to the unique characteristics of AM processes.

Firstly, AM does not necessitate tool manufacturing; therefore, it reduces the initial capital investment compared to conventional manufacturing technologies (e.g. injection moulding). This enables AM to reduce the impact of economics of scale where the volume of production leads to lower cost per part. In case of AM, economics of scale only applies until the production chamber is full; after which, the cost of manufacturing per part stays the same for similar parts. In other words, AM is capable of producing very small batches of products faster and cheaper than conventional methods. Moreover, AM enables toolless manufacturing, which allows for manufacturing flexibility (i.e. the production of customised parts is as easy as modifying the 3D CAD file).

Secondly, AM is a layer-based process, and this allows for the production of geometrically complex components in a single run. In other words, design for manufacturing is less restrictive in the AM process such that engineers can design components for function without being worried about manufacturability. As a result of this manufacturing freedom, AM can produce assemblies in one go and make lighter components without compromising strength. Lastly, AM reduces production waste in case of metal 3D printing (e.g. powder bed fusion) as much as 90% [10] by allowing reuse and recycling. This aspect is important, especially when printing with precious metals and titanium.

The limitations of this production method are related to the range of available materials, production finish quality, production rate, production chamber size, repeatability of production, and costs of machines and materials [14]. Although AM is not a widely used production process yet, however, technology advancements and improvements in AM processes, enhancements in the variety of available materials, and AM's distinct capabilities allows it to be considered as an important manufacturing process.

2.3. Literature gap

The foundation of this research is based on articles, such as [25], and Hopkinson et al.'s [11] book. In their article, Tuck et al. [25] explored the general impact of AM on supply chain management paradigms, such as lean and agile manufacturing, while studying real-world cases. Moreover, Hopkinson et al. [11] described a number of additive manufacturing implementations in detail. However, there is room for an objective investigation of AM impact on supply chain complexity.

Our contribution to the literature is that we examined the common belief that AM simplifies the supply chain [10], [12]. To achieve this, we utilised three real-world case studies.

3. Methodology

The methodologies selected for this paper are real-world case study and expert analysis. The case study research method was used, combining both objective and subjective as well as primary and secondary data. The goal is to achieve an in-depth understanding of AM's impact on supply chain complexity. Although there are disadvantages related to case study research (e.g. subjectivity, bias, reliability, validity, and generalizability of results), this cumulative method allowed us to aggregate knowledge, which is especially relevant for emerging technologies.

After problem explanation, we searched for companies that currently implement AM throughout their production operations. Our scrutiny resulted in three cases – companies that have implemented the AM in their value chain or have evaluated the AM for specific applications in their supply chain.

The first case, which is the implementation of AM for the production of fuel injectors for a popular jet engine manufactured by CFM International (i.e. a joint venture between General Electric Aviation and Safran), was analysed using secondary data available in scientific publications [16] and publicly available data [8], [13].

The second case is ABB company's use of AM for cable grommet manufacturing. The primary data for the ABB case was collected through a semi-structured interview with a senior design engineer.

The third case is Launzer Company's use of AM for action figures production. For the Launzer company case, the semi-structured interview with the chief executive officer of the company was conducted over Skype. In both ABB and Launzer cases, the interviewees have in-depth knowledge of AM technology within their company's production processes and supply chain. After analysing the interviews and the collected data, we created a holistic graphical representation of the companies' supply chain, considering all the suppliers up to the raw material suppliers and down to the end customers in the supply chain.

In this paper, we studied supply chain complexity based on three products for which manufacturing methods have shifted from conventional manufacturing (CM) to AM. For every case, a graphical representation of the focal company's supply chain with regard to the AM-produced products was constructed.

To compare supply chain complexity before and after the implementation of AM, we compared the graphs based on the number of nodes (i.e. processes, suppliers, and customers) and connections (i.e. information and material delivery). Moreover, to quantify the results, we utilised Mariotti's complexity factor [17] and Serdarasan [21] as bases for the measurement of supply chain complexity for CM versus AM modes. Mariotti proposed the complexity factor (CF) as a progress measurement and benchmarking tool that allows companies to diagnose complexity issues and track their progress in treating it. The formula directly relates the complexity of company operations to the number of produced stock keeping units (SKUs), number of distinct markets served, number of countries served, and summation of number of employees, suppliers, and customers. Mariotti's formula (1) also suggests a reverse relationship between CF and company's sales revenue.

$$CF = \frac{\begin{gathered} SKUs \times Markets\ served \times Countries\ served \times \\ Facilities \times (Suppliers\ +\ Customers\ +\ Employees) \end{gathered}}{Sales\ revenue} \quad (1)$$

Since our aim in this paper is the calculation of supply chain complexity, we utilised Serdarasan [21] to complement Mariotti's CF. The resulting formula, which we call supply chain complexity index (SCCI) captures the internal supply chain complexity and the supply and demand interface complexity, which is calculated as follows:

$$SCCI = \frac{\begin{gathered} SKUs \times Markets\ served \times Countries\ served \times \\ Manufacturing\ Processes \times \\ (Inventories + Factories +\ Customers\ +\ Employees) \end{gathered}}{Sales\ revenue} \quad (2)$$

The difference between SCCI and CF is that we focused on the whole supply chain, and we include supply chain internal complexity items, such as inventories and number of processes involved throughout the supply chain for the manufacturing of the product studied. Additionally, Supply and demand interface items, such as factories and suppliers in the supply chain, are included to the basic CF calculations (1). Notably, external supply chain complexity defined by Serdarasan, [21] such as market uncertainties, trends in the market, and new technologies are out of the scope of this research and are not measured by SCCI.

We did not calculate the complexity of each supply chain individually; however, a supply chain complexity comparison was conducted before and after the implementation of AM in each case study. To do so, we utilised the supply chain complexity ratio (SCCR), which is as follows:

$$SCCR = \frac{SCCI\ of\ CM}{SCCI\ of\ AM} \quad (3)$$

In (3), when the SCCR is above 1, it indicates the simplification effect of AM on the supply chain. When the SCCR is equal to 1, it means AM does not have any impact on supply chain complexity. When SCCR is lower than 1, it signifies increased complexity as a result of AM implementation. The SCCR has a holistic view of the supply chain where one calculation is performed to determine the impact of AM on the whole supply chain.

4. Results

This section presents the results of our analysis on three real-world implementation cases of AM in the supply chain. Table 2 presents the companies and their application of AM.

Table 2. Real-world industrial cases.

Name	Application
Fuel injector	Final parts
Cabling grommet	Mould making
Action figure sample product	Final parts

4.1. General Electric implementation of AM to produce LEAP jet engine fuel nozzles

General Electric (GE) Aviation, a major manufacturer of jet engines, decided to heavily invest in AM and take advantage of its capabilities for their future products. CFM International, a joint venture between GE Aviation and Safran Aircraft Engines, produces LEAP jet engines as the next generation of fuel-efficient commercial aircrafts engines. LEAP jet engines are designed to incorporate the latest materials and production techniques. There are up to 19 fuel injection nozzles on every engine, which were previously produced from 20 parts welded together [13]. However, AM allowed the production of the part in one piece, making it cheaper and more durable (see Figure 1a).

Figure 1a. Additively manufactured

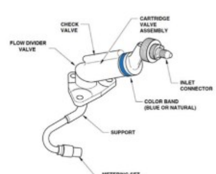

Figure 1b. Conventionally manufactured

Figure 1. Fuel nozzle for LEAP jet engine.

This example, which illustrates parts consolidation, is enabled by AM's feature that allows the production of complex geometries. As the change in the supply chain is the result of SKU reduction, it can alleviate supply chain complexity. To examine this further, we compared conventional manufacturing with AM for the production of fuel nozzles.

4.1.1. Conventional manufacturing supply chain of fuel nozzles. Figure 2 is a visual illustration of CFM56-3 jet engine fuel nozzles' supply chain, which was constructed based on publicly available data.

In Figure 2, we assumed the fuel nozzle to be composed of 20 individual parts [13], [16], which need to be individually produced through various manufacturing methods, such as casting, machining, forming, cutting, and finishing. Fuel nozzle manufacturing also requires other production steps, such as assembly, welding, and testing. Fully assembled tested nozzles are then integrated into the jet engine.

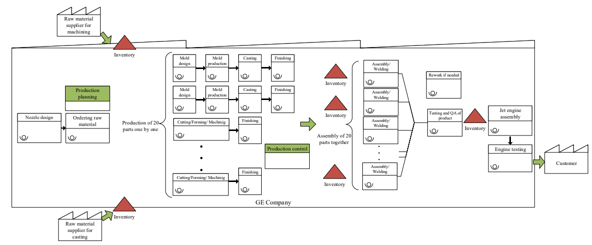

Figure 2. Conventional manufacturing supply chain for CFM56-3 jet engine fuel nozzles.

Finally, after passing through testing, the jet engines are delivered to the aircraft manufacturers for on-wing assembly.

4.1.2. AM supply chain of fuel nozzles. CFM International has integrated the production of the fuel nozzles into its internal operations by utilizing AM (see Figure 3).

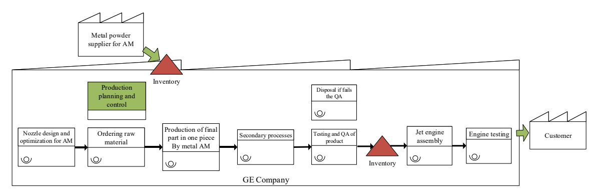

Figure 3. AM supply chain of LEAP jet engine fuel nozzles.

AM-enabled parts consolidation significantly shortens the chain of required manufacturing processes compared to conventional manufacturing; it also eliminates the work-in-progress inventory. Supplying raw materials is also simpler as the only required material is metal powder, while in conventional manufacturing, the raw materials for casting and machining processes are different.

4.1.3. Supply chain complexity ratio for fuel nozzle. With AM implementation, the number of production SKUs, required manufacturing processes, suppliers and inventories are all significantly reduced. Based on (2) and (3), the SCCR is therefore calculated as follows:

$$SCCR = \frac{\frac{24 \times Markets\ served_{CM} \times Countries\ served_{CM} \times 7 \times (3 + 23 + Customers_{CM} + \ Employees_{CM})}{Sales\ revenue_{CM}}}{\frac{3 \times Markets\ served_{AM} \times Countries\ served_{AM} \times 3 \times (2 + 2 + Customers_{AM} + \ Employees_{AM})}{Sales\ revenue_{AM}}}$$

$$SCCR = \frac{1456 + 56 \times Customers_{CM} + 56 \times Employees_{CM}}{12 + 3 \times Customers_{AM} + 3 \times Employees_{AM}}$$

$$If\ Customers_{CM} = Customers_{AM}\ and\ Employees_{CM} \geq Employees_{AM} \rightarrow SCCR > 1$$

Since a change in the manufacturing method of one component of a jet engine is not a justification to increase its price tag, and since this change can rarely result in higher sales volume, we therefore assumed the sales revenue of the supply chain final product (i.e. jet engine) to remain unchanged after switching to AM for fuel injectors production. Moreover, since the number of manufacturing processes and suppliers in the AM supply chain are reduced, it is safe to assume that the number of employees can also be reduced or maintained when shifting to AM. The SCCR analysis clearly indicates supply chain simplification as the result of AM implementation in the case of LEAP jet engine fuel injectors. Notably, markets served under conventional and additive manufacturing remains unchanged; this is also true for countries served in SCCR calculations.

4.2. ABB case study of direct tool making for injection moulding

In this case, ABB Company studied the use of selective laser melting AM method to produce injection moulding insert tool for a cone-shaped plastic cabling grommet (see Figure 4) that is 40 mm in diameter and 30 mm in height.

Figure 4. ABB Company cabling grommet.

The aim of the project was to replace an old injection moulding insert tool (i.e. without cooling channels) with a new one that is embedded with conformal cooling channels to shorten the cycle time. AM was utilised to produce various cooling channel designs before one was chosen as the optimal design. The testing showed a significant cycle time reduction from 60 to 20 seconds per part. For the selected design, AM was economically feasible since the conventional production required the manufacturing of the insert in multiple parts, which required assembly and additional work.

As the injection moulding of the cable grommets is done by a subcontracted company located in China, after the initial testing of the tool inserts, which are produced locally in Finland (see Figures 5a & 5b), a third party AM service provider in China was selected for the tool insert final production.

The first delivery from China indicated material weakness and observable cracks, which led to material change (i.e. from H13 to MS1) and reordering.

After issues with insert material were resolved, secondary processes, including heat treatment and surface finishing, on the part were also performed in China by the same subcontractor to meet the dimensional tolerances.

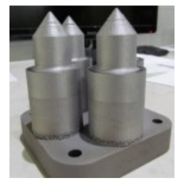

Figure 5a. Printed injection moulding inserts

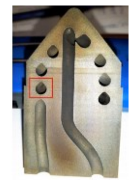

Figure 5b. Clogged cooling channel in the initial test batch

Figure 5. Tool inserts produced locally in Finland.

In the following section, the presented example is analysed, and the conventional supply chain for the production and delivery of the same part is visualised to facilitate the comparison of structure and complexity with the AM-enabled supply chain.

4.2.1. Conventional manufacturing supply chain of cable grommet. Conventional manufacturing of the cable grommet starts with designing the tool and insert and subcontracting the manufacturing of the tool to third party service providers. The tool is sent for the injection moulding to another subcontractor, and from there, the produced parts are shipped to the assembly line to be consolidated into the final product (see Figure 6).

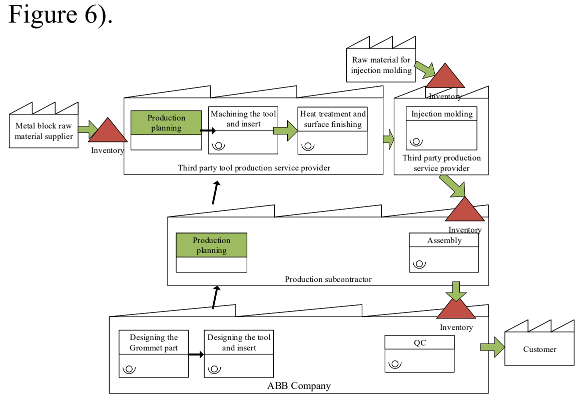

Figure 6. Conventional manufacturing supply chain of cable grommet production.

In this process, the tool and insert are designed for manufacturing with limited use of conformal cooling channels, which leads to longer cycle time.

4.2.2. AM supply chain of cable grommet. The introduction of AM in the case of cable grommet did not bring the production in-house since final part production with injection moulding is still done by subcontractors. Nonetheless, the supply chain is slightly changed by AM – the AM process is added to the subcontractor services, and the raw material for AM is also provided by another supplier (see Figure 7). Notably, AM's introduction to the supply chain improved the productivity of the injection moulding process; it shortened the cable grommet production cycle time.

In this case, although the addition of AM to the supply chain resulted in better productivity for cable grommet manufacturing; the complexity of the supply chain slightly increased.

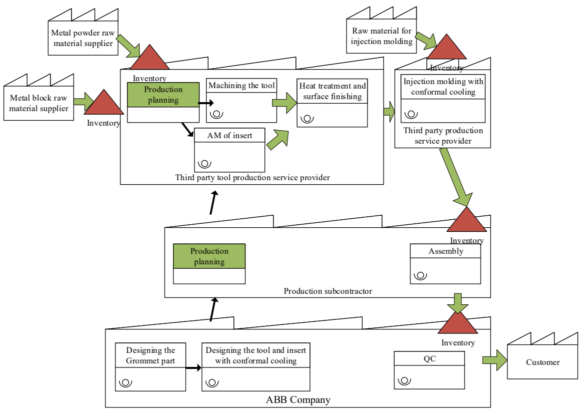

Figure 7. AM supply chain of cable grommet production.

4.2.3. Supply chain complexity ratio for cable grommet. With AM's introduction to the supply chain of cable grommet, the number of manufacturing processes, inventories, and suppliers slightly increased. Based on (2) and (3), the SCCR is therefore calculated as follows:

$$SCCR = \frac{\dfrac{6 \times Markets\ served_{CM} \times Countries\ served_{CM} \times 5 \times (4 + 6 + Customers_{CM} + Employees_{CM})}{Sales\ revenue_{CM}}}{\dfrac{7 \times Markets\ served_{AM} \times Countries\ served_{AM} \times 6 \times (5 + 7 + Customers_{AM} + Employees_{AM})}{Sales\ revenue_{AM}}}$$

$$SCCR = \frac{50 + 5 \times Customers_{CM} + 5 \times Employees_{CM}}{84 + 7 \times Customers_{AM} + 7 \times Employees_{AM}}$$

$$If\ Customers_{CM} = Customers_{AM}\ and\ Employees_{CM} \leq Employees_{AM} \rightarrow SCCR < 1$$

Since a change in the manufacturing method of one component in the cable grommet supply chain is not a justification to increase the price tag of the final product, and since this change can rarely result in higher sales volume, we therefore assumed the sales revenue of the supply chain final product to remain unchanged after switching to AM for cable grommet insert tool. In this case, the addition of AM, with its secondary processes and additional supplier requirement, caused a slight increase in the number of employees, and therefore, a slight increase in overall supply chain complexity.

Notably, markets served under conventional and additive manufacturing remains unchanged, and this is also true for countries served in SCCR calculations.

The utilization of AM-enabled conformal cooling enables shorter manufacturing cycle time, but this is not measured by the SCCI. However, the implementation of AM did not simplify the supply chain and, in fact, marginally increased its complexity.

Moreover, when the company introduced AM into its production, it initially confronted additional supply chain complexity in finding the right AM service providers and raw material suppliers. Conversely, when the AM process is more established and reliable and experienced subcontractors are available, it can improve supply chain productivity for cable grommet manufacturing.

4.3. Launzer case study of customised action figures and jewellery manufacturing

The Launzer Company was an online platform selling single-piece action figures and jewellery through third party AM service providers. In other words, Launzer was a virtual marketplace connecting designers (i.e. IP owners) to end customers. The Launzer's business model was build-to-order; customers could modify the objects' material (i.e. if it was in line with the IP owners' instructions), colour and size based on their preferences (see Figure 8). Third party AM service providers are among the enablers of such a business model, which eliminates the need for inventory.

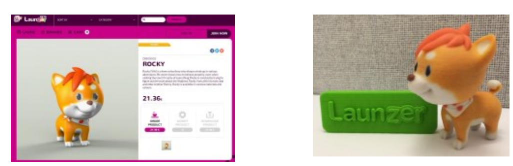

Figure 8. Launzer's platform and sample product.

The difference between Launzer and other similar companies, such as Shapeways, was Launzer's narrowed focus on the entertainment and gaming industries.

4.3.1. Conventional manufacturing supply chain of action figures. One of the conventional ways of ordering action figures is through a design bureau. Figure 9 presents the supply chain of a design bureau for a customised article, from the creation and design to delivery to the customer. In this case, design and production are triggered by the customer order in a make-to-order fashion; thus, there is no need for final product inventory. However, there is a need for close cooperation between the customer and the design bureau in the design and prototyping phase. After the model is accepted by the customer, the mould is created and sent to the third party for volume production through casting or injection moulding. The final items are returned to the factory for quality control, painting, and finishing before packaging and customer delivery.

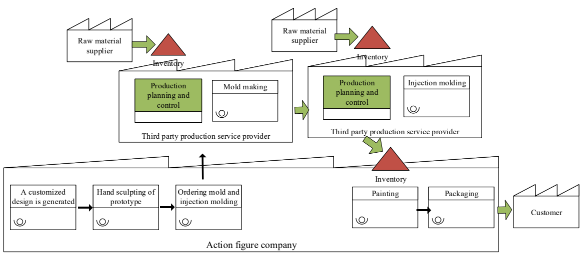

Figure 9. Visualised supply chain for action figures made by a design bureau.

4.3.2. Launzer supply chain for action figures. Figure 10 presents the Launzer supply chain, which utilises AM. This supply chain allows a medium level of customization due to design IP limitation, but in theory, this production method does not impose any design modification limits. This method allows for final product delivery in two weeks, without tooling and inventory cost barriers, which are the main differences between this supply chain and the design bureau conventional supply chain. Although the production of articles with AM is not as cheap as mass-produced, injection-moulded items, the lack of tool making makes it less risky for the manufacturer while improving the product time to market as Khajavi et al. [14] affirmed.

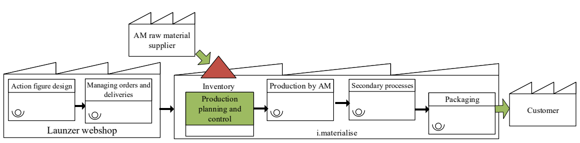

Figure 10. Visualised supply chain for action figures made by Launzer.

Launzer Company ceased operations at the end of 2015 due to slow business, resulting from a lack of market readiness and design flexibility issues with relevant IP owners.

4.3.3. Supply chain complexity ratio for action figures. Since there is no need for mould making, and manual painting in the Launzer supply chain, the process has fewer SKUs, manufacturing processes, inventories, and suppliers compared to the conventional supply chain of a design bureau. Based on (2) and (3), the SCCR is hence calculated as follows:

$$SCCR = \frac{\frac{6 \times Markets\ served_{CM} \times Countries\ served_{CM} \times 3 \times (3 + 5 + Customers_{CM} + Employees_{CM})}{Sales\ revenue_{CM}}}{\frac{2 \times Markets\ served_{AM} \times Countries\ served_{AM} \times 1 \times (1 + 3 + Customers_{AM} + Employees_{AM})}{Sales\ revenue_{AM}}}$$

In Launzer's case, the sales revenue and, consequently, the number of customers are not independent of the production method (e.g. additively manufactured or manufactured by injection moulding) because the end product is not a component of another assembly; it can be the final product of a supply chain by itself. Moreover, Launzer has the potential to serve more countries and more markets due to very low volume offering. Therefore, to analyse the impact of switching to AM using SCCR, we need to set a number of assumptions before determining the impact of AM on supply chain complexity. Assuming that markets served by AM and conventional methods are the same, that both methods serve similar number of countries, that the sales revenue for action figures manufactured by AM is equal to conventional manufacturing by a design bureau, and that the number of customers for both manufacturing methods are also similar, then the supply chain becomes less complex when the number of employees in the AM supply chain is lower than that in the design bureau supply chain. The assumption regarding the lower number of employees for the AM supply chain of action figures is not far from reality as there are less manufacturing processes and less suppliers in the AM supply chain. However, the exact outcomes of this case are vague because the AM creates a totally new supply chain for action figures where the production of a single item is possible without the need to invest for tooling or handcrafting. This means that Launzer could make single units of products, while the design bureau needs higher volumes to take advantage of economies of scale to bring the production cost lower. Thus, it can be concluded that the Launzer supply chain is unique due to the distinct characteristics of AM, which make it incomparable with conventional tool-based manufacturing supply chains.

4.4. Comparison of the three cases

In the case of GE's fuel injector, AM is used for the production of a final part. The change from conventional manufacturing to AM reduced SKUs, the number of processes, and work-in-progress stocks. This reduction is the result of subassemblies consolidation into a single component, enabling a significant potential reduction in supply chain complexity. Moreover, the use of AM in this case eliminated storage cost for tooling while extending the product life cycle. All in all, in the fuel injector case, the simplification mechanism of AM is in parts consolidation and process elimination.

The second case is the sourcing of a production tool by ABB where the AM allows for the production of conformal cooling in one go. The difference between this case and the other two is that the AM-produced component is not a final part but a tool insert for injection moulding. The tool insert produced in this case takes advantage of AM design for performance since AM enables manufacturing of complex geometries. The resulting AM mould significantly accelerated the cycle time of production and improved productivity of the injection moulding.

The main difference of the third case, which involves the manufacturing of action figures via Launzer, compared with other cases is the fact that the action figures are the final products of the supply chain and not a part of another larger subassembly. The value of AM in this case is related to the customization of items, which was not the case in GE fuel injector and ABB cable grommet cases where AM replaced a conventional manufacturing method for the production of specific standard parts.

5. Discussion

AM is currently in the forefront as various industries try to find applications for its capabilities without exposing themselves to its shortcomings [14], [26]. AM has been initially used for prototyping. However, as production quality and available material range have improved, this method is more and more adopted for parts, which are integrated into the final products [9], [11]. Awareness of managers regarding this novel production technology is therefore necessary.

To categorise various firms based on AM's implication on their supply chain complexity, further examination of several other cases is necessary. We consequently propose three other interesting cases that can be investigated. The first case is Bugatti's brake callipers. Conventional manufacturing for Bugatti brake callipers includes milling and forging techniques, which can lead to less efficient, large, and heavy callipers that hamper perfect ride and handling. For this reason, Bugatti [5] developed a 3D-printed titanium component that is stronger and that reduces the weight of the Chiron's brake callipers by 40%.

The second case is the Phonak hearing aids production. Before AM, all the shells for the hearing aids were handcrafted to fit each customer's ear, and this process did not always result in accurate products. With AM, Phonak [18] is able to produce hearing aids faster and more accurately than before. In case of product failure, AM allows the creation of a replacement without having to start the process all over from the beginning.

Finally, the third case is Croft Filters' metal 3D-printed filters. This company [6] previously utilised conventional manufacturing processes, such as punching, turning, and cutting. By utilizing AM, Croft Filters is able to manufacture structurally stronger filters with an improved design faster and at a reasonable cost.

6. Conclusions

In this study, we aim to examine the impact of AM on supply chain complexity. To achieve this goal, we utilised case studies and expert analysis. Before conducting case analysis, the term supply chain was defined, and drivers of complexity in the supply chain were identified.

In the next step, utilizing the literature, a supply chain complexity index (SCCI) is formulated. For the comparison between AM and conventional manufacturing supply chains, we introduce supply chain complexity ratio (SCCR) based on SCCI. Consequently, the analysis of three real-world cases is performed. Cases are selected to cover a range of production methods (i.e. AM) and complexity issues.

The results of the first case study (i.e. GE's use of AM for jet engine fuel injectors) shows that AM can reduce overall supply chain complexity through parts consolidation. AM proved to be efficient in reducing supply chain complexity for component designs that can be consolidated.

In the second case (i.e. ABB's use of AM to produce cable grommet mould insert), the company achieved a higher throughput in the injection moulding process through conformal cooling in the additively manufactured tool.

The third case (i.e. Launzer's production of action figures) has a unique AM-enabled business model for the manufacturing of customised items. In this case, AM reduced supply chain complexity for specific circumstances and shortened manufacturing lead time through a toolless process.

The main contribution of this article to the literature is the examination of the common belief that AM simplifies the supply chain. Our study illustrates that the introduction of AM to the supply chain can lead to varied outcomes –more complexity, less complexity, or no change in the complexity of the supply chain. The managerial contributions and implications of this article are as follows: When utilizing AM for production, it is important to understand that this technology does not necessarily lead to simpler supply chains. Generalization of outcome is therefore not appropriate; outcome should be evaluated on a case-by-case basis.

For future research, we suggest collecting more data from additional cases to fully verify the results of this research and to determine the mechanism within which AM can impact supply chain complexity.

7. References

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