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Citation for the original published paper (version of record):

Ahlsell, L., Jalal, D., Khajavi, S. et al (2023). Additive Manufacturing of Slow-Moving Automotive Spare Parts: A Supply Chain Cost Assessment. Journal of Manufacturing and Materials Processing, 7(1). http://dx.doi.org/10.3390/jmmp7010008

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Journal of
Manufacturing and Materials Processing

Article

Additive Manufacturing of Slow-Moving Automotive Spare Parts: A Supply Chain Cost Assessment

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Abstract: This study develops a cost model for the additive manufacturing (AM)-produced spare parts supply chain in the automotive industry. Moreover, we evaluate the economic feasibility of AM for slow-moving automotive spare parts by comparing the costs of the traditional manufacturing (TM) spare parts supply chain (SPSC) with centralized, outsourced AM SPSC. Data from a multiple case study of an OEM in the automotive industry regarding SPSC is utilized. The supply chain costs of 14 individual spare parts were analyzed, and the total SPSC cost for the AM and TM, were compared. Three of the fourteen parts showed potential for cost-savings, if they were produced with AM instead of TM. In this context, AM polymer parts showed greater potential than metal to replace TM as the more economical option of manufacturing from a total supply chain cost perspective. This study shows that the AM competitiveness to TM, from a financial perspective, increases for spare parts with low demand, high minimum order quantity, and high TM production price. The SPSC cost model included: cost of production, transport, warehousing, and service costs. This study contributes to the emerging field of part identification for AM and the existing literature regarding cost modeling in SPSCs.

Keywords: additive manufacturing; spare parts supply chain; cost assessment; automotive industry; slow-moving spare parts; part identification for AM

Citation: Ahlsell, L.; Jalal, D.; Khajavi, S.H.; Jonsson, P.; Holmström, J. Additive Manufacturing of Slow-Moving Automotive Spare Parts: A Supply Chain Cost Assessment. *J. Manuf. Mater. Process.* **2023**, *7*, 8. https://doi.org/10.3390/jmmp7010008

Academic Editor: Sebastian Thiede

Received: 30 October 2022
Revised: 19 December 2022
Accepted: 23 December 2022
Published: 28 December 2022

1. Introduction

After-sales services are highly profitable and, on average, services make up a significant percentage of a company's total revenue [1]. Furthermore, providing aftermarket services has become a unique selling point for companies in the aerospace and heavy vehicle industries because of long product life cycles. However, few actors have managed to successfully overcome the challenges when shifting from providing product value to customer value [1].

In the aftermarket, an original equipment manufacturer (OEM) needs to provide spare parts for goods currently and previously sold [2]. Activities in the aftermarket include forecasting demand, warehousing, and distribution of spare parts [1]. Spare parts must be provided for many years after finalizing the production of the vehicle [2]. Whilst different generations also have distinct parts, the OEM needs to be able to provide multiple times more stock keeping units (SKUs) in the aftermarket than during the manufacturing of the products. Moreover, parts need to be distributed to more locations in the aftermarket. Another challenge in the aftermarket lies within difficulties in forecasting the demand for spare parts due to stochastic product-breakdowns [2]. This creates long-tail spare parts, which in turn has increased the demand for consumer-adapted low-volume products [3]. Some of these obstacles could, according to Khajavi et al. [4], be overcome by a transition to additive manufacturing (AM).

AM is a manufacturing method that has received increasing attention, as the field of application has increased in line with the progression of the technology [5]. AM produces products based on 3D computer aided-design (CAD) model and the production process is handled by a computer program [5,6]. AM offers several benefits compared to traditional manufacturing (TM) such as shorter lead time and availability on-demand, and thus increased potential for higher customer satisfaction, flexibility, and shorter downtime [4,6]. Per part production cost of high-volume parts with AM could be several times more expensive than producing via TM if the design is not changed or optimized for AM [7]. However, when comparing the costs of TM and AM, many companies neglect the total cost of TM, consisting of manufacturing and supply chain costs [8]. AM offers new ways to distribute products and lowering the holding cost of locked capital [9]. Due to the complexity of the cost structure when comparing AM and TM, there is a need to fully and comprehensively understand and calculate the production and supply chain cost components of AM-produced spare parts.

This paper aims to evaluate and determine which spare parts can be switched from manufacturing via TM to AM from a financial viewpoint. This is performed through an understanding and comparison of costs in the supply chain for AM and TM. Therefore, the following two research questions are derived:

RQ 1: What are the supply chain cost components in the production of automotive spare parts with additive manufacturing?

RQ 2: How does the total supply chain cost differ between additive manufacturing and traditional manufacturing when producing automotive spare parts?

Rogers et al. [6] argue for a need for more research on the effects of AM on supply chains and Khajavi et al. [4] argue that research should be continued within the effects on supply chains by AM in non-military operations such as the automotive industry. Hence, this research adds to the existing literature within AM and supply chain cost evaluation, as well as supply chain modeling streams of research.

2. Literature Review

2.1. Aftersales and Spare Parts Supply Chain

Aftermarket services are highly profitable and constitute, on average, 25% of a company's total revenue [1]. However, operating a successful spare parts supply chain is challenging due to the stochastic nature of the problem and the requirement to align various functions to provide the right part to the right place with necessary skillful labor to perform the maintenance according to the principles of lean manufacturing [2]. Supply chain management aims to balance supply and demand [10].

According to Houtum et al. [11], if an OEM offers a service contract where they are responsible for the customer's downtime, they will then need to manage a spare parts network. The network is often divided into central- and local-warehouses and, usually, there are fewer central warehouses than local ones. If demand occurs at the installed base (customer site) then optimally, the demand is fulfilled by the assigned local warehouse. Should the local warehouse be out-of-stock of the requested SKU, then a backorder is created, and the central warehouse is responsible for providing the parts to the local warehouse. However, should the matter be urgent, for example, if there is a risk of costly downtime, then an emergency shipment or a lateral transshipment can be made. An emergency shipment is when the parts are sent directly to the customers-site from the central warehouse, whilst lateral transshipments are when the parts are provided from another local warehouse than the installed base is originally assigned to [11].

However, in the SPSC, the demand for certain spare parts can be unpredictable [2] as well as low and sporadic [12]. Considering economies of scale for traditionally manufactured products and the small demand for spare parts, this can lead to either high unit prices or large quantities of stored goods due to high minimum order quantities (MOQ) [12]. However, repair and maintenance of products are closely related to the actual availability of spare parts as the demand occurs [4]. Thus, the challenge lies in providing a high service level cost-efficiently, for difficult-to-forecast products with high downtime costs [13,14]. Moreover, a major challenge with providing aftermarket services is the number of SKUs that need to be provided is 15–20 times more than for manufacturing [2]. Subsequently, firms delivering spare parts must invest heavily in their SPSC operations. This investment can take the form of large inventory levels on multiple locations, which can lead to increased warehousing, obsolescence- and capital-costs for long-tail slow-moving spare parts [4].

The automotive industry adds additional complexities to SPSC management [15]. According to European Union law, OEMs in the automotive industry need to provide spare parts for consumers for a minimum of 15 years after original production ends [16]. These spare parts will need to meet the same technical and functional quality parameters as the originally manufactured parts. In addition, the automotive industry is often characterized by a diversity of models, a large number of spare parts as well as shortening product life cycles [15]. Further, maintaining a high service level is essential for the automotive industry in order to secure vehicle up-time for the customer [17]. Neglecting the customers' needs could damage the profitable relationship the aftermarket provides [17].

Safety stock is needed to prevent stock-outs and offer a high service level to customers [18]. However, increased safety stock also means increased inventory carrying cost [19] through increased capital costs, storage space cost, and obsolescence cost [20]. There is a trade-off between service level and safety stock, i.e., inventory carrying cost. In addition, it can be noted that the relationship is exponential and not linear. This means approaching a 100% service level requires incrementally greater increases in safety stock and, consequently, inventory carrying cost.

MOQ is a constraint that could make the ordered quantity deviate from the financial-optimal order quantity. According to Park and Klabjan [21], MOQ is the imposed minimum quantity required to be purchased from a supplier. Furthermore, the authors argue that an MOQ is set by the supplier in order to achieve economies of scale in operations throughout their value chain.

2.2. Additive Manufacturing

AM is a production technology that, in contrast to subtractive manufacturing, produces a product by adding two-dimensional layers on top of one another to achieve a three-dimensional object [5]. AM can utilize materials such as ceramics, metals, and polymers while not demanding any tooling or adaption from object to object which has led to widespread adoption in small volumes, high customization industries such as medical [22], consumer goods [23] and aerospace/military [4,24]. According to Eyers [25], AM enables customization by providing a more flexible production. Therefore, AM has potential in the automotive industry, where customization is important for OEMs to attract final customers [25].

The first commercially viable AM technology was stereolithography which was developed in 1987 [26]. Since then, many new technologies have emerged and the usage has shifted from mainly developing prototypes, to actually producing products [5]. While AM is characterized as a rapid manufacturing method, AM contains multiple steps. Depending on the object and the usage of the object the steps might differ [5].

AM offers several benefits compared to TM, such as shorter lead time. While the speed of production is quite average for AM, the speed of the entire chain of production increases due to the lack of, e.g., tooling and set-up time [6]. AM also offers greater flexibility and possibilities for customer adoption in comparison with TM due to being a digital design-based process [4–6]. Therefore, AM could potentially be used to reduce downtime cost [13,14]. Further, AM provides a quick digitalized product development process [5]. All steps are digitalized, and the actual building takes place in one step indifferent from the complexity of the object due to the layer-based process, whereas for TM, multiple stages of construction are often needed and increasing as the geometrical complexity increases [5].

According to Holmström et al. [27], with AM it is financially feasible to produce smaller batches. Hence, AM could have potential addressing long-tail slow-moving spare parts [4], as these have a lower demand, and consequently require smaller batch sizes if high inventory levels are to be avoided. According to Holmström et al. [28], the cost of a part not being used, obsolescence cost, could arise from lack of demand. This becomes prominent for parts in the phase-out stage, and a risk AM could potentially mitigate through on-demand production [28]. In conjunction with Khajavi et al. [4] and Holmström et al. [28], AM has the potential to produce slow-moving spare parts in the end-of-life phase. Heinen et al. [29] found 8% of a company's SKUs in their aftermarket portfolio could be produced through AM instead of TM from a financial viewpoint. This was according to the authors, driven by high MOQs for TM, high fixed cost for TM, and low demand.

Two different approaches for the deployment of AM in SPSCs are suggested, the first one being centralized, and is referred to as locating the AM machines in the central inventory. The second approach, decentralized AM SPSC, is to have the AM production further down in the supply chain, i.e., closer to the customer [27]. AM can be introduced for slow-moving spare parts that are not urgently needed in the centralized supply chain, which leads to a reduction in inventory holding costs. Further, a decentralized structure would also reduce the downtime by being located closer to the customer and thereby enabling a faster provision of spare parts [27].

Liu et al. [30] investigated a case study of implementing AM in an aircraft SPSC. Consequence analyses of safety inventory levels are made for three different scenarios; The authors concluded that a centralized AM SPSC would be most beneficial for parts with low average demand and high fluctuation. Whereas a distributed AM SPSC would be more favorable for parts with high demand.

According to Chan et al. [31], the greatest barrier for deploying AM is the manufacturing cost. Furthermore, the quality of additive manufactured parts is also a well-documented limit of the technology [25], as well as a lack of materials to print parts with [32]. Lastly, Salmi et al. [33] recognize the lack of CAD files as one of the six largest barriers to print parts.

2.3. Cost Models of Additive Manufacturing Deployment in SPSC

Considering the total supply chain cost and not only the purchasing price is important to stay competitive [34]. According to Van Weele [35], purchasing costs are constituting between 60 to 80% of the cost of goods sold in the automotive industry. However, other cost components exist in the supply chain and should be considered when developing a supply chain cost model. The replacement of TM with AM will affect areas such as batch sizing and inventory management [36]. This would imply changes in the structure and the cost components in the supply chain. Hence, there is a need to investigate AM cost models in previous research. This section will therefore address previous literature on AM SPSC cost models and how to assign overhead costs.

In a study by Khajavi et al. [4], a supply chain cost model is used to quantify and compare the cost of providing AM spare parts for an F-18 Super Hornet in various scenarios. The model used in their study consisted of eight cost components and can be found in Table 1. Further, they studied two different supply chain structures, centralized and decentralized. In a later study, a hub configuration was included as a structure and the same supply chain cost model was used [37]. Thus, the cost-structure from Khajavi et al. [4] can be applied to various structures and not limited to only one.

According to Holmström et al. [27], the following cost components should be considered when deploying AM in an SPSC: manufacturing cost (material and production cost), distribution cost, inventory obsolescence cost, and the customer's life cycle cost, i.e., downtime cost. In this context, Holmström et al. [27] further describe three trade-offs that need to be considered, these being: centralized vs. decentralized AM SPSC-structure, mass-production vs. on-demand production, and general vs. specialized manufacturing. The same authors state that decisions regarding these three trade-offs will impact the previously mentioned cost components. They argue that in circumstances where there is a high risk for large obsolescence costs, introducing AM for an on-demand production would be advantageous since AM is decoupled from the length of production runs.

Khajavi et al. [4] assert that deploying a decentralized AM SPSC becomes particularly interesting in industries characterized by urgent downtimes. A general-purpose technology has, in contrast to a specialized technology, an impact on various activities in several industries [38]. Holmström et al. [39] argue for AM being a potential general-purpose technology through its ability to produce objects using digital models without being constrained by the lot size. According to Holmström et al. [27], general AM enables pooling of parts, which would consequently lead to cost-savings in inventory holding through a reduction in physical inventory. Currently, airlines are pooling spare parts between them. However, deploying general AM could increase the pooling capacity of manufacturing spare parts between airlines, but also other industries [27]. Thus, an AM service provider of this type could therefore provide spare parts for aircraft, generator turbines, and similar equipment [27].

Table 1. AM SPSC cost models.

Article	The Model Composition	Differences with This Paper
Khajavi et al. [4]	• Manufacturing cost (including personnel cost, material cost and depreciation cost from the AM machine) • Transportation cost • Inventory carrying cost • Aircraft downtime cost • Inventory obsolescence cost • Annualized cost of producing initial inventory	Case study in aviation without perspectives on long-tail slow-moving spare parts.
Li et al. [13]	• Transport cost • Manufacturing cost • Inventory cost • Administrative cost	Case study in aviation with no perspectives on long-tail slow-moving spare parts.
Holmström et al. [27]	• Manufacturing cost (including material, and production cost) • Distribution cost • Inventory obsolescence cost • Life cycle cost, i.e., downtime cost	A conceptual cost model in aviation without perspectives on long-tail slow-moving spare parts.
Thomas [40]	• Material inventory cost • AM machine-related costs • Finished goods inventory cost • Wholesale trade cost • Retail trade cost • Transportation cost	A conceptual cost model in automotive without perspectives on long-tail slow-moving spare parts.
Alogla et al. [41]	• Volume flexibility • Mix flexibility • Delivery flexibility	This research is not focused on the spare parts supply chain cost modeling. A case study of plastic pipe fitting is used.

In a case study by Li et al. [13], an SPSC cost model is adopted to compare the cost of providing spare parts through AM and TM. This cost model consists of four components. Thomas [40], with a supply chain perspective, composes a cost model for AM and CM but the model is generic and conceptual without taking into account the implication of producing long-tail slow-moving spare parts with AM. Alogla et al. [41] proposed a flexibility model for AM supply chain where they presented a cost model for AM parts; however, their work is only focused on the value of supply chain flexibility and does not study spare parts supply chain cost models. The supply chain cost models in

Khajavi et al. [4], Li et al. [13], Holmström et al. [27], Thomas [40], and Alogla et al. [41] are presented in Table 1.

Comparing the five supply chain cost models presented in Table 1, it can be recognized four out of five models include manufacturing and inventory cost. The model from Li et al. (2017), Thomas [40], and Alogla et al. [41] do not consider inventory obsolescence and downtime cost, which Khajavi et al. [4] and Holmström et al. [27] do. Li et al. [13] is, however, the only model considering the administrative cost.

In Knofius et al. [42], a top-down approach is used to identify potential articles to be produced through AM. The approach deploys three goals; secure supply, reduce downtime and reduce costs. In the case study by Knofius et al. [42], securing supply is measured as a probability for a spare parts supplier being available within one year. This is an element not implicitly considered in the cost models by Khajavi et al. [4] and Li et al. [13]. Hence, Knofius et al. [42] contribute with securing supply as a cost component that is required to be considered when deploying AM in a SPSC. Because, if the supply for spare parts is not secured, then a cost of missing sales would consequently occur.

2.4. Gap in the Literature

Some studies have investigated the production costs of AM, such as Atzeni and Salmi [43], Hopkinson and Dicknes [44], Lindemann et al. [45], Ruffo et al. [46] and Thomas and Gilbert [47]. However, none of these studies considered a supply chain perspective of AM, something that was conducted by Khajavi et al. [4,37]. However, these studies were addressing the structure and quantifying AM SPSC costs rather than comparing the cost of AM to TM SPSC. This was carried out by Li et al. [13], but the cost structure they developed only contained the following cost elements: transport cost, manufacturing cost, inventory cost, and administrative cost. This case study research intends to discover the necessary cost elements to realistically capture and compare the total spare parts supply chain cost with AM and TM and to create a more comprehensive cost model for automotive slow-moving SPSC. A conceptual study of the SPSC in the automotive industry with outsourced AM was performed by Meboldt and Klahn [48]; however, they did not present any real-life cases and quantification of the cost components are missing. Thus, this research aims to address this by quantifying and investigating the supply chain costs for slow-moving spare parts in the automotive industry for AM and TM, using a number of cases chosen in collaboration with a well-known European automotive manufacturer. Knofius et al. [49], developed an approach for dual sourcing (AM-TM) based on an aviation case study. Their method improved the cost 30% compared to any single sourcing scheme. In their paper, they considered changes in reliability, unit costs, and lead times while keeping the spare parts configuration unchanged. However, they fell short of examining the dual sourcing for “last-time order” items or for the vastly different automotive industry. Moreover, in this research we compared the AM and TM SPSC costs for both metal and plastic parts.

3. Methodology

3.1. Case Study

This article deploys a multi-case study scenario analysis approach and the data from an OEM in the automotive industry regarding SPSC is utilized [50]. The data used in this research is both qualitative and quantitative. Qualitative data is collected in the form of interviews to develop the structure of the SPSC cost model. Thereafter, the model was tested and validated with quantitative data.

The aim of the study is to quantify and compare the supply chain costs for AM and TM for long-tail automotive spare parts. A planning report was initially made to derive the scope of the paper. The planning report was used to create alignment between various stakeholders including the OEM. Moreover, to achieve the aim of the study, the research questions have been designed to firstly map the cost components in the SPSC, and secondly to quantify them using either TM or AM as a production method. To answer the research questions the following actions were performed (Figure 1);

i. The planning report was created to align various stakeholders. In addition, an initial literature review of the current research streams and previous case studies of SPSC cost models was conducted. Cost models from prior research were used to lay the foundation of the cost model, with amendments during interviews. The supply chain cost models by Khajavi et al. [4], Li et al. [13] and Holmström et al. [27] were used as the basis of the model. Case studies were used to describe the warehousing costs.
ii. An SPSC cost model for AM and TM spare part operations was developed. This was conducted by interviewing stakeholders at the OEM. From the interviews, a map of the supply chain value flows for TM was constructed. The TM SPSC value flow was then amended to resemble the AM production flow.
iii. The created cost model was compared with the literature, and was verified with the OEM to resemble the actual SPSC and its inherent characteristics.
iv. Fourteen spare parts for TM and AM were selected and the data was collected to calculate their supply chain costs. The selection of parts was carried out by assessing them from a financial and technical perspective. This was conducted by accessing databases, tools, and data sheets gathered from the interviewees. Interview and data gathering was with an AM supplier.
v. After the calculation of the costs and comparison of different scenarios, analysis of the findings was performed.

Figure 1. Research process.

3.2. Data Collection

The collected data in this study consisted of interviews and accessing company-specific databases (Appendix A). To situate the study in a relevant field and to align with previous research, a literature study was commenced. To gather the case-specific details of AM and TM at the OEM, interviews were held with stakeholders in various business functions that were responsible for AM and TM cost drivers.

Data was gathered from databases, programs, and data sheets used internally at the OEM. In total, nineteen interviews were held, with eighteen different people from various functions. These functions included: Technology, Aftermarket, Operations, Purchasing, Logistics, and an external AM supplier. Interviews were held until no new data was obtained by additional interviews, described as theoretical saturation by Bryman and Bell [51]. All interviews have been voluntary, anonymous, and confidential. Further, the business methods and competitive resources of the studied OEM will remain undisclosed.

The studied OEM has several business units within the automotive industry, serving around 200 markets. Only one of these business units is examined in this research. However, the SPSC is shared with the other business units. Therefore, the model developed in this research could be extended to their spare part portfolios as well.

3.3. Part Information and Pre-Screening Process

In total, fourteen spare parts from the OEM's product portfolio were examined by the SPSC cost model developed in this research. To derive these fourteen parts, a pre-screening process was conducted from both financial and technical perspectives. More details about the parts pre-screening process can be found in Appendix B. The pre-screening process aimed to derive spare parts with a high likelihood of showing positive business cases for AM. In Table 2, the chosen spare parts and their characteristics are presented. In total, four parts were made out of polymer (P). Ten parts were made out of metal (M), including five steel parts, three spheroidal graphite iron parts, and two aluminum parts.

Table 2. Description of the fourteen spare parts researched in this research.

Item No.	Name	Material	Weight [Grams]	Volume [cm^3]	Annual Demand	MOQ
P1	PROTECTING COVER	Polymer	150	92.73	23	500
P2	TAPPET	Polymer	407	433.26	6	50
P3	A-PILLAR	Polymer	193	157.13	6	243
P4	SWITCH PANEL	Polymer	52	44.97	29	192
M1	SPACER	Aluminum	410	155.07	2	95
M2	HUB	Steel	1310	164.66	3	100
M3	BRACKET	Steel	2015	264.4	3	60
M4	INTERMEDIATE SECTION	Graphite Iron	696	96.09	6	100
M5	HOLLOW DRIFT	Steel	1600	198.22	4	50
M6	CUP	Steel	2900	366.01	16	150
M7	BRACKET	Graphite Iron	1650	175.04	17	100
M8	BRACKET	Steel	117	15	32	170
M9	ATTACHING PLATE	Graphite Iron	1868	265.12	5	54
M10	CONNECTOR	Aluminum	81	28.45	9	60

3.4. The OEM's Spare Parts Supply Chain

The OEM's current supply chain in the aftermarket is formed by Regional Distribution Centers (RDC), Central Distribution Centers (CDC), Support Distribution Centers (SDC), and Dealer Warehouses. The Dealer Warehouse can be owned by either the OEM or by a third party. The CDC's are the main warehouses and spread out on three continents, Europe, North America, and South America. From these CDC's, more frequently ordered parts are sent out to SDC's and RDC's, which are spread out across the globe, in close proximity to numerous dealers and customers. When moving down in the supply chain, from CDC's to SDC's and RDC's, the assortment becomes narrower and locally adapted.

The OEM has the following four alternatives to utilize AM in their SPSC:

I In-house centralized SPSC
II In-house decentralized SPSC
III Outsourced centralized SPSC
IV Outsourced decentralized SPSC

This paper studies the third option, outsourced centralized SPSC, as the OEM has expressed that their maturity within AM technology is low, and that option III would be the least risky option from a financial perspective.

4. Results

4.1. AM and TM Cost Components of the OEM's SPSC

The total cost of the supply chain for long-tail spare parts was revealed by mapping various cost drivers throughout the journey from production to ultimately customer delivery and use.

To answer the RQ1, we formulate the SPSC total cost model that is presented below.

$$\begin{aligned}\textbf{\textit{Total SPSC Costs}} \\ &= Production + Inbound\ transport + Warehousing \\ &+ Outbound\ transport + Service\end{aligned}$$

The identified cost components were retrieved from our interviews and is explained in this section.

4.1.1. Cost of Production

Cost of production will, in this research, solely refer to the cost of buying the spare parts from an AM- or TM-supplier, i.e., the production is outsourced and should not be confused with in-house production. Thus, the production cost refers to the invoice price received by the supplier, excluding all types of administration and logistical costs.

For TM, the unit production cost was retrieved from one of the OEM's databases. Some minor calculations were required to derive the cost of production, as the data was originally stated in the standard price. To derive the total production cost, the unit price was multiplied with the LOQ (last ordered quantity). All researched parts were procured from external suppliers, and not produced in-house. The model assumes the tooling cost for TM to be incorporated into the part's invoice price.

For the AM, the production price was derived by sending inquiries to an AM supplier. Two assumptions have been made to derive this data. Firstly, the model is not considering the cost of developing the 3D-drawing if the drawing is missing or if adjustments are required before it can be printed. Secondly, the cost associated with conducting quality controls to approve a spare part has been excluded from the model.

4.1.2. Cost of Inbound Transport

The transport cost from the supplier to Europe CDC for TM was derived by multiplying the historic average shipment cost per kilo from the given supplier to the Europe CDC, times the weight of the shipment. The historic shipment cost is used currently at the OEM and is based on invoices from freight forwarders, divided by the total weight shipped. The weight of the shipment was calculated by multiplying the weight of the article times the LOQ.

For AM, the location of the supplier, and thus the inbound transport cost would be unclear. Thus, the average transport cost per kilo for all the analyzed parts was used and multiplied with the weight and quantity produced with AM.

The OEM is usually obligated to make a payment to a supplier within 90 days after the invoice has been received. In this study, it is assumed the inbound transport has ended before these 90 days, and therefore capital costs are excluded in this step of the supply chain.

4.1.3. Cost of Warehousing

To estimate the cost for storing articles in the Europe CDC, a previous case study is used as support in this research. The case study was made in 2018 by the OEM's Footprint Design team and referred to as the Cost to Serve Simulation Tool.

In this study, the Footprint Design team conducted an ABC analysis, where they started with identifying cost components in the warehouse. Thereafter, they assigned cost drivers to each component and divided the total cost for each component with its respective cost driver. For example, one identified cost component was "Goods in", which refers to the activity of transporting the goods from the truck to the location in the warehouse. The driver for this activity is the number of received lines in the Europe CDC. The total cost for transporting goods inside the warehouse during a year was divided by the numbers of received lines during a year in the Europe CDC to quantify the cost driver. The warehousing cost components formula is as follows;

$$\begin{aligned} \boldsymbol{Warehousing} &= Goods\ in + Capital\ costs + Packaging + Procurement \\ &+ Warehouse\ overhead + Order\ office \\ &+ Warehouse\ building + Development \end{aligned}$$

The cost sub-components of warehousing with their respective cost driver, along with a description, can be viewed in Table 3.

Table 3. Cost sub-components of warehousing.

Cost Sub-Component	Factor and Cost Driver	Description
Goods in	# of SEK (Swedish krona) × # of received lines * during the year. [SEK/received delivery]	Cost for handling and transporting goods from the truck to the location inside the warehouse, e.g., labor cost and forklift cost.
Capital costs	# % of the stock value at the beginning of the year. Percentage value based on Internal Rate of Return. [SEK/inventory value ***]	Alternative cost for the capital not being invested in other lucrative businesses and thereby generate positive cash flow to the OEM.
Packaging	# % of the annual turnover. [SEK/turnover value ****]	Cost for packing the goods before sending them to the dealer.
Goods out	# of SEK × # of order lines ** during the year. [SEK/order line]	Cost for handling and transporting goods from the location inside the warehouse to the truck, e.g., labor cost and forklift cost.
Procurement	# of SEK × # of received lines during the year. [SEK/received delivery]	Personal cost for maintaining the relationship with the supplier.
Warehouse overhead cost	# of % of annual turnover. [SEK/turnover value]	Salaries for managers running the warehouse.
Order office	# of SEK × # of order lines during the year. [SEK/order line]	Personal cost for administering the orders made by the dealers.
Warehouse building	# of SEK × average weight stored in the warehouse during the year. [SEK/Kg]	Cost for storing goods in the warehouse.
Development	# of % of annual turnover. [SEK/turnover value]	Personal cost for developing the service market logistics.

* Number (#) of received lines, Number of times an article arrives at the European CDC. Not dependent on the quantity. ** Number (#) of order lines, Number of times an article is shipped to the customer from the European CDC. Not dependent on the quantity. *** Inventory value, refers to the value of an SKU in-stock. Calculated by multiplying the invoice price of the component by the average inventory level. **** Turnover value, refers to the revenue a certain SKU has during a year. This is calculated by multiplying the invoice price with the demand per year. Thus, it does not consider the profit margin and, therefore, the turnover value is not fully accurate.

In this research, some cost drivers are multiplied with a factor to allocate the cost of storing an article in the warehouse. Continuing on the example of "Goods in", the number of annually received lines for a particular article is the factor multiplied with the cost driver, # of SEK. By doing so, the annual cost for "Goods in" of a particular SKU is quantified.

One limitation in the modeling concerning Europe CDC is the absence of scrapping cost, where obsolete parts are treated as waste and have to be, for example, sent to a recycling center. For AM this cost will be quite small since the safety stock is set to one (see Inventory control for additive manufacturing in Results Section for explanation). For TM this cost could be quite high since all remaining parts must be scrapped when the article is eventually phased out.

4.1.4. Inventory Control

This section will describe the modeling regarding inventory management. More specifically, this section will address how the inventory level is measured, replenishments, safety stock, service levels, and planning horizon. Since there are differences between how the inventory is handled between TM and AM, the section has been divided into these two manufacturing methods. A comparison of the inventory control between AM and TM is provided in Table 4.

Table 4. Comparison between inventory control of TM and AM in the model.

Area	TM	AM
Replenishment	One received shipment for the whole planning horizon	Annual Replenishments
Safety stock	Safety stock equivalent to where service level is equal to target service level.	Safety stock set to one pc.
Service level	Probability for average inventory level to be greater than average yearly demand, changing between years.	SERV1, constant for all years
Average inventory level	(Inventory level at the beginning of the year + inventory of the next year)/2	Safety stock + (order quantity)/2

Inventory Control for Traditional Manufacturing

The inventory level for the TM scenario is based on the actual LOQ and subtracted by the demand per year. Hence, for TM, only one shipment is received during the whole research period and then, for every year that passes, the inventory level decreases with the annual demand. The demand per year is based on historical demand from the inventory database and it is assumed to be constant in the future. A delimitation in the model is therefore not using forecasted demand. The OEM conducts forecasts but for slow-moving spare parts, the forecasts are too inaccurate to use. In addition, only the upcoming year is forecasted and sometimes even missing due to the difficulty in forecasting intermittent demand. The OEM's forecast of demand has therefore not been incorporated into this model. The average inventory level for TM was computed by taking:

$$\frac{\begin{pmatrix} Inventory\ level\ at\ the\ beginning\ of\ year\ n+ \\ inventory\ at\ the\ beginning\ of\ year\ n+1 \end{pmatrix}}{2}$$

$where\ n\ \epsilon\ (1,\ 2,\ 3,\ \ldots 14)$

All spare parts used in this research have, according to the OEM's inventory database, a Poisson distributed demand with a specified target service level (measured in SERV1). As only one shipment was received for the entire period for TM, the service level was calculated on a yearly basis with the annual demand and average inventory level. The following function in Microsoft Excel was used:

$$POISSON.DIST(X, \lambda, TRUE),\ where\ X = Avg.\ inventory\ level\ for\ the\ year\ and\ \lambda \\ = annual\ average\ demand$$

The distribution was set to TRUE to derive the cumulative probability. Thus, this service level calculation expresses the probability of being able to provide the spare part for a given year.

Planning horizon refers to the number of years the OEM will provide the spare part in the model and, consequently, also the period investigated in the cases presented. The planning horizon used in this research starts from the date of LOQ for TM. Hence, this research studies the hypothetical outcome of what would have happened if the spare parts were in the past manufactured through AM rather than TM. This implies AM being as cost-efficient then, as now.

Furthermore, there are three restrictions terminating the planning horizon, where the first occurring restriction sets the end of the planning horizon:

- The Responsibility (Resp.) Year is set by the OEM internally and represents the planned final date of sales for a spare part.
- Max. value, the planning horizon cannot be longer than 15 years in the model. In reality, the OEM could provide spare parts for a longer time but are, according to regulations, only required to for 15 years after the end of production. This restriction was added to demarcate the model.
- SL < TSL, the year before the service level (SL) for TM falls below the target service level (TSL) as the TSL can be seen as a form of minimum safety stock level.

As such, TM's inventory level is one of the deciding factors of the length of the planning horizon. Further, in order to compare the cost of production between AM and TM, the planning horizon is set to be the same for both manufacturing methods. For the fourteen parts analyzed in this research, the Resp. date was setting the limit in eight cases, TM's SL in six cases, and the max. value was reached only once. Description of the fourteen parts planning horizon can be found in the Table 5.

Table 5. Planning horizon for the researched spare parts.

Item No.	Planning Horizon Years	Reason for Planning Horizon End
P1	15	Max. value
P2	7	SL < TSL
P3	11	Resp.
P4	5	S L< TSL
M1	14	Resp.
M2	4	Resp.
M3	9	Resp.
M4	6	Resp.
M5	7	Resp.
M6	7	Resp.
M7	4	SL < TSL
M8	4	SL < TSL
M9	9	SL < TSL
M10	5	SL < TSL

Inventory Control for Additive Manufacturing

In contrast with the TM scenario, the inventory level for the AM scenario is based on the demand per year and safety stock. In this scenario, replenishment is performed every year with an order quantity equal to the demand per year. Hence, the reordering point is set to the safety stock. The formula for calculating the average inventory level is thus [19]:

$$Average\ inventory = safety\ stock + \frac{order\ quantity}{2}$$

The safety stock for the AM scenario is based on the average demand during the lead time (SERV1), where the safety stock should give a service level higher than the TSL. The annual demand is no more than 40 (derived in the pre-screening process as shown in Appendix B), and the lead time for AM is assumed to be one week. Since there are 52 weeks in a year, the average demand during the lead time for AM will always be less than 1, since $40/52 < 1$. Therefore, a safety stock of one will yield a service level of more than 90% which is substantially higher than the TSL of 60%. Hence, a safety stock of one is chosen for all AM scenarios. Since the safety stock and the average demand during the lead time are constant for all years in the planning horizon, the service level for AM will be constant.

4.1.5. Cost of Outbound Transport

The outbound transport, meaning the transport from Europe CDC to the customer, was derived by taking a historic average cost, measured per kilogram transported, times the weight shipped. The historic average cost was, similar to inbound transportation, computed based on data from the freight forwarders. Rush costs are included in the cost per kilo from Europe CDC to a dealer. In this way, the outbound transport presents an average for the transport costs, either rushed or line transport. The cost used in the model was the average cost for all transports from Europe CDC to a European customer. The demand is set to be the same for the AM- and TM scenarios and thus also the outbound transport cost.

In addition, capital will be tied up during the time the goods are transported to the dealers. This, consequently, leads to a capital cost emerging in this stage of the supply chain. Assuming the goods will be in transit for one week and using the same logic as when computing the capital costs at CDC Europe, the capital costs during the outbound transport can be derived.

The total outbound transport cost is therefore the sum of the transportation and the capital costs during the time the goods are in transit.

4.1.6. Cost of Service

Cost of service follows the following formula;

$$\boldsymbol{Service} = Vehicle\ off\ road + Badwill + Cost\ of\ lost\ sales$$

Cost of Vehicle off Road

The OEM provides service contracts to their customers. More specifically, the company provides three types of contracts: gold contracts, silver contracts, and blue contracts. The contracts aim to increase customer loyalty by reducing the downtime of their customers' vehicles. Depending on the type of contract the customer holds, the OEM offers their customers various services such as preventive maintenance and repairs from wear and tear. The gold contract offers the highest level of service, thereafter silver and lastly blue. Customers holding a gold contract are assured of 100% uptime of their trucks by the OEM; this is referred to as the Uptime Promise.

The OEM categorizes backorders into regular, urgent, or emergency backorder. An emergency backorder is the most critical one and is referred to as VOR. A VOR occurs when a part of a truck breaks and makes the car unusable until the part is replaced. If a VOR occurs for a customer holding a gold contract, the OEM is obligated to:

- Offer a replacement truck if the truck is not repaired within the first four hours.
- If the OEM is not able to provide a replacement truck, the company is required to pay a VOR penalty fee. This penalty fee grows the longer the truck is out of use. Consequently, this makes the OEM keen on solving the VOR quickly which is carried out through a fast provision of spare parts.

The cost model developed in this research breaks down VOR cost into two cost components, VOR cost whilst having the SKU in stock and VOR cost when the SKU is out of stock. The sum of these two components adds up to the total cost of VOR. The reason why the VOR cost has been broken down into components is because the time required to solve a VOR will be different whether the SKU is in stock or not, and consequently, the penalty cost.

The formula for how the Total VOR cost is calculated:

$$Total\ VOR\ Cost = Cost\ for\ stockout\ VOR + Cost\ for\ stocked\ VOR$$

The cost for out of stock (stockout) VOR is calculated by taking:

$$\begin{aligned} & Cost\ for\ stockout\ VORs \\ & = Service\ loss \times share\ of\ VOR\ cases\ with\ Gold\ Contract \\ & \times number\ of\ VORs\ per\ SKU\ and\ year \\ & \times Avg.VOR\ penalty\ cost\ for\ stockout\ SKU\ (different\ for\ AM\ and\ TM) \end{aligned}$$

$$where\ the\ service\ loss = 1 - service\ leve$$

The cost for VORs that are stocked:

$$\begin{aligned} &Cost\ for\ stocked\ VORs \\ &\qquad = Service\ level \times share\ of\ VOR\ cases\ with\ Gold\ Contract \\ &\qquad \times number\ of\ VORs\ per\ SKU\ and\ year \\ &\qquad \times Avg.\ VOR\ penalty\ cost\ for\ stocked\ SKU\ (same\ for\ AM\ and\ TM) \end{aligned}$$

The following paragraph entails numbers that are sensitive to the operations of the OEM and is therefore anonymized. The duration of a VOR with stocked spare parts is, on average, X1 days for both AM and TM. This will lead to an average penalty cost of approximately Y1€ per VOR with parts in-stock. The average length of X1 days was derived by taking the median of 2019′s VOR length. The median was chosen instead of the average to give the outliers less influence. The lead time of a TM supplier is, according to the OEM's inventory database, so long that a VOR on a stockout item for the TM scenario will lead to the maximum fee of Y2 EUR charged. The lead time from an AM supplier is estimated to be around X2 days, which means the average penalty cost for VOR on stockout-parts will be Y3 EUR. In the estimation of the lead time from AM suppliers, the time required to conduct quality-checking's is excluded.

The risk of VOR is the same for the AM- and TM scenarios as the breakage of parts is independent of the manufacturing method of the spare part. However, the service levels will differ between the manufacturing methods.

Number of VORs for an SKU was derived by multiplying number of annual order lines for an article, times the probability of an order line being a VOR. The probability of an order line being a VOR was found by dividing the total number of recorded VORs in Europe for 2019 by the total number of order lines in Europe CDC during 2019. This is a rough estimation since orders in Europe are sent from RDCs and SDCs and not just Europe CDC.

It is unlikely for several SKUs, such as an ashtray, to cause a VOR. At the OEM, however, customers can report any spare part as a cause of a VOR. Therefore, all articles investigated in this research will be subject to VOR.

Cost of Badwill

The cost of badwill occurs when the OEM cannot provide a spare part to a customer due to stockout which leads to the OEM's brand getting damaged. This cost is calculated by taking the service loss, times the number of annual order lines of a certain part, to retrieve the number of lost orders per year. The badwill cost is calculated through:

$$\begin{gathered} Badwill\ cost = number\ of\ lost\ order\ per\ year \times badwill\ multiple \\ \times badwill\ cost\ per\ order\ line \end{gathered}$$

All spare parts at the OEM are assigned a Parameter Reference Set (PRS). The PRS provides information on the multiple and the badwill cost per order line. The badwill multiple is dependent on two other multiples, namely the life cycle and the brand. The life cycle ranges from initial to prime, decline, and phase-out, where the articles stage in the life cycle will impact differently on badwill if the spare part is not provided. At the OEM, the stages in the life cycle are segmented by Resp. year and the demand, where the demand is projected to, roughly, increase from initial to prime and thereafter decline as spare parts move through the decline and eventually the phase-out stage. The second multiple, brand, refers to some brands within the OEM being more exclusive than others and, consequently, having a higher multiple. Further, the badwill cost per order line is divided into three segments: critical, competitive, and default, which segments the criticality of the order.

Cost of Lost Sales

The cost of lost sales is based on the service loss and relates to all orders not being fulfilled due to stockout. The cost of lost sales is calculated through:

$$\begin{aligned} Cost\ of\ lost\ sales \\ &= Service\ loss \times annual\ profit\ for\ the\ SKU\ per\ year \\ &\times lost\ sales\ multiple \end{aligned}$$

The annual profit is derived by multiplying the standard price, times a profit margin, times the demand per year. Similar to the badwill multiple, the lost sales multiple depends on three multiples: the life cycle, the segment, and the brand. These multiples have the same structure and meaning as the corresponding badwill multiples but with different values. PRS is in this case also providing all data regarding multiples.

The rest of this section aims to answer RQ2. Therefore, the total AM and TM SPSC costs are presented, broken down to their components, and compared. For the OEM's sake, no absolute numbers are presented explicitly in this research. Further, some specific spare parts are highlighted and examined in more detail, as they present interesting business cases for AM.

4.2. Average Total Cost of Spare Parts Supply Chain

The fourteen studied spare parts were evaluated by the cost model and the result was clustered into the following four segments:

- Polymer parts produced with TM
- Polymer parts produced with AM
- Metal parts produced with TM
- Metal parts produced with AM

Figure 2 displays the average SPSC cost between the four segments. On average and for polymers and metals, the total cost increased by 19% and 1 756%, respectively, when switching from TM to AM. The total cost is being significantly impacted by the production and warehousing, whilst service and transport have a marginal influence on the total cost. For polymers, the production cost increased by 130%, whilst the non-production costs (service, transport, and warehousing) decreased by 70% when changing the production method from TM to AM. However, the cost-savings in non-production components are smaller than the increase in production cost. Consequently, this results in the total SPSC cost for polymers, on average, increasing by 19% when transitioning from TM to AM. As for metal parts, the production cost increased by 3224%, and the non-production components increased by 194% when changing the manufacturing method from TM to AM. This leads to AM being 1756% more expensive than TM from a total cost perspective.

AM's production price is based on the use of various AM-technologies. SLM is used to produce metal parts, whilst FDM, SLS, and indirect printing are technologies used to manufacture polymer spare parts. Indirect printing refers to using both AM- and TM-technology. The master pattern is manufactured through the AM method, stereolithography. The master is used to produce the mold, where the mold is used in the production of the spare parts. The mold and the parts are manufactured through the TM method, vacuum casting.

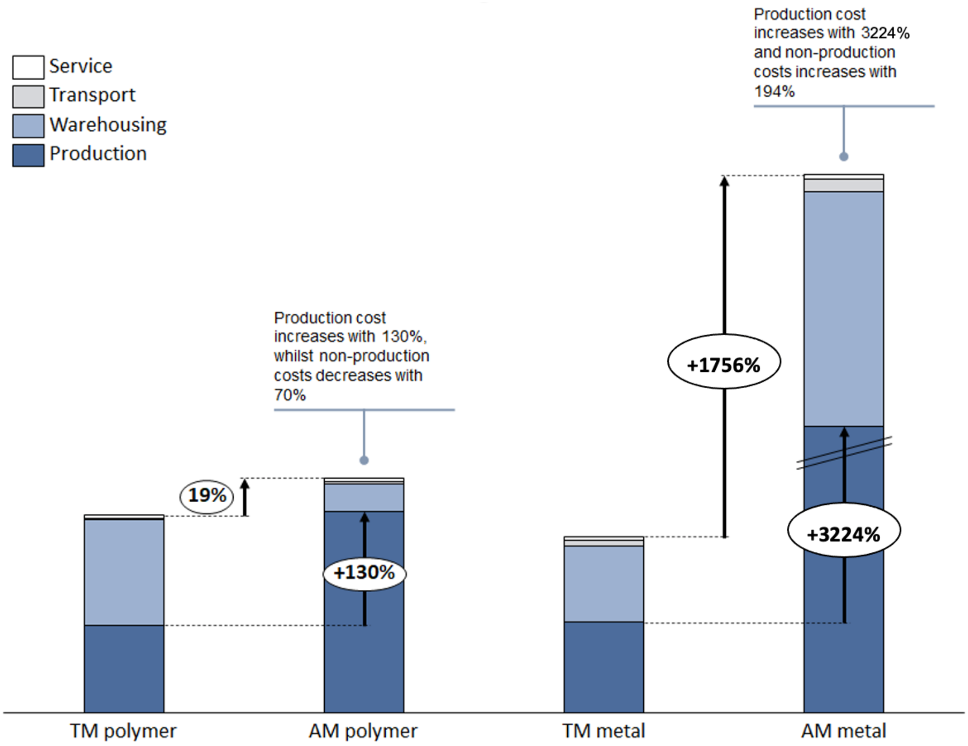

Figure 2. Relative average cost for the four segments.

4.3. Total Cost Analysis of SPSC for Individual Parts

The SPSC total cost for each individual part during the entire planning horizon can be viewed in Figure 3.

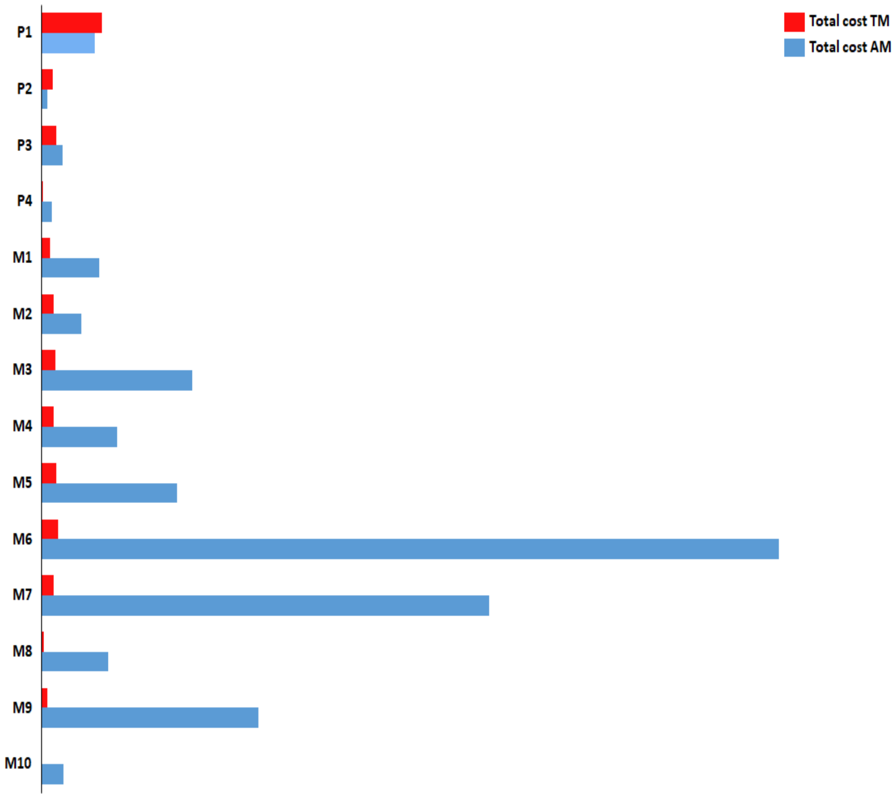

Figure 3. Comparison of total costs between AM and TM for individual spare parts.

The AM process technologies used for these 14 parts are presented in Table 6.

Table 6. The AM process technologies and raw material used for the 14 case study parts.

Item No.	Material	AM-Technology
P1	Polymer: Polyurethan	Indirect AM *
P2	Polymer: Thermoplastic	FDM
P3	Polymer: PA12	SLS
P4	Polymer: Polyurethan	Indirect AM *
M1	Metal: AlSiMg10	SLM
M2	Metal: SS316L	SLM
M3	Metal: SS316L	SLM
M4	Metal: SS316L	SLM
M5	Metal: SS316L	SLM
M6	Metal: SS316L	SLM
M7	Metal: SS316L	SLM
M8	Metal: SS316L	SLM
M9	Metal: SS316L	SLM
M10	Metal: AlSiMg10	SLM

* Indirect AM refers to the use of both AM- and TM-technology. The master pattern is manufactured through the AM method, stereolithography. The master is used to produce the mold, where the mold is used in the production of the spare parts. The mold and the parts are manufactured through the TM method, vacuum casting.

Although, on average, the total SPSC cost increases when deploying AM, feasible business cases have been identified. Three parts show some potential to be produced through AM from a financial perspective sometime during the planning horizon, these being P1, P2 and, P3. However, only P1 and P2 are less costly to be produced through AM considering the entire planning horizon. These three parts are all made out of polymers, where two of them are in their prime stage in the life cycle and one is in the phase-out stage. These three parts will be presented in further detail in this section.

4.3.1. P3—A-Pillar

P3, being in the phase-out stage of its lifecycle, is more expensive to produce with AM than with TM, as seen in Figure 4. The graph for AM accumulated SPSC costs is linear whilst the TM accumulated SPSC costs decline over time. The major cost component for AM is the production cost, hence, it will drive the total cost. Since a new order is also made every year in the AM scenario, the AM accumulated SPSC costs will therefore increase linearly over time. However, in the TM scenario, the warehousing cost constitutes a larger part of the total cost. In addition, since the inventory in the TM scenario is depleted successively after each year, the warehousing cost will decrease as well. Therefore, the TM accumulated SPSC costs curve gradually flattens out over time.

Figure 4. AM and TM accumulated SPSC costs for P3 over the eleven-year planning horizon.

The planning horizon was set to 11 years, limited by the Resp. date. However, the MOQ (243 pcs.) was quite high compared to the annual demand (six pcs.), this led to the first 5 years AM being indeed cheaper, but as time proceeded, it became more expensive. The cost of production for AM was roughly three times higher than for TM. The decreased warehousing costs could not make up for the increased production costs (Figure 5).

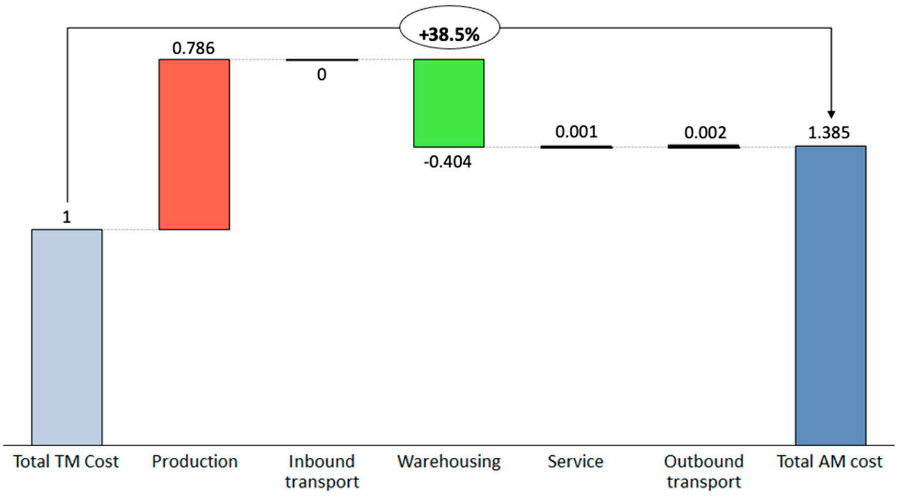

Figure 5. SPSC total cost difference between AM and TM for P3, shown in normalized values.

4.3.2. P2-Tappet

P2 currently being at the prime stage of its life cycle has an MOQ of 50 pieces and an annual demand of six parts. P2 is a positive business case to be produced by AM, as the total SPSC cost for AM was lower than for TM over the entire planning horizon. This is clearly visible in Figure 6, where the planning horizon was set to 7 years, limited by the service level declining below the target service level.

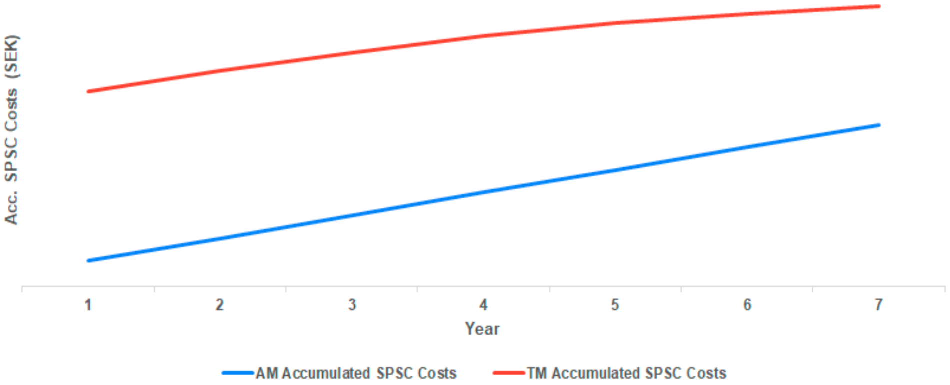

Figure 6. AM and TM accumulated SPSC costs for P2 over the seven-year planning horizon.

Using AM reduces both the cost of production and warehousing. The cost-savings in production price for P2 is partially explained by FDM AM having a 10% lower unit price than TM. In addition, in the TM scenario, the MOQ requires the OEM to purchase eight pieces in waste, whilst only one piece (the safety stock) ends up as obsolescence costs in the AM scenario. Thus, cost-savings in production costs can be made when switching to AM. The TM scenario has a high warehousing cost which is driven by capital costs. In conjunction, the TM scenario has a higher unit price and will have more units in stock, consequently, resulting in higher capital costs (Figure 7).

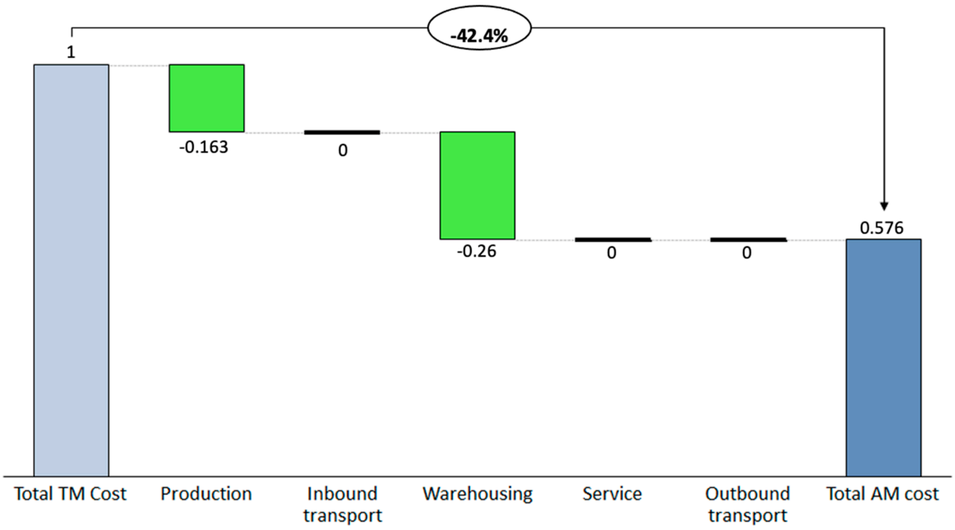

Figure 7. Difference in cost between AM and TM for P2, shown in normalized values.

4.3.3. P1—Protecting Cover

P1 currently being at the prime stage of its life cycle has an MOQ of 500 pieces and an annual demand of 23 parts. P1 is also a positive business case for using AM (Figure 8).

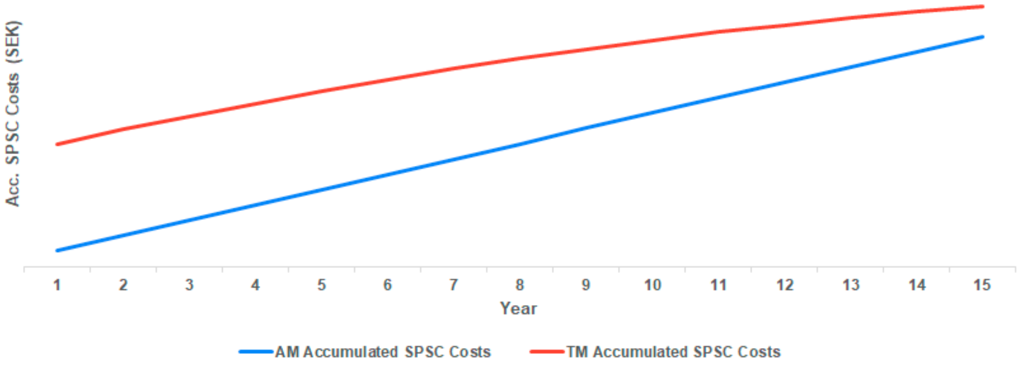

Figure 8. AM and TM accumulated SPSC costs for part P1 over the seven-year planning horizon.

The price of production was higher for AM, roughly having a twice as high unit price. However, larger cost-savings were achieved in warehousing, making P1 a positive business case. The full planning horizon of 15 years was analyzed, and while the accumulated costs gradually converged, the total SPSC costs were still greater for TM (Figure 9).

Warehousing cost for TM stands out because it is driven by capital costs. The capital costs for TM constitute 93% of the total warehousing costs and 54% of the total costs. Thus, the large inventory procured in year one was costly, but the capital costs connected to this procurement were even larger.

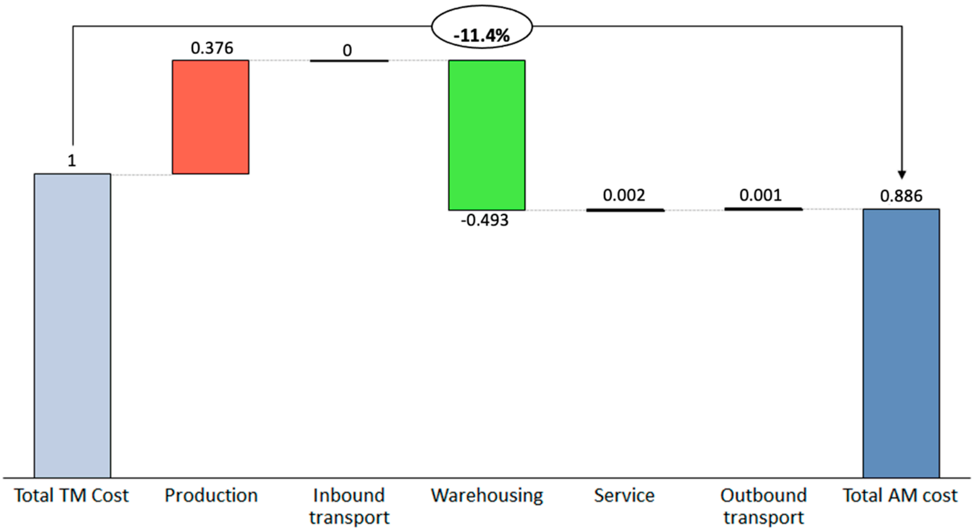

Figure 9. Difference in cost between AM and TM for P1, shown in normalized values.

5. Discussion

As the AM technology advances, quality of printed parts improves while the technology becomes more accessible and less costly. This allows companies in different industries to use AM for final parts production. Spare parts production is among the high potential AM industrial applications. In this study, we developed a cost model for spare parts supply chains in automotive industry that can be used to identify the parts with economic potential to be produced by AM, replacing the inventories with production service providers' capacity.

Differences and similarities can be found when comparing the SPSC cost model developed in this research with models used in previous case studies. The model developed in this research has similarities with the models in Khajavi et al. [4] and Holmström et al. [27], as several cost components are shared-manufacturing, transport, inventory, and downtime. The difference is that the new model is more detailed and contains parameters that suit the SPSC in automotive industry. Moreover, our SPSC cost model investigates the use of third-party AM production service providers instead of in-house AM production capacity.

SPSC cost differs between AM and TM. In a centralized production, Khajavi et al. [4] found the share of the costs related to centralized production (including personnel, material, machine depreciation, and production) to account for 75–79% of the annual SPSC costs depending on the AM machine for in-house production. This could partially explain why the share of total costs was less than what was found in this study, as in this research, the production costs were retained from a third-party AM supplier which included a profit margin in the sales price.

In the study by Khajavi et al. [4], transport accounted for 5.6–7.6% of the total costs, which is significantly higher than the results shown in this research, which was in the realm of 0–1%. In their research, they used transport costs retrieved from the UPS company, which was based on the size and destination of the part. In this study, the OEM already has line transports from the proximity of the AM supplier and very high consolidation. This makes the costs of transport in this study very small and provides an explanation for the difference between the results of this research and findings of Khajavi et al. [4]. In contrast to this, the study by Li et al. [13] describes transport costs as a dominant cost driver in the centralized AM supply chain, representing 49% of the total SPSC costs. However, in the study by Li et al. [13], the cost of AM production is based solely on the variable costs and thus not the investment in the AM machinery. This makes the share in total cost incomparable to this research as well as to the study by Khajavi et al. [4], as AM machinery is capital-intensive and a major cost driver of production costs.

The cost related to downtime or, as described in this research, VOR, was lower in this research than that of Khajavi et al. [4], which is not surprising as their study took place in the context of the military/aerospace industry, in comparison with the less capital-intensive automotive industry studied in this research.

Three of the fourteen researched parts (P1, P2, and P3) showed a positive business case for AM sometime during the planning horizon. All these parts were polymer parts, due to the AM production cost being lower for polymers than metals. The AM cost of production for metal parts is required to decrease by 72–99% before reaching the B/E point and being positive business cases. This coincides with current research streams, as these claim producing metal parts with AM is far more expensive than producing polymer parts with AM [52]. Our results indicate that it is more plausible to deploy AM for polymer spare parts in the near future. However, due to the rapid development of AM technology, it is difficult to discount the application of metal AM for spare parts production in the long-term.

P1 and P3 resulted in potential business cases through cost-savings retained in warehousing. Whereas P2 obtained cost-savings in warehousing, and also production. Cost-savings in warehousing through the deployment of AM is something Holmström et al. [27] acknowledged. The cost-saving in the production of P2 is due to AM having a lower unit price, as well as avoiding the MOQ inherent to TM which would lead to the TM scenario ordering more parts than the AM scenario. The extra parts produced by TM results in an obsolescence cost, which Holmström et al. [28] predicted to occur. In line with the findings of this research, Holmström et al. [27] suggest AM being a financially feasible option for manufacturing smaller batch sizes and, as this study shows in the case of P2, AM's unit price can be lower than TM's in the automotive industry.

We provide several insights regarding how AM should be utilized by an OEM to reduce the total SPSC cost. Starting with P3, the OEM is no longer required to provide the article as the Resp. year of 2018 has already passed. Assuming the stock is depleted, and the OEM wishes to provide the article for no more than six additional years, then, the company should produce these parts through AM since the SPSC total cost would be lower. As for P2, it is currently feasible to utilize AM and the Resp. year for this spare part is set to 2039 and the stock is expected to be depleted in the upcoming years. Both production and warehousing costs are lower using AM compared to TM and it is clear that continuing with AM would be beneficial from an SPSC cost perspective. As for P1, although it would make financial sense to print the article, the inventory level for the part is at the moment so high it is unlikely to be depleted until the 2030 Resp. year. Nonetheless, suppose it happens, the OEM should highly consider printing the part (assuming conditions, such as demand and MOQ, remains unchanged).

With AM, the order quantities can be kept closer to the annual demand as long as the cost of reordering is lower than the cost of warehousing over the consumption period. In other words, a shorter planning horizon would be beneficial for AM over TM since the SPSC costs for AM increase linearly over time whilst the accumulated SPSC costs for TM flatten out. This implies that AM may be used for the spare parts in the phase-out stage of their life cycles. The phase-out stage SKUs are also more suitable to be printed since they may have lower demand and therefore lower production batch sizes [28]. Furthermore, the Resp. year can be included in the part selection filtration to derive articles with shorter planning horizons. This can result in identifying more cases with higher feasibility to be printed. Nonetheless, our study showed that in addition to SKUs in the phase-out stage, parts that are still in their prime stage of their lifecycle can also be suitable candidates to be produced with AM.

The cost of production is higher for AM compared to TM for all articles researched in this study, except for P2. This does not necessarily imply the AM technology is not matured and cost-efficient enough. A reason for the high AM production price could be due to the parts not being designed for printing as they are for TM. If the parts are designed initially, or later redesigned for AM, cost-savings can be made through, e.g., part unification [6]. However, redesigning the drawing would also entail costly engineering labor costs. Therefore, the benefit of redesign in case of spare parts needs to be evaluated against the increased labor cost, to derive the optimal production price.

Forecasting future demand will be a prerequisite for the OEM to be able to deploy AM in their SPSC. Currently, the company is having trouble forecasting demand for slow-moving spare parts due to their inherent intermittent demand. These are also the parts that are interesting for AM. If a forecast is missing, the underlying data to support a decision regarding re-ordering through TM or AM will be poor. The principle here is similar to the use of AM for new product launches with unknown demand levels, as discussed by Khajavi et al. [53] who conclude that TM in these cases involves an investment risk compared to AM.

In this research, a centralized AM SPSC is deployed at the OEM. A decentralized AM SPSC would, however, exploit various benefits of the AM technology [27,37]. Hence, this research could be perceived as not fully taking advantage of AM and consequently identifying too few positive business cases of the OEM's spare parts portfolio. A dispersed AM SPSC was not investigated in this study since the production was outsourced and, from a supply chain cost perspective, a decentralized structure is of greater relevance when the production is in-house. The OEM argues that a decentralized supply chain is probably not an option in the short-term future due to a potential loss of control in quality assurance and also because of an alleged increased risk around intellectual property rights that comes with having a dispersed SPSC.

6. Conclusions

This paper identified and quantified the SPSC cost components of slow-moving parts produced with AM and TM. This is achieved by developing a supply chain cost model for an OEM in the automotive industry. The spare parts supply chain cost components are: production, inbound transport, warehousing, outbound transport, and service costs. The cost of warehousing contains the following subcategories of cost drivers: goods in, capital costs, packaging, goods out, procurement, warehouse overhead costs, order office, warehouse building, and development. The service costs contain the following subcategories of cost drivers: cost of lost sales, badwill, and cost of vehicle downtime (VOR).

Fourteen spare part SKUs were selected and examined to understand the cost competitiveness of AM and TM SPSC in the automotive context. Three out of the fourteen parts showed potential for cost-savings, if they were produced with AM instead of TM. AM parts made out of polymers showed greater potential than metal parts to replace TM as the cheapest option of manufacturing from a total SPSC cost perspective. The results of our analysis indicate that, on average, the total TM SPSC cost is driven by the cost of warehousing and production, while for AM, the total cost is mainly driven by production. The remaining cost components, transport and service, had a marginal impact on the total cost.

Our results showed that the spare parts in the phase-out stage of their life cycle should have the greatest potential for AM. However, in this research, parts in other stages of the life cycle have shown potential for AM. Therefore, this study suggests it is not only phase-out articles that are suitable to be additively manufactured. Moreover, this study showed that polymer spare parts with low demand, high MOQ, and high TM production price are better candidates for AM SPSC feasibility.

For future research, it is recommended to increase the quantity of the studied spare parts to validate the parameters used in the cost model. In addition, adding the element of decreasing average demand levels, and simulating demand for each period using, e.g., Monte Carlo simulation. Combining this with the effects of life stage analysis would likely decrease the SPSC costs for AM. This requires an improved forecast of future demand for slow-moving spare parts compared to the one the OEM is currently holding. The effects of in-house AM production should also be investigated, as well as the cost drivers of doing so and possible economies of scale in AM. This study is one of few studies investigating the implementation of AM in a SPSC in non-military operations and there are many possibilities in other industries where future studies on this topic are worth exploring.

Author Contributions: Conceptualization, S.H.K., P.J., L.A. and D.J.; methodology, L.A., D.J.; software, L.A., D.J.; validation, S.H.K., L.A., D.J., P.J. and J.H.; formal analysis, L.A. and D.J.; investigation, L.A. and D.J.; resources, L.A. and D.J.; data curation, L.A. and D.J.; writing—original draft preparation, L.A. and D.J.; writing—review and editing, L.A., D.J. and S.H.K.; visualization, L.A. and D.J.; supervision, S.H.K., P.J. and J.H.; project administration, P.J.; funding acquisition, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Direct Operations Project under Grant 323831.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 presents data sources used in this research and data incorporated into the development of the model from each respective source. However, this would not suffice to conduct a comprehensive SPSC cost comparison between AM and TM; the AM production price is also needed. This information was obtained by sending a "request for proposal" (RFP) to the OEM's trusted AM supplier, containing 3D-drawings of the selected parts, annual quantities, and materials.

Table A1. List of the OEM's databases and systems used in this research.

Type of Database	Use in Model
Engineering database	Weight, material, dimensions, CAD-models
Warehouse Management System	Inventory, yearly demand, MOQ, standard price
Outbound transport database	Outbound transport cost
Inventory optimization tool	Cost of lost sales and badwill cost
After-sales-service software solution	Demand distribution
Inbound transport database	Inbound transport cost
Simulation Tool/Cost to serve	Warehousing costs
Database of operative operations	VOR
Supply and demand planning database.	Responsibility year

Appendix B

The parts pre-screening process entails two steps, a financial screening and a technical screening. This was conducted in order to retain spare parts which can be produced through AM, and possibly also showing positive business cases.

Financial pre-screening

Firstly, a financial pre-screening was conducted to identify parts that could create a business case for AM. The first step in the financial screening was to filter on inventory data retrieved from one of the OEM's databases. The filters used and motivations behind the filtration can be viewed in Table A2.

The OEM's database over the historic demand for a part per year was not deemed to be trustworthy and was rather irregular, except for the latest twelve months. Due to this, the demand per year was calculated by deducting the current stock balance (SB) with the LOQ divided by the number of years since the last received quantity until 2020. After all of the filters were applied, a total of 100 parts were selected for further analysis.

Table A2. Financial spare parts filtration over inventory data.

Filter Type	Condition	Motivation for Filtration
Article Price	>25 SEK	If the article price for TM was below 25 SEK, a business case for AM was deemed to be unfeasible, as AM is a significantly more expensive means of production.
Stock Value	>10,000 SEK	To find articles where the OEM could profit a significant amount.
Demand per year	>0; <40 pcs.	Less than 40 as a higher demand per year would likely benefit TM via economies of scale. Greater than 0 to remove outdated and non-active SKUs.
Current MOQ	LOQ = MOQ	To exclude cases where the MOQ has changed since the last shipment. In addition, to solidify the quantity ordered in LOQ was due to the suppliers MOQ-requirement.
LOQ-date older than 2018	Older than 2018	The demand data would have been inadequate for parts with a LOQ earlier than 2018.
SB higher than 0	SB > 0	The yearly demand data would have otherwise not been able to be computed.
Spare part being located in Europe CDC	-	The model developed in this thesis concerns Europe CDC.
Spare parts in specific business unit of OEM's product portfolio	-	Request from stakeholders at OEM.
Weight restriction	Weight < 3000 g	Heavier parts lead to too high AM production prices.

After applying these filters, the ratio between MOQ and the demand per year was computed for each SKU. This was performed in order to find cases where the MOQ is excessively higher than demand and thereby identify parts that might be suitable for AM. After this sorting, 30 parts with the highest ratio between MOQ and demand were selected for further analysis.

Except for inventory data, the vital code was considered during the selection of spare parts. The Vital code provides information on the maintenance needs of a part. At the OEM, all spare parts are assigned a Vital code. Parts with certain Vital codes used in scheduled maintenance are excluded in this study since the model developed in this thesis does not consider planned demand. This thesis will therefore investigate spare parts with all other Vital codes.

Technical pre-screening

After the financial screening, a technical screening was commenced. The technical pre-screening was carried out mostly through the help of our supervisor (an additive manufacturing specialist) at the OEM. Some parts are not suitable for additive manufacturing, e.g., due to constraints in form of precision and tolerance (moving parts), extensive quality control (safety parts), or due to the needed flexibility, stiffness, or solidity of the desired object.

Further, function groups were used to exclude certain parts. The OEM divides parts into various groups depending on the usage in the vehicle, referred to as function groups. In this thesis, parts belonging to a certain function group which are used in the engine are needed to withstand deformation and are therefore excluded.

After the technical pre-screening, the 30 parts selected in the financial pre-screening were reduced to 14 parts. These parts were deemed to have potential for AM from both a technical and a financial perspective.

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