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Assessing the potential of additive manufacturing for the provision of spare parts

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Abstract

Spare parts are a particularly interesting application for switching production from traditional manufacturing (TM) to additive manufacturing (AM). Research assessing AM has primarily addressed cost models centering on the production process or the operations management of separate spare parts. By combining case study, modeling, and design science elements, we adopt a holistic perspective and develop a design to examine the systematic leverage of AM in spare parts operations. Contextually grounded in problems faced by a leading material handling equipment manufacturer that is challenged by common characteristics of after-sales operations, we engage with practice to propose a portfolio level analysis examining the switchover share from TM to AM. Using a data set of 53,457 spare parts over 9 years, we find that up to 8% of stock keeping units (SKUs) and 2% of total units supplied could be produced using AM, even if unit production costs are four times those of TM. This result is driven by low demand, high fixed costs, and minimum order quantities in TM. Finally, we present the evaluation by the case company's management and highlight five areas of opportunity and challenge.

KEYWORDS

3D printing, additive manufacturing, portfolio level analysis, spare parts management, switchover share

1 | INTRODUCTION

Production and management of spare parts are among the most promising applications of additive manufacturing (AM, commonly called three-dimensional printing [3DP] in an industrial setting), and these AM applications are progressively being adopted across different industrial domains (Müller & Karevska, 2016). Daimler, Volvo Construction Equipment, and Deutsche Bahn are a few prominent examples of companies that have already produced their first spare parts using AM technology (Daimler, 2017; Deutsche Bahn, 2018; Volvo, 2018). With the technological advancement of AM, research

has identified the potential that this technology holds for new supply chain solutions around spare parts operations (Walter, Holmström, & Yrjölä, 2004). Reducing costly inventories by systematically shifting spare parts to flexible AM production is viewed as a key advantage in the application of AM for spare parts (D'Aveni, 2018; Holmström & Gutowski, 2017; Khajavi, Holmström, & Partanen, 2018).

In reality, firms frequently manage large portfolios of spare parts that often consist of tens of thousands of individual stock keeping units (SKUs) (Guenir & Erel, 1998; van Wingerden, Basten, Dekker, & Rustenburg, 2014). This portfolio complexity makes the detailed analysis of each part

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infeasible for obtaining systematic insights into the overall AM potential. Given the growing strategic importance of spare parts and after-sales operations in many firms (Cohen, Agrawal, & Agrawal, 2006; Cohen & Lee, 1990; Dennis & Kambil, 2003; Kastalli & Van Looy, 2013), practitioners often would like to attain an initial understanding of how many spare parts candidates could be potentially shifted to AM in their specific settings. In fact, a possible lever could be generated from a comparatively small share of slow-moving spare parts that are crucial to a firm's after-sales strategy but that tie up significant financial and operational resources. Reducing the risk for excessive inventory levels and obsolescence resulting from, for instance, a lack of demand or changes in part design and specifications can offer great potential for reducing inventory costs without changing existing after-sales strategies (Holmström & Gutowski, 2017). Here, it would be important to learn how many total units supplied would switchover from traditional manufacturing (TM) to AM. Such insights would help managers prioritize their AM efforts, understand future requirements for AM capabilities building, and plan their overall operations strategy for introducing AM (Roca, Vaishnav, Mendonca, & Morgan, 2017).

The motivation for our research came from a leading material handling equipment manufacturer that informed us of the challenges it faced when selecting potential spare parts for AM. Although the company was aware of the many opportunities that AM promises for spare parts operations, the company found it difficult to identify and quantify the overall potential of AM. Redesign benefits such as weight reduction and customization do not play a role in the spare parts portfolio of the company. Hence, the company was less interested in individual part identification and more interested in a systematic perspective of AM along the spare parts supply chain. Leveraging elements of design science research, we address the challenge of the case company by exploring and evaluating an initial solution (Holmström, Ketokivi, & Hameri, 2009; van Aken, Chandrasekaran, & Halman, 2016). The overarching objective is to evaluate how the company can benefit from a one-for-one replenishment solution for spare parts by a switchover from TM to AM. Furthermore, we leverage design science to interact with practice and gain knowledge on the operational factors associated with the proposed switchover from TM to AM.

Other assessments currently presented in the literature focus on the feasibility of using AM for certain part groups based on various characteristics such as size, material, estimated processing time, performance improvements, and economic aspects (Conner et al., 2014; Klahn, Bastian, & Meboldt, 2015; Lindemann, Reiher, Jahnke, & Koch, 2015; Westerweel, Basten, & van Houtum, 2018). However, the challenges of supporting strategic decisions based on a large

number of parts are generally ignored. By contrast, we examine the share of SKUs and parts that would be economical to switchover from TM to AM, as AM cost premium changes. Conceptually, the switchover share of the portfolio is closely related to the switchover quantity for individual parts proposed by Khajavi, Deng, Holmström, Puukko, and Partanen (2018). Whereas the switchover quantity specifies the demand level when a part is economical to switchover, the switchover share specifies the share of SKUs that are economical to shift to AM as production- and inventory-related costs change. Grounded in established concepts and models of inventory management, we aim to assess the leverage that AM exerts on manufacturing an entire spare parts portfolio. Using a large empirical data set, we find that high real-world order quantities that go along with very low-demand rates result in high inventory levels for TM. Switching manufacturing to AM enables a significant supply chain cost reduction for these parts. For the case company, we also find evidence for cost-efficiency leverage. While 8% of SKUs would be produced using AM, only 2% of total units supplied would be manufactured using AM technology, if AM unit production costs had a 300% cost premium (i.e., four times the cost) compared to that for TM. However, this switchover can reduce overall system costs by 6.4%.

The remainder of this article is structured as follows. In Section 2, we provide the research context, including an introduction of the case company and an outline of our research process. In Section 3, we use empirical data to analyze the potential leverage of AM in the spare parts supply chain of the case company. In Section 4, we evaluate our results, and in Section 5, we discuss our contribution.

2 | RESEARCH CONTEXT

The research was carried out in close cooperation with a leading material handling equipment manufacturer interested in assessing the AM potential for after-sales operations. By engaging with practice, we identify challenges and requirements of the case company's spare parts operations and explore a possible solution for the adoption of AM. In addition to focus group discussions and expert interviews, we collect data and documents provided by the case company to obtain a complete picture of the after-sales business. Table 1 provides an overview of the field problem highlighting some statements from our discussion.

After-sales services offer the company significant value creation potential. Compared to its peers, the company's clearly stated objective is to achieve leading customer service in the after-sales business. Distributing more than 330,000 spare parts per month, it achieves a delivery readiness of greater than 95% and delivery punctuality of 99.9%

TABLE 1 Field problem

Problem	Statement	Stakeholder
After-sales strategy with high costs	"In general, we stock parts to offer service 10–15 years after series production."	Category manager
	"The premium standard is extremely high due to the continuous, direct sales. [...] we prefer to have a part too much in stock instead of somehow losing availability."	Vice president
	"Depending on the region, we achieve an annual inventory turnover rate of less than 1 to 2."	Director supply chain
High minimum order quantities	"Parts that do not move at all need to be scrapped once per year."	Category manager
	"Sometimes, it is the mold cavity. In one run, the supplier makes 10 parts. There is no way that he can cut out only one part."	Category manager
	"And then, there is also the fact that we require special materials (with a minimum order quantity from the supplier). Now, the supplier lets the machine run for 10 min, and then, you have to take 100. Once the material is heated, it cannot be used anyway."	Category manager
	"When we have a fast-turning part, we try to fill at least one cage pallet in the warehouse."	Category manager
Limited experience with on-demand production	"In house, we have a so-called 'short-path assembly' for certain hoses and chains. Those parts are produced just in time."	Director supply chain
	"Only for volume requirements higher than 10 do we transfer such parts as a stock item in the warehouse."	Director supply chain
	"We made make or buy decisions years ago, and at that time, we clearly opted to buy."	Category manager
Limited expertise with AM	"Our highest potential for 3D printing lies in inventory and logistics. We do not aim for better performing or customized parts."	Category manager
	"We have conducted a test for 11 selected plastic spare parts for which the required tooling was missing."	Category manager
	"The materials we received in the quote differed from the current material. PA12 was the given alternative in nearly all cases."	Category manager
	"Serial production is difficult because 3D printing is expensive and very slow. However, this is state of the art today and is changing rapidly."	Vice president
	"It costs 59 cents per part today if I order 50 pieces. For 3D printing, I would otherwise have to pay 100 euros for a single part. Even if I throw away 49 pieces, it is cheaper to opt for the current option."	Category manager

and utilizes after-sales service as a lever for competitive differentiation. In fact, in many industries, the importance of after-sales markets has increased with a rising installed base that has become much larger than markets for new equipment (Cohen et al., 2006). Cross-industry estimates indicate that 30% or more of total revenues are accounted for in after-sales services (Bundschuh & Dezvane, 2003). Similar to the case company, an increasing number of companies recognize the strategic importance and value that after-sales services offer (Wagner, Jönke, & Eisingerich, 2012).

However, this service objective results in an *after-sales strategy with high costs*. Due to its growing installed base across the globe, more diversified product portfolios, customer requirements for short downtimes, and increasing supply chain complexity, the case company is faced with tremendous challenges in equipping its after-sales services with the required spare parts. The original equipment manufacturer's (OEM) current strategy to counter these difficulties is to operate a centralized spare parts system storing more than 60,000 SKUs supplying four regional warehouses with

a considerably smaller selection of SKUs, and more than 5,000 service technicians in the field. Relying mostly on spare parts sourced from external suppliers, in-house production is limited to less than 5% of the total portfolio. Again, this situation is common across OEMs and is supported by Wagner and Lindemann (2008), who find that the majority of spare parts—more than 60% on average—are sourced from external suppliers and that 40% are sourced in-house from the firm's own production line.

By sourcing from suppliers that utilize TM and requiring specific materials that offer scale advantages for larger purchases, the company is exposed to *high minimum order quantities* for its parts. As a consequence, orders arrive in batches and increase inventory levels well above demand requirements. This results in spare parts stocks that cover demand over a long horizon. Ultimately, a considerable share of spare parts remains as residua that virtually do not move at all and, in the most unfavorable case, are scrapped at some stage.

Besides minimum order quantities, the high dependency on external suppliers goes along with *limited experience with on-demand production*. For only a very small number of customized spare parts (i.e., hoses and chains), the case company has incorporated on-demand production as a so-called “short-path assembly.” Since the variety of these customized parts is great and internal production is feasible, in-house production is utilized to avoid costly batch production and increased inventory requirements. It is this advantage above all that could offer potential to introduce AM along the company's after-sales operations.

Despite the opportunity, the company currently has *limited experience with AM*. Existing trials with AM service providers have revealed that cost comparisons that focus purely on production costs result in cost disadvantages for AM. In addition, managers of the case company highlighted technological challenges like slower production speeds and limited material availability.

By comparison, the challenges identified along the spare parts operations of the case company are common to OEMs in sectors where products are expensive and used for a long time. High-capital equipment such as aging aircraft are often serviced long after production of the aircraft has stopped (Li, Dekker, Heij, & Hekimo, 2016). Asset-intensive engineering industries require the control of a wide and highly variable spare parts assortment (Suomala, Sievak, & Paranko, 2002; Wagner & Lindemann, 2008). Customer-oriented industries like auto manufacturers are faced with reduced product life cycles and the highest service standards (Cohen & Lee, 1990; Dennis & Kambil, 2003).

Building on the insights gained by expert interviews and operations data, we develop a solution proposal for the introduction of AM, and for the analysis of switchover in the case

company. Switchover analysis, proposed by Khajavi, Partanen, Holmström, and Tuomi (2015) for product introduction, is here adapted for guiding managers in assessing the potential for AM in their spare parts portfolio as AM technology improves. To ensure constant practitioner input, we involve experts from the case company throughout the research process. In addition to framing and scoping the problem, we draw on their expertise to evaluate the design of our proposed solution and provide practical insights on the consequences of introducing one-for-one replenishment in spare parts operations.

In designing the solution, we combine elements of design science, modeling, and case study research to identify a solution for a situation in which an implementation seems very likely only in the foreseeable future. As a result, we draw on design science, which explicitly focuses on improving practices and discovering designs to create solutions that do not yet exist (Holmström et al., 2009). In fact, providing an intervention with a new technology in a practical context is noted as a key criterion for using design science in the operations management domain (van Aken et al., 2016). Following a problem-centered approach (Peffer, Tuunanen, Rothenberger, & Chatterjee, 2007), we ground our proposed design in the context of the case company to develop knowledge that facilitates valid and reliable solutions within the field problem (van Aken, 2004). To this end, we not only utilize quantitative operations data but also interact with practitioners to gain an understanding of resulting operational factors (Browning & de Treville, 2018).

As shown in Figure 1, we follow the context-intervention-mechanism-outcome (CIMO) logic (Denyer, Tranfield, & van Aken, 2008; Kaipia, Holmström, Småros, & Rajala, 2017). After framing the problem in the context of the case company and designing the intervention—consisting of a proposition for one-for-one replenishment and the assessment of switchover share in the portfolio—we investigate the mechanisms of one-for-one replenishment utilizing spare parts data from the case company. Finally, we evaluate the outcome from an operational perspective and review the proposed intervention with company experts. Although design science remains a relatively novel research strategy across the operations management community, it has become increasingly popular to “address field problems and exploit promising opportunities” (van Aken et al., 2016). Operationalized on a tactical level by common methods for data gathering and analysis (van Aken et al., 2016), we utilize established concepts of operations management to explore a switchover from TM to AM on a portfolio level of spare parts operations.

Forming the basis of the analysis, we leverage readily accessible supply chain operations information including demand, inventory, and supply chain cost data. Reviewing

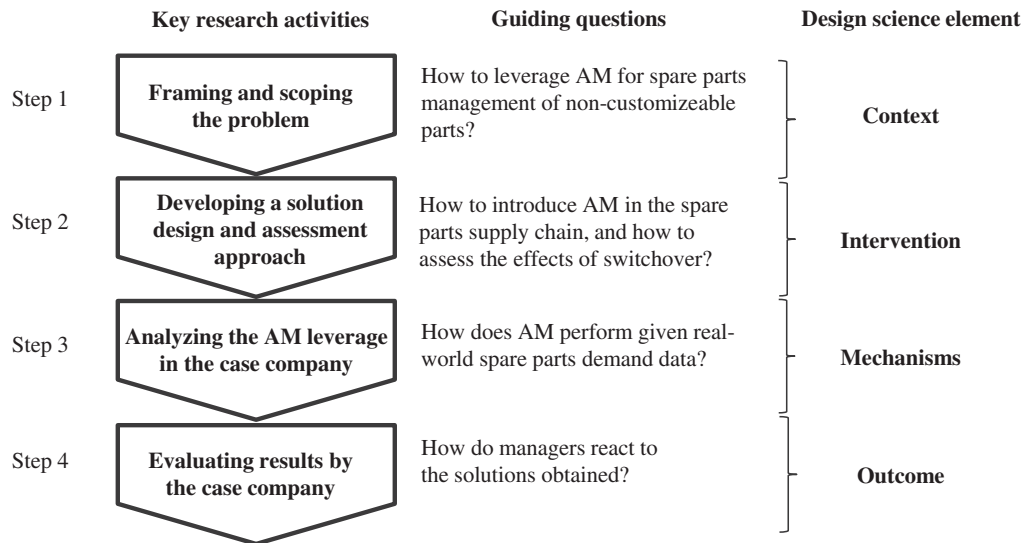


FIGURE 1 Research approach

the factors influencing the technology decisions reported by Holmström, Partanen, Tuomi, and Walter (2010), we account for all factors that require no alteration of the product design and that are directly associated with supply chain management of spare parts.

3 | ADDITIVE MANUFACTURING LEVERAGE IN THE CASE COMPANY

In step three of our research process, in a real-world setting, we explore the switchover share across the comprehensive spare parts portfolio of the case company. We aim to understand the volume that could switchover from TM to AM and what leverage this switchover offers cost-wise for the entire spare parts operations.

Our analysis rests upon an extensive data set of the case company covering part-specific monthly inventory and consumption data of 67,219 stocked spare parts for 9 years (e.g., 108 months). In addition, we collect part-specific data on the net purchase price per part, planned delivery time in days, and minimum order quantity per part. The only data not available on an individual part basis are those for holding and backorder costs. Managers, however, confirmed the assumption to set the holding and backorder costs annually as a percentage of the net purchase price, while considering high service-level targets ($h = 20\%$ of the net purchase price and $b = 200\%$ of the net purchase price). Furthermore, since no specific information about the release data on each specific part was available, we utilize the first month in which a demand or inventory was recorded. We further assess average order sizes based on the interplay of inventory and consumption data. While the data provide information about the expected lead time using TM technology for many parts, no

information is available for AM. For simplicity, we assume the same lead time for both technologies, although AM could very likely decrease the average lead time of 49 days.

To obtain a reasonable sample for our analysis, we apply a number of cleaning steps, removing spare parts with no demand occurrence during the observation period of 108 months or parts released only toward the end of the observation period (< 12 months). While parts with no demand are likely to be obsolete, we suppose that these parts with demand only toward the end have observation periods that are too short for accurate switchover decisions. By contrast, spare parts exceeding a mean annual demand greater than 100 are excluded too. The preceding numerical experiments showed that the benefit of AM diminishes with an increasing annual demand rate greater than 100. In such cases, AM is a suitable alternative only for a very low AM cost premium and highest fixed order costs for TM. In total, we removed approximately 20% of the sample, leaving 53,457 spare parts from the full data set for the analysis. To pursue the cost calculation and inventory optimization for the part-specific switchover decision, we fit a Poisson distribution based on the demand observations of each individual spare part (see Appendix A for the fit of statistical distributions).

We determine the switchover of the entire spare part portfolio using a step-wise approach. For inventory modeling, we use an (r, q) policy for TM and an $(S-1, S)$ policy for AM (see Appendix B for further information). For TM, the inventory is particularly influenced by the setup cost that is driving the order quantity. By contrast, the inventory for AM with one-for-one replenishment is typically considerably lower and only driven by the safety stock requirement. To decide on the switchover for each individual SKU, we rely on SKU-specific cost and demand data to calculate the

optimal inventory policy parameters for TM (i.e., reorder point r and production quantity q) and AM (i.e., base stock level S) based on the algorithms presented in Appendix B. However, we also account for SKU-specific minimum order quantities that prevent the case company from following optimal inventory decisions for TM. There are many reasons for minimum order quantities, such as production cost or time needed to set up the machine; the need to obtain, adapt, and return tooling equipment; and prescribed price arrangements and discounts. Second, we compute for each SKU the expected costs for both TM and AM; that is, we calculate the sum of inventory-related and production costs. For TM, we approximate production costs by the net purchase price of each spare part currently paid by the case company. For AM, we add a cost premium (Δ^{AM}) that accounts for the higher production costs of AM compared to TM. Since the production costs of AM greatly depend on the part properties and only detailed cost assessments are required, we examine a wide range of price premiums as a surplus on the current net purchase price. Third, we determine the preferred manufacturing technology for each SKU and determine the switchover share in the portfolio by selecting for each SKU the manufacturing process with the lowest costs. We repeat this procedure for all AM cost premiums $\Delta^{\text{AM}} \in [0, 3]$. As Figure 2 shows, we then provide different perspectives of the portfolio level analysis. To illustrate the detailed step-by-step approach that we have taken to obtain the results, we refer to Appendix C for an exemplary switchover analysis with two SKUs.

Figure 2a shows the switchover share of SKUs selected for AM. We find that AM can be an economically viable option for a significant share of SKUs, even with low fixed-order costs in TM. Although the low cost premium may not hold given the current state of AM technology, it is evident that there is considerable potential for AM as unit production costs decrease over time. For a conservative setting with low fixed costs in TM and expensive AM production represented by a cost premium of 300%, approximately 8% of SKUs could be produced using AM.

Figure 2b shows the share of total units supplied for the same parameter settings. It is calculated based on the switchover share of all SKUs and the related demands. This perspective allows us to draw conclusions on the actual spare part volumes that can shift to AM production. Interestingly, the share of total units lies well below the SKU level, suggesting that AM can achieve an even higher lever for single units. Considering an AM cost premium of 300%, only 2% of the total units supplied, which translates to 4,183 SKUs and 11,235 units supplied, are required to be produced additively. Comparing this share of total units supplied to an 8% share of SKUs, the underlying mechanism becomes clear: shifting the slowest-moving SKUs as potential candidates for AM requires an even smaller share of total units supplied.

Finally, Figure 2c shows the resulting total costs given the switchover shares. For the same assumptions, the systematic shift to AM results in a total cost reduction of 6.4%. Compared to the share of total units supplied, this cost lever is relatively large, emphasizing the potential that AM holds,

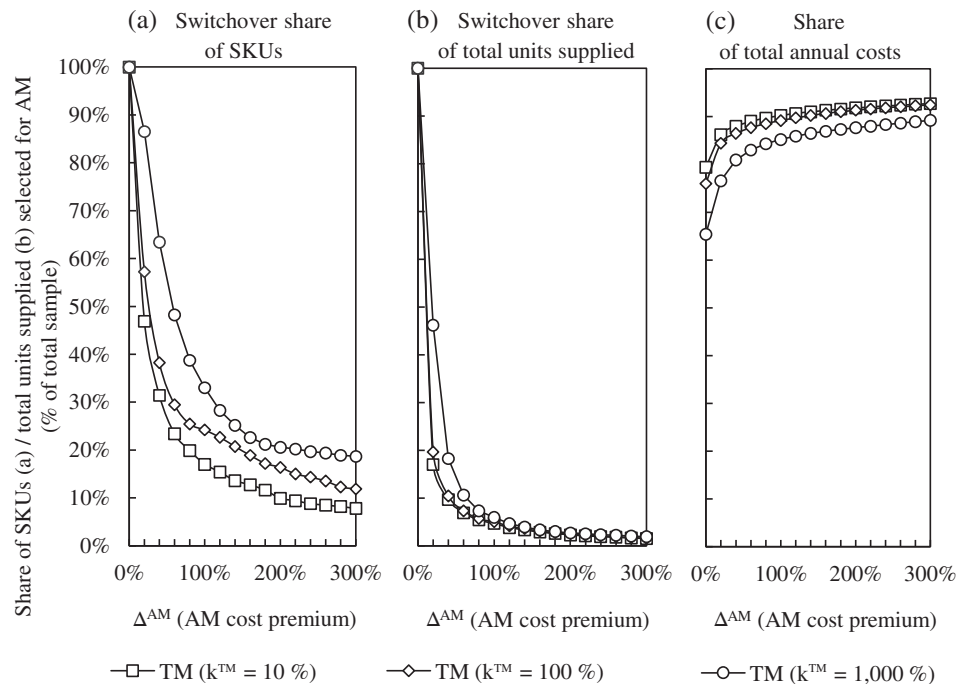


FIGURE 2 Switchover share of SKUs and total units supplied given minimum order quantities of TM orders

Note: k^{TM} (TM setup costs as a percentage of unit production costs)

even if only a small share of supplied units switches. The leverage is particularly interesting because, from a production process point of view, AM is characterized by a high degree of flexibility. The technology allows, on the one hand, for a straightforward shift between SKUs without time consuming and costly production changeovers between multiple builds and, on the other hand, for parallel production of individual parts in a single build (Baumers, Dickens, Tuck, & Hague, 2016; Khajavi, Holmström, & Partanen, 2018). For full utilization of the technology, a parallel build of individual products reduces the problem of excess capacity for distinct builds (Baumers, Beltrametti, Gasparre, & Hague, 2017). Finally, comparing less conservative estimates of fixed costs as well as less expensive AM production, the share of total units shifted to AM and the respective cost lever increase substantially.

4 | EVALUATION

In the concluding step of our research process, we evaluate our proposed solution design. First, we present limitations and simplifications of our design and highlight how these factors bias the switchover from TM to AM. Second, we evaluate operational factors based on direct discussions with representatives of the case company.

While our approach assumes the production of unit sizes of one in a single production run, AM unfolds its greatest potential if the utilization of the machine is maximized by the parallel printing of different parts in a single build (Baumers, Tuck, Wildman, Ashcroft, & Hague, 2011; Holweg, 2015). The cost advantage of AM increases if multiple parts are packed in one build (Khajavi, Holmström, & Partanen, 2018) and build packing should be considered in Δ^{AM} .

Furthermore, the design initiates with the assumption that a digital model of the spare part exists or can be easily obtained. However, in practice, the design file may be unavailable (since it is the intellectual property of the supplier), nonexistent (as is often the case for obsolete spare parts), or insufficient (like in the case of 2D drawings) (Chekurov, Metsä-Kortelainen, Salmi, Roda, & Jussila, 2018). In addition, new products require various product development activities, for example, master data, performance testing, and validation (Krishnan & Ulrich, 2001). This is particularly the case for a shift to AM during the product life cycle. Neglecting product design underestimates the costs of AM and, consequently, biases the switchover to AM.

Closely related, we consider constant part performance and exclude potential AM performance benefits enabled by a change in the part design. One prominent lever for AM to offset higher production costs relative to TM consists of design optimizations for function, as well as additional functions (Holmström et al., 2010) or lightweight constructions (Wagner & Walton, 2016).

Neglecting potential performance benefits from changing part designs biases the switchover to TM.

When summarizing the effects of simplifications on the technology decision, it becomes evident that biases influence the production switchover in both directions. We leave these aspects explicitly open for future research to examine the relevance and magnitude of each impact. As an example, Knofius, van der Heijden, and Zijm (2018) only recently present a detailed operational assessment of spare parts from an OEM indicating that higher cost savings for AM are already available. In use cases where lead time reductions, lower inventory-related costs, and tooling redundancy can be achieved, investments in AM should be encouraged sooner rather than later.

Since the case company has so far struggled to identify potential levers to introduce AM within its spare parts operations, we jointly developed a solution to switchover slow-moving spare parts from TM to AM. We additionally wanted to understand the pragmatic validity of our results by focusing on the effectiveness and analyzing the causes of the solution design (van Aken et al., 2016). In terms of the proposed design, we are interested in the evaluation of the switchover by the intended users (Hevner, March, Park, & Ram, 2004). Therefore, we presented our results to managers and experts (at all hierarchical levels) from the case company. In particular, we discussed the proposed solution design, as well as the findings and their implications for the organization. The case company generally agreed with the operations strategy opportunities around one-for-one replenishment with AM (see Table 2). However, certain potential

TABLE 2 Operations strategy opportunities and challenges

Opportunities	Challenges
<i>One-for-one replenishment</i>	<i>Digitalization of physical designs</i>
<ul style="list-style-type: none"> • Avoidance of minimum order quantities • Portfolio level switchover of part candidates from TM to AM 	<ul style="list-style-type: none"> • Limited availability of digital files for existing spare parts • Missing strategy to digitize parts inventory
<i>After-sales strategy</i>	<i>Organizational setup</i>
<ul style="list-style-type: none"> • Potential to reconsider given service requirements • Support toward an emerging trend of distributed storage with reduced inventories and direct replenishment 	<ul style="list-style-type: none"> • Expertise in new equipment department is needed for technical release of digital spare parts
	<i>Warehouse operations</i>
	<ul style="list-style-type: none"> • Increases in goods receipt efforts and related transaction costs • Storage bins are for large batch sizes

implementation challenges around the digitalization of designs, the organizational setup around technical drawings, and warehouse operations were highlighted.

In general, the *one-for-one replenishment* solution was well received by the case company, as AM seems to offer a viable alternative to current TM, especially with further technological advances. In particular, managers were eager to avoid minimum order quantities that relate to multiple years of demand. The VP After Sales highlighted that “[...] the sum makes a difference, of course! If I will be able to save on a five-digit number of different spare parts in the future by such a solution, this is surely an interesting option.”

In addition, the proposed design facilitated a discussion of the overall *after-sales strategy*. The assumption of always following a make-to-stock production strategy became an interesting point of discussion: managers raised the alternative that the current 48-hour-availability policy could be eased for very slow-moving parts that could alternatively be printed on demand. Relaxing the high service level restriction would accordingly even increase the impact of the AM solution design. Similarly, further discussion developed around the current spare parts distribution strategy. Although the current network is highly centralized, the company recently introduced warehouses in Europe and Asia. The central warehouse continues to hold the largest volume to cover demand for the next 6 months, while regional warehouses cover only the inventories for immediate demand. A manager emphasized: “If you produce and store [parts] in the regional warehouse, you do not have to store them centrally. Or you store them only in the central warehouse and perhaps even manufacture [regionally] directly; then, we don't need it in the regional warehouse.”

Apart from strategic opportunities to leverage AM for the case company's after-sales operations, discussions also point to operational challenges and organizational complexity. As stated above, a critical point identified as a challenge in implementing AM is the *digitalization of physical designs*. At this point, the company lacks essential requirements to introduce AM: a large share of spare parts is not digitalized. “We don't have so many 3D drawings. Of course, that's increasing now. But the older ones, where now the tools are broken, there are no 3D drawings.” So far, the company has not decided on a clear way forward to digitize its spare parts portfolio as a whole. However, the analysis triggered interest in this issue, and a status quo analysis is being conducted to quantify the current availability of digital files.

Additionally, in the case company's *organizational setup*, technical know-how is present mostly in the new-equipment business and not within the spare parts business. If technical drawings are missing, close collaboration with colleagues from the development and engineering departments is required, leading to delays and potential conflicts between

the different stakeholders. As the vice president stated, “What I do not know is how we should handle the issue of technical release [...] When changing suppliers, I often have the problem of the technical release by the new equipment business unit.” However, the management stated that the overall process is subject to review.

In addition to complications in digitizing spare parts inventories, there were also concerns raised with regard to the operational efficiency of *warehouse operations* when reducing order sizes to one. Goods receipt of spare parts is exclusively conducted at the central warehouse and is aligned with the stock-taking of unit-sized packages. Lowering order quantities will increase the number of goods receipts and could cause significant increases in transaction costs. These transaction costs, for example, due to identification, approval of quantity, and condition checks, are likely to soar, if order sizes are reduced and cannot be covered by current processes.

Another challenge relates to the current warehouse storage bins designed to accommodate large quantities of a SKU. In the current operational setting, smaller order sizes and allowing for lower inventory levels would not free up space in the warehouse, as one storage bin is exclusively occupied by a single SKU. The inventory manager highlighted that “The more frequently we order, the more boxes we occupy. Because today, we don't add anything to a given box.” The introduced design solution would, however, allow for highly reduced inventory levels that do not match current storage bins. Even if this solution cannot be reconciled with the current layout, it might be possible to restructure bin sizes and split the given space for usage by multiple SKUs.

With respect to the overall design, the case company appreciated the insights gained by systematically analyzing the shift to AM and taking advantage of a cost-efficiency lever. Furthermore, the ease of usage and data requirements was seen as strengths. In terms of outcomes, it was emphasized that this strategic perspective warrants further consideration. As the VP After Sales concluded, “Where do I get the most of such a solution? I would focus on low-value and less critical spare parts and go for a wide selection of parts.” In fact, practitioners received an insight that was previously missed in selected trial runs that merely focused on process cost comparisons. By pursuing the strategic path further to introduce AM within its spare parts operations, the company would like to take the next step and explore the technical selection of parts. It is interested in understanding the requirements for identifying suitable spare parts candidates (e.g., based on available files, materials, process properties) and supplementing the strategic assessment with a technological evaluation.

5 | OUTLOOK

We presented an approach to explore on a portfolio level the potential to switchover slow-moving spare parts from TM to AM. Rather than assessing the leverage of AM for individual spare parts, we focused on assessing a large empirical data set. The results identified the possibility of a systematic shift in spare parts manufacturing from conventional manufacturing processes to AM, with important implications for practitioners. First, we find on a portfolio level that spare parts operations can benefit from AM and identify a leverage of shifting slow-moving parts to AM. Only a small share of the spare parts can potentially benefit from lower inventories, fewer orders, and less transportation associated with AM if the unit production cost premium is high. For a cost premium of 300%, the number of AM SKUs corresponds to 8% of the SKUs considered. Second, while the number of AM SKUs is relatively small for high AM cost premiums, the proportion of total parts produced with AM is even smaller. For a cost premium of 300%, only 2% of total units supplied would be manufactured using AM. One-for-one replenishment with AM particularly favors SKUs with low demand rates, while SKUs with higher demand rates would still be manufactured using TM. As a consequence, the total AM manufacturing capacity required to achieve the benefits is relatively low.

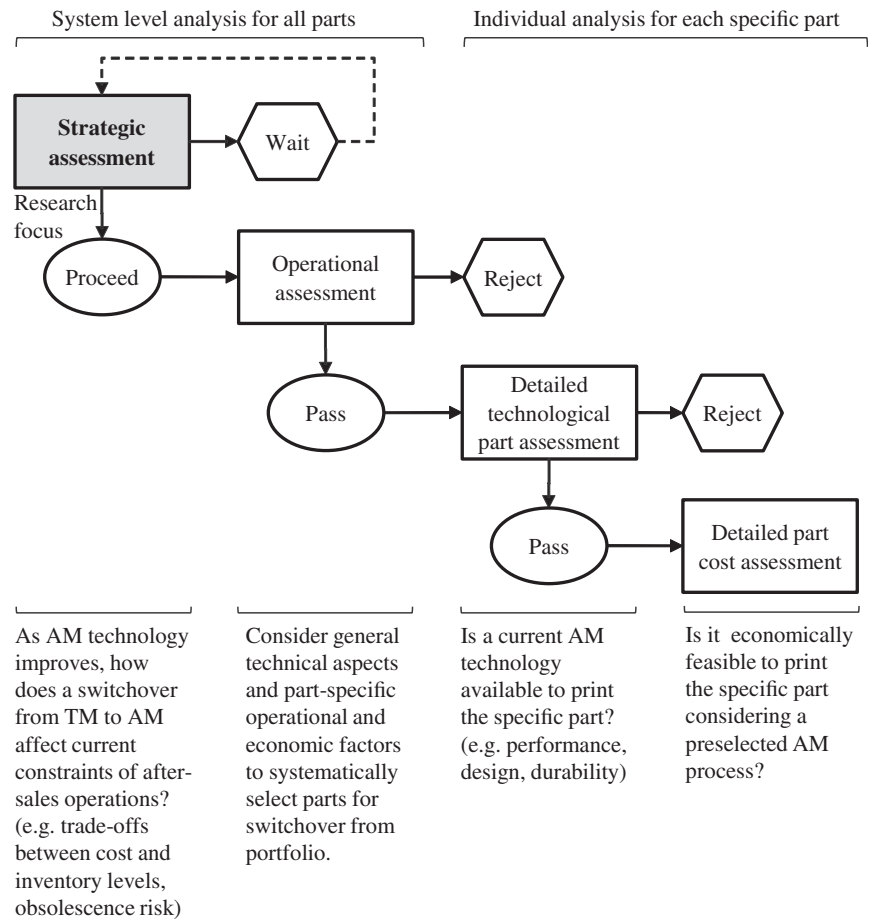
Moving from the individual SKU perspective to a total units supplied level, we emphasize for practitioners that inventory reductions and cost savings can be relatively high, given the comparatively small part selection. Such cost-efficiency levers are identified only if entire spare parts portfolios are examined and large-scale shifts in production technologies are assessed. In contrast to previous analyses focusing on carefully preselected single parts, our design moves beyond operational aspects and is, to the best of our knowledge, the first strategic attempt to examine an overall switchover without altering product designs and significantly rearranging given supply chain operations. The empirical application and evaluation demonstrate a paradigm present only from a systematic vantage point. Manufacturing shifts from TM to AM for only a small share of SKUs (and an even smaller share of parts). However, this relatively small share does have a relevant impact on supply chain costs. It is supported by AM with its ability to overcome minimum order quantities and offer more flexible replenishment options, particularly for slow-moving spare parts. Not only the ability to reduce the total inventory across the supply chain but also the resulting cost-efficiency lever achieved by a relatively small share of parts to be shifted is crucial.

Similar cost-efficiency levers are not uncommon in operations. In particular, mass customization (also seen as a promising area of AM [Reeves, Tuck, & Hague, 2011; Tuck, Hague, Ruffo, Ransley, & Adams, 2008]) can benefit from the systematic leverage of a specific manufacturing technology for a

relatively small share of parts or components. Comparing product characteristics of mass customized products to spare parts, certain commonalities are obvious, for example, high product variety, unreliable demand forecasts, and challenges in inventory management (Anderson, 2004). To solve these challenges, manufacturers of mass-customized products often decide to adopt a modular product design with postponement (Su, Chang, & Ferguson, 2005). Standard components (e.g., axles for cars or zippers for apparel) that do not require customization are common across all products and are mass-manufactured to capture efficiency and economies of scale from traditional production processes (Duray, Ward, Milligan, & Berry, 2000; Holweg & Pil, 2004). Other components that enable differentiation (e.g., seats for cars or patches for apparel) are customized to offer high product variety or to create individual solutions using highly flexible manufacturing processes (Feitzinger & Lee, 1996). In line with our AM setting, the system benefits from a large number of SKUs produced in high quantities at low costs and a much smaller number of SKUs customized and manufactured at higher costs.

While we use empirical data and direct feedback to evaluate our design, the design research remains in an early stage. Following a problem-centered approach, we have so far limited the exploration to a single case company. The approach has not been tested in other companies, which limits the generalization of the design across various application domains (van Aken et al., 2016). In framing the problem, we do identify commonalities with other OEMs and find in the literature common after-sales conditions and requirements across industries, providing initial evidence that the results may be transferable (Bundschuh & Dezvane, 2003; Cohen & Lee, 1990; Hu, Boylan, Chen, & Labib, 2018; Huiskonen, 2001; Kennedy, Patterson, & Fredendall, 2002; Wagner et al., 2012; Wagner & Lindemann, 2008). Nevertheless, we leave it to future research to investigate the assessment of switchover share in other empirical settings. For example, we have identified the cost-efficiency leverage that AM holds in shifting spare parts from TM to AM. While we model and test this production shift given real-world data, we have not implemented one-for-one replenishment using AM. Although we are well aware of the given drawbacks, it is the urgency for new approaches that inspired our research efforts. Currently, only a certain share of SKUs might be technically feasible for AM. Nonetheless, future declines in machine prices, advances in material availability, and increases in machine capabilities will very likely involve a notable share of parts candidates (D'Aveni, 2018).

For this reason, our results guide practitioners on decisions regarding which fraction of the spare parts portfolio systematically switches toward AM. As shown in Figure 3, it functions as a strategic assessment following a system-level perspective. Thus, this assessment functions only at the beginning for the final selection

FIGURE 3 Research classification for parts selection

of suitable part candidates. Upon this initial strategic assessment, further operational assessments that consider a wider range of part-specific operational and economic factors are needed. As a next step, Knofius, van der Heijden, and Zijm (2016) present a systematic ranking procedure for selecting potential parts for switchover in a spare parts portfolio. As Jarzabkowski and Kaplan (2015) point out, such system level assessments provide useful perspectives for facilitating strategic and operational change in practice. Considering the unpredictability of advancements in AM, strategic assessments can then provide the basis for exploring new possibilities and ways forward to adopt AM in spare parts operations (Jarzabkowski & Kaplan, 2015; Whittington, 2006). In line with these ideas, we extended our approach by a scenario analysis to examine the impact of the locations of warehousing and production, and find that the switchover share from TM to AM is relatively robust across centralized and decentralized supply chain footprints.

In conclusion, given the continuous technological progress of AM and the associated broadened areas of application, we aim to explore and understand the underlying mechanisms of utilizing AM in spare parts operations. Taking a holistic view of the entire spare parts portfolio, we propose a novel area of applying AM in real-life operations. The potential for rapid implementation of one-for-one replenishment of AM spare parts can again be illustrated by

a comparison to mass customization: within less than 500 days, the entire hearing aid industry in the United States shifted the production of mass-customized hearing aid shells from TM to AM (D'Aveni, 2015). Such short periods of time leave no doubt that foresight and preparation for switchover is the right approach also in after-sales operations.

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APPENDIX A CASE STUDY INFORMATION

In the following, we provide further information about the data set collected from the case company. A detailed analysis of the spare parts demand characteristics reveals a

TABLE A1 Spare part monthly demand data descriptive statistics

	Overall average	% zero values	Average value if nonzero
Mean	1.1	70.7	3.2
SD	1.6	25.1	4.3
Maximum	8.3	99.1	400
75 percentile	1.3	92.6	3.6
50 percentile	0.4	79.8	2.0
25 percentile	0.1	54.6	1.3
Minimum	0.0*	0.0	0.0*

Note: *due to rounding equal to 0.

TABLE A2 Demand data distribution fitting

	$\lambda \leq 5$		$\lambda \leq 10$		$\lambda \leq 50$		$\lambda \leq 100$	
	Strong fit (%)	Good fit (%)	Strong fit (%)	Good fit (%)	Strong fit (%)	Good fit (%)	Strong fit (%)	Good fit (%)
Normal	0.0	0.0	0.0	0.0	0.15	0.78	1.5	2.1
Poisson	92.4	2.8	82.2	3.9	64.6	4.7	60.4	4.7
Gamma	32.0	6.8	25.2	5.6	18.7	5.1	19.6	5.6
Neg. Bin.	83.2	1.0	78.6	0.1	83.6	1.3	81.9	1.7

common demand pattern for spare parts. As presented in Table A1 and highlighted in Section 2, the case company is challenged by intermittent demand with an average overall monthly demand of 1.1. On average, in 70.7% of all months, an SKU has no demand.

Considering the characteristic demand features of spare parts, we apply a Poisson distribution to model the spare part demand for every single SKU. To support this decision, we analyze the fit of statistical distributions to the provided demand data by comparing the selected Poisson distribution to several other common distributions. Following the approach of Syntetos, Babai, and Altay (2012), we chose the Kolmogorov–Smirnov (K-S) test to assess the statistical goodness of fit and find a strong fit for Poisson. A comparison of different distributions is provided in Table A2.

APPENDIX B INVENTORY MODELING FOR AM AND TM IN SPARE PARTS SUPPLY CHAIN

As part of the portfolio level analysis to examine the switchover share from TM to AM, we model two different inventory systems for AM and TM. For each manufacturing technology, we apply a different inventory policy (i.e., (r, q) for TM and $(S-1, S)$ for AM). For demand, we assume a stochastic process that follows a Poisson distribution with a mean of λ per year, which is a commonly applied assumption in spare parts management (Syntetos et al., 2012) (compare Appendix A).

In line with our focus on supply chain- and inventory-relevant costs, we consider cost parameters as shown in Table B1 and assume for simplicity that all of the other parameters are the same for AM and TM (e.g., reliability, performance or lead times). The variable unit production costs for AM and TM per part are c^{AM} and c^{TM} , respectively. We generally assume that the unit production costs of AM and TM differ and that AM's variable production costs are greater than or equal to those of TM, that is, $c^{\text{AM}} = (1 + \Delta^{\text{AM}}) \cdot c^{\text{TM}}$ with $\Delta^{\text{AM}} \geq 0$. Δ^{AM} represents the AM unit cost premium as a percentage of TM's variable production costs.

Furthermore, we consider inventory holding costs h per unit per year and backorder costs b per unit per year. Unfilled demand is backordered since there are no alternative sources or substitutes. We define h , b , and k^{TM} as

percentages of the unit production costs of TM. All of the costs are considered as the average cost per year, and we abstract from the discounting effect over longer time horizons. On a final note, we do not consider the application of either production technology for the same product.

For inventory management in TM, we assume a classic fixed production quantity (r, q) inventory policy. Following the notation of Zipkin (2000, 177–178) for the inventory decision variables, the policy is defined by the reorder point r and the production quantity q ; a production of size q is triggered as soon as the inventory position reaches the reorder point r . The objective function Z^{TM} , representing the sum of inventory-related and production costs in TM, is defined as follows:

$$\min Z^{\text{TM}} = \frac{k^{\text{TM}} \cdot PF + h \cdot I^{\text{TM}} + b \cdot B^{\text{TM}}}{\lambda} + c^{\text{TM}}$$

The simultaneous optimization of (r, q) in TM follows an optimization algorithm proposed, for example, by Nahmias (2009, pp. 305–306) (see also Hadley and Whitin (1963, 162–167)).

In contrast to TM, AM follows a base stock $(S-1, S)$ inventory policy, indicating that a reorder is placed once any demand occurs and the inventory position drops below the base stock level S (Feeney & Sherbrooke, 1966). This policy is also known as the “sell-one/buy-one” or “one-for-one” policy, in which inventory is reviewed continuously (Schultz, 1989). This model is particularly appropriate for expensive parts subject to a very low demand rate (Schultz, 1990). Given the free-forming capabilities of AM, fixed production and unit-specific setup costs are limited (Gibson, Rosen, & Stucker, 2015, 9–10), rendering the $(S-1, S)$ inventory policy a viable alternative (Schultz, 1990). Some researchers contend that AM overcomes the traditional concept of economies of scale, and the difference in producing a lot size of one or of 100 lies solely in the variable production costs of the consumed building materials and machine usage. However, preprocessing and postprocessing exercises can be resource intensive. Examples include not only the digitalization and preparation of a printable file but also the preparation and optimization of print bed use (Khajavi, Holmström, & Partanen, 2018) (please see Section 4 for further details).

TABLE B1 Overview of cost parameters

Variable	Notation	Unit cost (in €)
Backorder costs	b	Per unit of demand per year
Holding costs	h	Per unit in inventory per year
Variable AM production costs	c^{AM}	Per unit produced
Variable TM production costs	c^{TM}	Per unit produced
Fixed TM production costs	k^{TM}	Per production run

Analogous to TM, the objective is to minimize the steady-state average cost per part produced. Accordingly, the objective function Z^{AM} for AM is as follows:

$$\min Z^{AM} = \frac{h \cdot I^{AM} + b \cdot B^{AM}}{\lambda} + c^{AM}$$

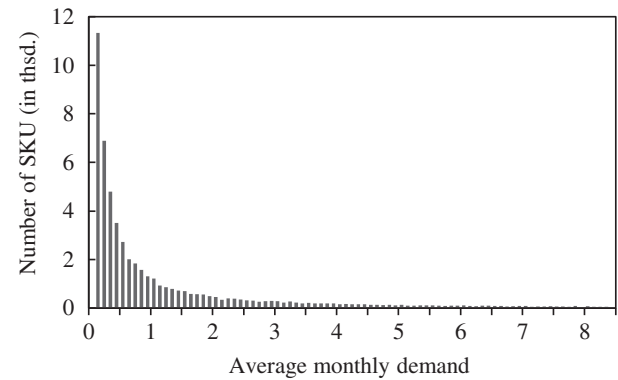
To calculate S , we follow the approach proposed by Zipkin (2000, p. 447) (see also Hadley and Whitin (1963, 204-205)), which leverages a bisection procedure that solves for the complementary cumulative Poisson distribution function.

APPENDIX C EXEMPLARY SWITCHOVER ANALYSIS FROM TM TO AM IN SPARE PARTS SUPPLY CHAIN

In the following, we outline the step-wise approach used to calculate the costs for using TM and AM for two sample SKUs from our full data set with 53,457 spare parts. In line with the interest of the case company to remain confidential, we simply refer to these SKUs as SKU A and SKU B. We follow the steps outlined to define the switchover decisions for each SKU in line with the summary of the approach described in Section 3.

We first present the raw data that was used to obtain the switchover decision. Then, we estimate the demand parameter for each SKU using the Poisson distribution and calculate the goodness-of-fit. Next, we calculate the optimal inventory policy parameters for TM and AM. Then, we use the obtained parameters to calculate the total expected costs for TM and AM. Finally, we decide on the switchover for each SKU (based on the lowest cost) and calculate three key performance indicators for the sample portfolio.

It is the objective to illustrate the approach used and to clearly demonstrate how to get from the raw data to the outcome. Accordingly, we selected SKU A and SKU B from the full data set. Given the mean monthly demand of SKU A ($\lambda = 0.80$) and SKU B ($\lambda = 0.21$), the SKUs are fairly representative for low volume demand items in the data set (see Figure C1 below for the average monthly demand by SKU for all SKUs).

**FIGURE C1** Frequency of mean demand for all SKUs

Data

We obtained monthly demand data for 108 months and additional SKU-specific information for each of the 53,457 SKUs. The monthly demand for the 108 months is provided in units in Table C1.

The aim of the methodology was to keep the data collection process for the company as simple as possible. Accordingly, additional data provided by the case company is as in Table C2.

Fit of Poisson distribution

Based on the demand for the 108 months, we fitted the Poisson distribution for the monthly demand parameter λ . Following the approach of Syntetos et al. (2012), we chose the Kolmogorov–Smirnov (K-S) test over the chi-square test to assess the statistical goodness-of-fit. In line with Syntetos, Lengu, and Babai (2013), we consider that we have a strong fit if the K-S test statistic is less than the critical value for 5% and a good fit if the K-S test statistic is less than a critical value of 1% but larger than a critical value of 5%. In the given example with a sample size of 108 months, the critical values are 0.131 (5%) and 0.157 (1%). The goodness-of-fit test indicates a strong fit for both SKUs in Table C3.

Calculation of optimal inventory policy parameters

For inventory modeling, we use a (r, q) policy for TM and a $(S-1, S)$ policy for AM. With the estimated demand parameter λ calculated in the previous step, we can derive the optimal inventory policy parameters for TM and AM.

The inventory policy for TM requires a more complex specification of two inventory policy parameters: the reorder point r and the order quantity q . The simultaneous optimization of (r, q) in TM follows an optimization algorithm proposed, for example, by Nahmias (1981) (see also Hadley and Whitin (1963)) to model inventory systems defined with demand

SKU A												
Year/month	1	2	3	4	5	6	7	8	9	10	11	12
2007	0	3	1	0	0	0	1	1	1	0	0	0
2008	3	2	0	4	0	0	0	0	0	1	5	3
2009	0	1	1	0	2	0	1	0	0	1	1	0
2010	0	1	0	0	0	1	0	0	1	3	2	0
2011	1	1	0	1	0	0	0	0	0	0	2	4
2012	0	1	0	1	2	1	1	1	0	2	3	1
2013	0	0	0	0	0	3	2	0	1	0	0	0
2014	4	0	1	1	1	2	1	0	0	1	0	0
2015	1	1	0	1	1	0	0	0	1	1	1	0
SKU B												
Year/month	1	2	3	4	5	6	7	8	9	10	11	12
2007	1	2	0	1	1	2	1	0	1	0	0	1
2008	0	0	1	0	0	1	0	1	0	0	0	0
2009	0	0	0	0	1	0	0	1	0	0	1	1
2010	0	0	0	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	1	0	0	0	0	0	0	0
2012	0	0	0	0	1	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	1	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0	2
2015	0	0	0	0	0	0	0	0	0	0	0	1

TABLE C1 SKU A and SKU B monthly demand data in units

TABLE C2 Additional SKU-specific information

	Unit cost (Euro)	Minimum order quantity (units)	Planned lead time (days)	Inventory at cutoff date (units)	Material group
SKU A	29.66	1	10	2	Metal (DIN)
SKU B	48.75	50	10	27	Metal (small)

TABLE C3 Poisson parameter estimation and goodness-of-fit

	Estimated λ	K-S test statistic
SKU A	0.80	0.054 (strong fit)
SKU B	0.21	0.006 (strong fit)

following a Poisson distribution. The iteration algorithm can be summarized as follows:

1. Compute an initial production quantity using EOQ

$$q_0 = \sqrt{\frac{2 \cdot k^{TM} \cdot \lambda}{h}}$$

2. Calculate reorder point r using production quantity q_0 . In the conservative strategy, round to the larger r

$$r_0 = \left\lceil P^{-1} \left(\frac{q_0 \cdot h}{b \cdot \lambda} \right) \right\rceil$$

3. Assess the expected number of stock outs during the lead time, given r_0

$$E(r_0) = \lambda \cdot L \cdot P(r_0) - r_0 \cdot P(r_0 + 1)$$

4. Compute the revised production quantity q_1

$$q_1 = \sqrt{\frac{2 \cdot \lambda \cdot [k^{TM} + b \cdot E(r_0)]}{h}}$$

5. Calculate the revised reorder point r_1 using production quantity q_1

$$r_1 = \left\lceil P^{-1} \left(\frac{q_1 \cdot h}{b \cdot \lambda} \right) \right\rceil$$

6. If $|r_1 - r_0| < \varepsilon$, the optimal solution is found for q and r ; otherwise, continue from step three.

Note that we calculate the optimal reorder point and the optimal order quantity without any restrictions. However, in a practical setting, the order quantity may be bounded, for example, due to a minimum order quantity imposed by the supplier or based on logistics aspects, such as package or pallet sizes. If the minimum order quantity of a SKU exceeds the optimal order quantity, we update the reorder point accordingly.

In contrast to the optimal inventory policy for TM, the optimal inventory policy for AM employs only the base

stock level S as a single parameter. To calculate S , we follow an approach proposed by Zipkin (2000) (see also Hadley and Whitin (1963)) that leverages a bisection procedure that solves for the complementary cumulative Poisson distribution function. The algorithm can be summarized as follows:

1. Calculate the critical ratio CR based on the cost ratio of holding and backorder costs

$$CR = 1 - \omega = 1 - [b/(b + h)]$$
2. Apply a bisection search procedure to compute the optimal base stock level S that ensures that the backorder probability $G^0(S)$ does not exceed the critical ratio

$$G^0(S-1) > CR \geq G^0(S)$$
3. If $G^0(S-1) \leq CR$, the optimal base stock level is found

These algorithms provide the optimal reorder point r and order quantity q for TM and the optimal base stock level S for AM. We ran the analysis for three parameter values k^{TM} for the fixed production for TM: 10, 100, and 1,000% of the variable production costs.

For this example, we use the $k^{TM} = 100\%$ setting. For SKU A, the optimal TM order quantity $q = 10$ is feasible given the minimum order quantity of one. However, for SKU B, the optimal order quantity $q = 6$ is below the minimum order quantity 50 offered by the supplier. Accordingly, instead of $q = 6$, $q = 50$ is selected as the order quantity for TM for SKU B. For AM, the minimum order quantity is one and not a source of concern. As a result, we use the following inventory parameters in Table C4.

Calculation of expected costs

For TM, we approximate the production costs by the net purchase price of each spare part currently paid by the case company. For AM, we take the TM production cost and add a cost premium (Δ^{AM}) that accounts for higher production

costs with additive manufacturing. For this example, we use the cost premium of $\Delta^{AM} = 100\%$.

We obtain total expected costs per year based on the sum of production cost (allocated to the parts demanded) and inventory-related costs. The (annual) production cost can be easily calculated by multiplying the expected annual demand with the unit costs for AM and TM. Given the monthly demand, rate $\lambda = 0.80$, the total annual production costs for TM for SKU A can be calculated as $0.80 \cdot 12 \cdot 29.66$ Euro = 284.74 Euro. For SKU A with AM, this is $0.80 \cdot 12 \cdot 59.32$ Euro = 569.47 Euro. Recall that AM has a cost premium $\Delta^{AM} = 100\%$, that is, unit AM production cost doubles to $c^{AM} = (1 + \Delta^{AM}) \cdot c^{TM} = 59.32$ Euro. For SKU B, the calculation is likewise.

The inventory-related costs are based on the holding costs and backorder costs. Based on the discussions with the case company, we jointly defined the annual inventory holding cost rate $h = 20\%$ and backorder cost rate $b = 200\%$. In line with the company's current approaches, holding costs relate to all physical and financial holding costs (as well as potential depreciation of obsolete stock).

The expected inventory and backorder levels are calculated based on the formulas provided by Zipkin (2000). We illustrate the calculation for our example for SKU A. The expected inventory for TM can be approximated by taking the reorder point plus half the cycle inventory, which is $2 + 10/2 = 7$. Given the annual inventory holding cost rate of 20%, this yields inventory-related costs of $7 \cdot 0.2 \cdot 29.66 = 41.52$ Euro. The remaining inventory-related costs are given by the expected backorder costs of 3.73 Euro.

For AM, the expected inventory for $S = 1$ is close to 1 (actually a bit lower due to the few demands and lead time to replenish the items). Accordingly, the holding costs could be approximated as $1 \cdot 0.2 \cdot 59.32 = 11.86$ Euro (actually it is 10.48). The expected backorder costs are 0.97 Euro. The exact total inventory related costs are 10.48 Euro + 0.97 Euro = 11.45 Euro. For SKU B, the calculation is likewise with the only difference

TABLE C4 Comparison of optimal and applicable TM and AM inventory parameters

	Optimal inventory parameters			Applicable inventory parameters		
	TM		AM	TM		AM
	r	q	S	r	q	S
SKU A	2	10	1	2	10	1
SKU B	1	6	1	1	50	1

TABLE C5 Expected annual cost (in Euro)

	TM			AM		
	Production costs	Inventory-related costs	Total costs	Production costs	Inventory-related costs	Total costs
SKU A	284.74	45.26	330.00	569.47	11.45	580.92
SKU B	122.85	258.57	381.42	245.70	18.83	264.53

that the expected inventory for SKU B is driven by minimum order quantity 50. This yields an expected inventory of $1 + 50/2 = 26$.

The following Table C5 summarizes the expected costs.

Switchover decision

Based on the calculated expected total annual cost we can easily decide on switchover from TM to AM. For SKU A, the switchover to AM is not beneficial for $\Delta^{AM} = 100\%$ as the AM costs are higher than TM. For SKU B, the costs for AM are lower for $\Delta^{AM} = 100\%$. The resulting cost saving for SKU B is 30.6%. Both decisions taken are highlighted in bold in the table above.

To bring this switchover decision into context for the sample portfolio with only two SKUs, this results in the following key performance indicators:

1. 50% of the SKUs are switched to AM (i.e., one out of two SKUs)
2. 20.79% of the total units supplied are produced with AM (i.e., given the total expected monthly demand of $0.80 + 0.21 = 1.01$ units)
3. Total expected cost are 83.57% compared to the prior costs based on the switchover of SKU B to AM

If we compare these numbers to Figure 2, it would relate to one data point provided at $\Delta^{AM} = 100\%$ for the $k^{TM} = 100\%$ curve (given this small sample portfolio of two SKUs).