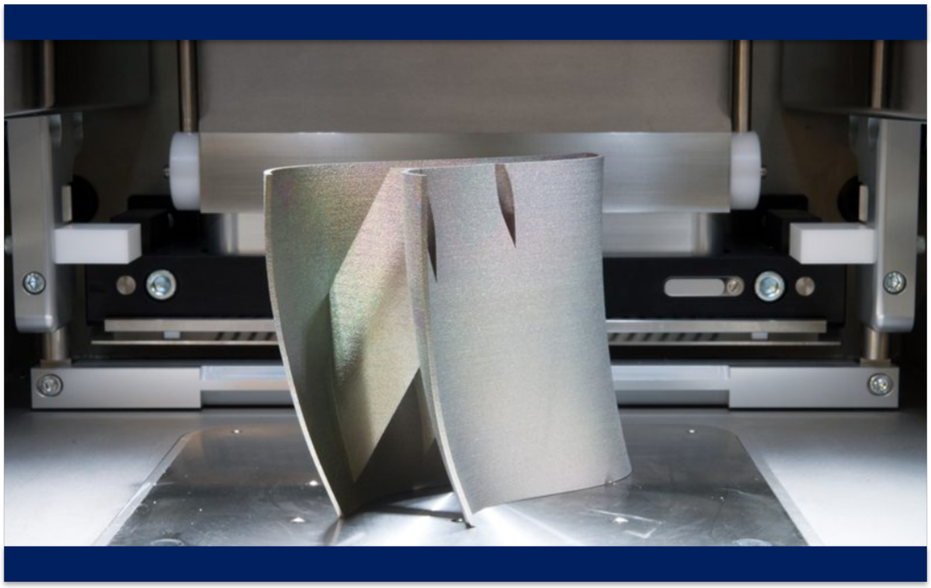
Towards a Digital Spare Parts Supply Chain



A Roadmap for Implementation

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June 2020

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Background

In the last decades, offshoring was a major trend across industries. Lower labor cost, economies of scale, or greater access to human capital were only some of the incentives for pushing decision-makers to carry out business activities around the globe. However, this approach came at a cost. Simple regional supply chains grew into complex multi-national supply networks controlled by a multitude of stakeholders. More and more resources hat to be allocated to balance conflicting goals and coordinate specialized know-how. Fueled by political tensions and recent supply disruptions, it comes without surprise that the consideration of reshoring initiatives are a centerpiece of many strategic management meetings.

But does this development indicate a turning point – from a global economy back to regional economies? The clear answer is no. Instead, recent reshoring initiatives indicate that resource requirements to balance and coordinate global supply networks outweigh their benefits. Thus, the question arises, how can balancing and coordinating efforts be reduced while continue benefiting from global supply networks? Next to political initiatives aimed at slashing trade barriers, perhaps the more reliable route is realizing the improvements offered by various technologies.

A key concept in this regard is the digital spare parts supply chain. Instead of distributing and stocking spare parts worldwide, global know-how is used to manage spare parts digitally. Accordingly, the demanded spare part is produced only if required based on the most recent design close to the point of use. A digital spare parts supply chain lowers resource requirements of global supply networks while the benefits of a global economy remain largely intact.

1 Motivation and Outline

For a long time, a digital spare parts supply chain has been considered infeasible primarily because of lengthy setup times and the necessity of dedicated tooling. However, with the maturation of Additive Manufacturing (AM) technology, these obstacles disappeared. A short AM setup time and no requirement for dedicated tooling support digital spare parts provisioning. Furthermore, utilizing generic AM processes relaxes the dependency on suppliers and therefore increases supply chain resilience. However, digitizing the spare parts' assortment is a complex task. Many stakeholders must be aligned and are required to challenge established working routines. As a result, practitioners are challenged to develop a well-structured digtization initiative fit for their specific needs.

In this article, we will advice practitioners on how to approach a digitalization initiative. Therefore, we draw from our experience gained from different digitalization initiatives in different industries over the last years. This article is structured into two parts: First, we will provide the reader with the required background knowledge about digital spare parts' supply chains and, second, we will give specific advice on how to organize a digitization initiative and explain proven tools and methods that contribute to a successful implementation.

2 Part I: Fundamentals of Digital Spare Parts' Supply Chains

Additive Manufacturing (AM), also known as 3D printing, is a key enabler of digital spare parts' supply chain. It is motivated by its unique capabilities. In Section 2.1, we will first familiarize the reader with the key benefits and challenges of AM to offer the reader an impression about the capabilities of the technology. Next, in Section 2.2, we will summarize the opportunities of digital spare parts supply chains to clarify its motives.

2.1 Additive Manufacturing Technology

AM technology has matured to a level at which final part production becomes an established process. However, technological advancements are still rapid and thus add to the quality and variety of AM producible parts. Today, a wide range of industrial AM technologies are available, of which the most important ones are selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), digital light processing (DLP), and fused deposition modeling (FDM). Detailed descriptions of these technologies fall outside the scope of this work; it suffices to say that they differ widely in terms of the amounts and types of materials used, their speeds and accuracies, and their domains of application. For a more comprehensive discussion on the differences between the various AM technologies, we recommend the work by Gibson et al. (2010). For an overview of the current AM production capabilities, please refer to Wohlers Report (2020).

The unique production process of AM technologies has several implications for the future of manufacturing. Table 1 summarizes the most widely discussed benefits and challenges. In Section 2.1.1, we will focus on the potential benefits derived from the basic properties of AM technologies. In Section 2.1.2, we will discuss the challenges of today's AM technologies and the trade-offs involved when compared to conventional manufacturing methods.

Tab. 1: *Benefits and Challenges of AM as compared to conventional manufacturing methods.*

Benefits	**Challenges**
General-purpose equipment	Pre- and post-processing requirements
Design freedom to produce complex and tailored parts	Limited range of printable parts
Reduced material waste and operational energy consumption	Diminished part characteristics
High level of customization and fast changeovers	Design rights and liability
Faster time-to-market	High marginal production costs
	Technological obsolescence and missing standards

2.1.1 Benefits

(+) *General-purpose equipment*

Shifting between designs on conventional manufacturing equipment often requires both a lengthy setup process and change in the dedicated tooling. By applying AM technology, this process is likely to significantly simplify, since both setup process and tooling are replaced by restarting the printing process from another digital file. In many printing processes, it is even possible to print several completely different parts in parallel. The resulting flexibility not only reduces the investment and storage costs of dedicated tooling but also increases productivity and asset utilization. Furthermore, business models that allow companies to rent out their excess production capacities may also become profitable or help to cover the fixed costs.

(+) *Design freedom to produce complex and tailored parts*

The design freedom afforded by AM technologies is certainly one of the primary benefits. Design compromises to improve manufacturability are significantly less limiting when applying AM technologies rather than conventional manufacturing and thus facilitate designing parts for their intended use. Complex structures can be built that strike a nearly optimal balance between strength and material usage, which is not feasible using subtractive technologies. Benefits can be observed in the aerospace industry where light-weight designs, which are only producible using AM, lead to significant fuel savings. Other common examples for design improvements concern heat exchangers or valves for which thermal control or flow resistance is improved.

(+) *Reduced material waste and operational energy consumption*

The reduction of materials used is a clear result of applying additive processes. It should be noted that the materials are fed to an AM machine in modes different from those used in subtractive processes. For example, Achillas et al. (2015) refers to cases in which a 40% reduction in material consumption was achieved compared to conventional manufacturing methods. Combined with the more uniform requirement for raw materials, this characteristic may compensate for the often energy-intensive production process inherent to AM. Indirect effects caused by lower weight or optimized part properties may further reduce energy consumption. Hence, from a life cycle perspective, the energy balance of 3D-printed parts may well turn out to be positive.

(+) *High level of customization and fast changeovers*

The opportunity to design products according to customer specifications and manufacture them on demand by only using basic materials is entirely a result of both the design and manufacturing process being highly digitalized. Tooling or product-dependent setup processes are usually not required, thereby making AM a highly flexible technology. For instance, design changes or product changeovers can easily be realized while the production process remains unaltered. Especially for medical and dental applications where customer-specific solutions are paramount, AM has already transformed entire supply chains.

(+) *Faster time-to-market*

The fact that the design and manufacturing processes are so closely intertwined, along with the fact that the product is built in one piece from only raw materials, simplifies the development phase and eliminates a number of steps involved in the assembly process. Hence, AM can significantly reduce the time-to-market, which may yield a competitive advantage. Risks associated with market failure decrease, given the low setup and tooling costs. Accordingly, AM may likely support an aggressive market strategy. Furthermore, rapid design changes based on market feedback appear less demanding and thus give rise to more dynamic business models.

2.1.2 Challenges

(–) *Pre- and post-processing requirements*

Most prominent is the misperception that an AM process itself produces industrial-grade parts. The reality usually involves various process steps, each of which may require software, equipment, and high levels of expertise. Before starting the printing process, the printing design must be generated, and the AM equipment may require preparation. For instance, it may be necessary to change the feed stock which, in the case of metal printing equipment, involves extensive cleaning of the build chamber. Further, major post-processing steps are often required to meet quality standards. Support structures may need to be removed, or treatments may be required to improve material properties. Furthermore, process variability, inherent in today's AM methods, often necessitates extensive quality controls that increase both production lead time and cost. Both technological improvements and increasing standardization of the production process gradually lessen the burden of this challenge.

(–) *Limited range of printable parts*

While AM technology certainly offers a high degree of design freedom, it also has limitations. For instance, printing bulk structures remains challenging, as both porosity and the risk of thermal stress may occur more frequently. Hence, most industrial printing processes must adhere to printing size and density limitations. Furthermore, depending on the printing process, the limited number of materials and the inability to combine multiple types decrease the feasible range of printable parts. For instance, printing complex electronics is more likely to remain infeasible in the foreseeable future due to the necessity of composite structures. However, technological advancements expand the range of feasible materials and relax possible design constraints. In addition, depending on the part, it may be feasible to achieve the same part's functionality with a different design or material.

(–) *Diminished part characteristics*

The characteristics of an AM part may not compare favorably to those of their conventionally manufactured counterpart. For example, based on the process characteristics of AM, the unit cost and reliability of a conventionally manufactured equivalent may be superior. Moreover, conventional parts that are assembled from components can often be repaired by replacing a malfunctioning component, after which the part can be re-assembled. However, on a part-by-part basis, these limitations can often be compensated by design or supply chain improvements. For instance, in practice, cases may arise in which a three times higher piece price can be compensated by significantly decreased inventory cost through a short AM lead time.

(−) *Design rights and liability*

Currently, the design rights of a significant number of parts that are suitable for printing are owned by another entity. Acquiring the design rights may prove to be cumbersome and may potentially require high investments, in particular if it would impact future business opportunities of the existing design holder. To overcome this challenge, the supply chain stakeholders need to find a fair allocation of the possible supply chain benefits that can be achieved using AM.

Additional concerns are raised by the digital nature of AM methods. With increasing flexibility, businesses worry about both the protection of intellectual property rights and product liability. The latter is clarified by a simple example. Consider an innovative company that offers 3D-designs of its products for sale. If a customer printed this product (maybe with slight alterations to the design) and it subsequently failed, the following question would arise: Who is responsible for the failure; the company, the service provider, or the AM equipment manufacturer? At present, no standardized legal agreements are in place, which creates uncertainty around otherwise promising new business models. To address this challenge, it is likely that track & trace solutions will play a prominent role. This will grant full visibility of the use of certain designs and thus allow enforcing qualification and certification procedures.

(−) *High marginal production costs*

If compared to a production method such as injection molding, it becomes clear that AM addresses a specific market segment. Injection molding, which itself offers high design freedom, is essentially the opposite of AM in terms of flexibility. High upfront investments in dedicated molds require a high degree of commitment while changeovers to another product, which involves changing the molds, may be time-consuming. Despite this, unit costs are low for high volumes, and since the actual production time of a single product may be a matter of seconds, the technique is typically suitable for mass production.

On the other hand, AM is not at all suitable for mass production. The printing of large and complex product geometries may take several hours, and is often highly energy intensive. In combination with low economies of scale, this leads to high marginal production costs. As technological improvements are unlikely to allow AM technologies to compete on production speed with conventional manufacturing methods, it is likely that AM technology will usually be relevant for low-volume market segments.

(–) *Technological obsolescence and missing standards*

Another problem arises due to the novelty and short development cycles of AM technology. If a company invests in AM machinery, its equipment may well become outdated after only a short period of time. Although leasing or outsourcing concepts may lower these risks, rapid technological advancements also demand a high degree of organizational flexibility. In particular, the absence of standards often forces businesses to reorganize production processes on a per-part basis. However, initiatives become increasingly successful in establishing industry-wide standards that gradually decrease the negative effects of this challenge.

2.2 Drivers of the Digital Spare Parts Supply Chain

The digital spare parts supply chain offers several opportunities for improvement compared to conventional spare parts supply chains. In this section, key opportunities are summarized.

- **Inventory reductions**

  Long and uncertain lead times force businesses to keep high stock levels to achieve a desired response time. Associated inventory costs resulting from the cost of capital, handling, stock-outs, and overstock are the largest cost contributors to the total life cycle cost of most capital goods. The production of parts on demand, close to the point of use with AM technology, may substantially decrease the inventory requirement while achieving the same response time.

- **Simplify the operation of complex supply chains**

  To benefit from the global economy, most businesses operate complex supply chains. Such supply chains result in high risks associated with supply disruptions and high resource requirements for the coordination of stakeholders and distribution of goods. By producing parts with AM on demand and close to the point of use, the physical goods flow is replaced by a digital exchange of information. This approach increases supply chain resilience and reduces inefficiencies associated with the coordination of stakeholders and the distribution of goods.

- **Support maintenance of legacy systems**

  Most capital goods span a life cycle of several decades. Sourcing spare parts becomes increasingly difficult, particularly for legacy systems. For example, suppliers may no longer exist or may decide that the production of certain spare parts is no longer economically viable. Frequently, this situation forces businesses to an expensive system redesign or to inefficient, large final orders. In the worst-case scenario, entire systems must be taken out of service, which causes significant financial loss. With the production flexibility of AM technology, it often becomes possible to replace the conventional part with an AM-produced form-fit-function and thus reestablish the supply continuity.

- **Ad-hoc part supply for overhauls and corrective maintenance**

  The spare parts requirements during general overhauls or corrective maintenance is difficult to predict. Hence, businesses often face extensive system downtime due to unavailable spare parts. Alternatively, businesses may carry excessive “just-in-case” stock or rely on expensive emergency supply channels. Producing spare parts on demand with AM technology may offer a better option -– even if AM only allows the production of an inferior form-fit-function part that supports the temporary operation of the system until the original replacement part arrives.

- **Increased system performance**

  Dedicated tooling or high setup costs inhibit regular design improvements and modifications. However, system users may realize that a system modification can improve system performance. AM technology does not rely on product-specific tooling and thus may increase the viability to perform a system redesign or make modifications to improve system performance.

- **Extension of repair capabilities**

  Spare parts demand that originates from maintenance activities may be positively affected by an increasing number of repair options. For instance, worn-out parts that were previously discarded or too expensive to repair may well become repairable using AM, which subsequently may significantly reduce maintenance costs. Moreover, lower-level repairs may become feasible, thereby increasing the potential to extend the life cycle of complex components at low costs.

- **Increased sustainability**

  Complex supply chains and large spare parts inventories contribute to the extensive resource requirements of the global economy. For example, fuel consumption for transportation, the requirement of packing material, and the disposal of overstock negatively affect the eco-balance of complex supply chains. Evidently, a digital spare parts supply chain has the potential to significantly decrease these effects.

3 Part II: Implementing a Digital Spare Parts Initiative

In the second part of this article, we will continue with specific recommendations on how to structure a spare parts digitization initiative. Therefore, we will discuss a project roadmap with specific actions for each project phase in Section 3.1. Next, in Section 3.2, we will introduce the reader to specific tools and methods that can be used to support a digital spare parts initiative.

3.1 Roadmap of Digital Transformation

Implementing a digital spare parts supply chain is non-trivial. Various existing processes and perceptions must be challenged. The needs of different stakeholders must be addressed, and business-specific challenges must be overcome. In this section, we will use our experiences from different industries to establish a roadmap. The roadmap offers practitioners orientation and inspiration on how to structure their own digital spare parts initiative. The roadmap is organized into five phases that are summarized in Figure 1. Next, we will discuss each phase in further detail.

3.1.1 Phase 1: Build Internal Support

In the first phase, the organization must create awareness about AM and educate key personnel within the organization. Ideally, this process is coordinated and governed by a cross-functional project team. In the project team, functions from engineering, procurement, logistics, maintenance, and leadership should be represented.

Often, at this stage, it is advisable to install basic AM equipment and offer training programs that educate interested personnel about the fundamentals of AM technology. For many initiatives, hosting internal case competitions turned out to be an efficient practice. Internal competitions not only stimulate the curiosity of key personnel and leadership but also lead to additional cases.

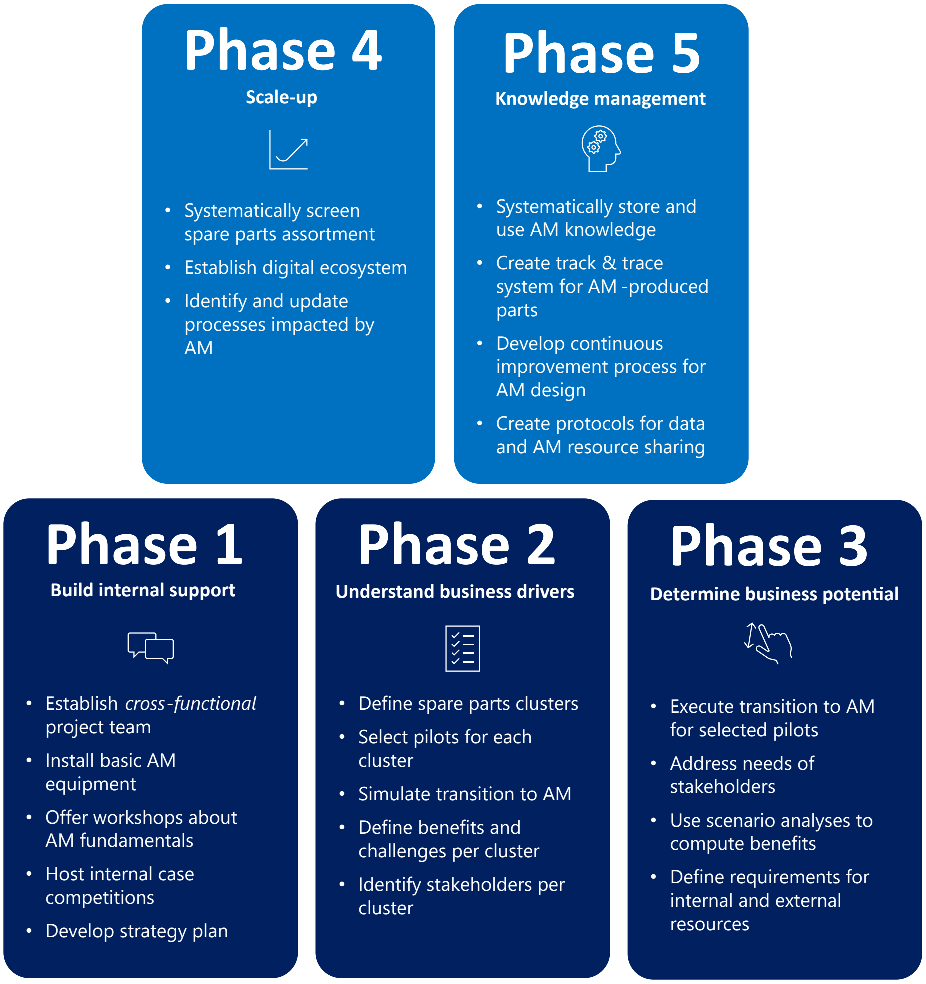

Fig. 1: *The different phases of a spare parts digitization initiative*

Initial cases such as tools or simple parts should be regularly presented to professional AM service providers, first, to educate key personnel with feedback about their own cases and, second, to gain better insights into technological constraints and challenges. The first phase should conclude with the formulation of a strategy plan that outlines the objectives and schedule of the spare parts digitalization initiative. The strategy plan is ideally approved and supported by leadership.

3.1.2 Phase 2: Understand Business Drivers

After the first phase has exposed several cases, the second phase should be used to focus the initiative. To this end, it becomes more important that the organization recognizes the benefits and challenges related to specific case types. To obtain an overview and to coordinate the initiative, it is advisable to categorize cases into different clusters. An example categorization is shown in Figure 2.

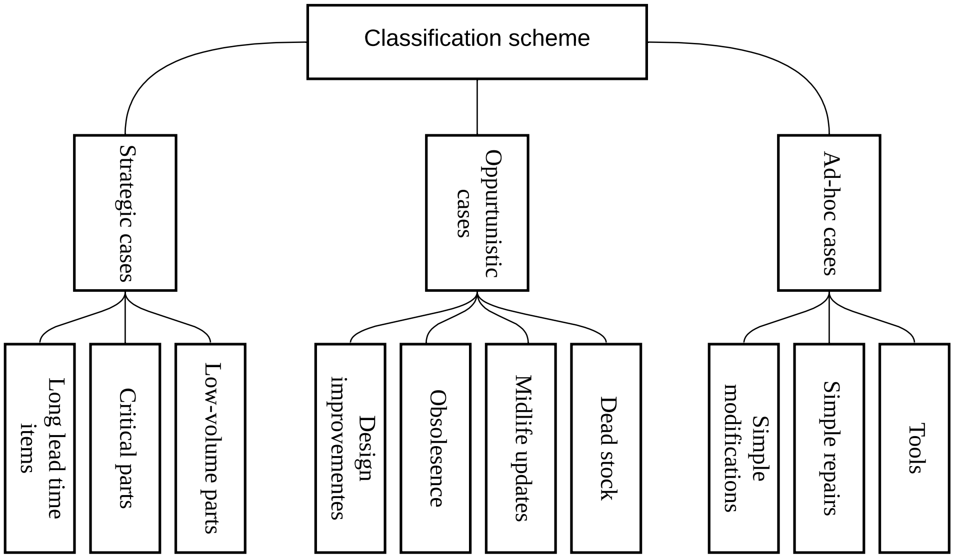

Fig. 2: *Possible case classification scheme*

After the clusters have been defined, the project team (and possibly external AM experts) should select a set of representative cases for each cluster as pilots. For these pilots, a full transition to a digital spare parts supply should be simulated. For this purpose, the project team should gather information about the following aspects: cost-benefits, part redesign requirement, design qualification, certification, IP rights, production, quality assurance, and installation. It should be noted that the amount of detail with which these aspects are considered should vary depending on the complexity. At this stage, only a broad overview is required.

For example, it may turn out that the digitization of certain clusters requires new agreements with the IP rights holder, or that for certain clusters strict quality requirements must be met. Furthermore, the simulation of the transition usually yields insights which stakeholders are important for each cluster. All results should subsequently be documented and used to further prioritize efforts during later phases. Note that the prioritization step implies that the completion of the following phases will be achieved at different speeds depending on the cluster. The project team should regularly revisit each cluster to set and monitor goals.

The outcomes of the second phase provide a first overview of the benefits and challenges of each cluster. Additionally, the project team and the leadership should agree regarding the focus clusters that are prioritized during the following phases.

3.1.3 Phase 3: Determine Business Potential

The pilot studies in Phase 2 provided first insights about each cluster. The goal of Phase 3 is to further define the business potential. For this purpose, it is necessary to understand the requirements of each stakeholder in more detail. An efficient approach to reveal the needs of the cluster-specific stakeholder is to challenge them with the pilot cases. For some cases, this will lead to complexities that cannot be resolved in a timely manner but will require a more involved project. Here, it is advisable to document the observed challenges and discuss further pursuit within the project team. In general, the project team should avoid lengthy projects at this stage. Fast rewards are important to increase the initiatives' recognition and support the recruitment of additional resources to solve more challenging cases.

Likewise, performing scenario analysis is essential to obtain a better assessment about the business potential for the considered clusters. Later, in Section 3.2.1, we will discuss a possible approach to perform the scenario analysis in further detail. For now, it is important to realize that a pure qualitative assessment of the business potential will no longer be sufficient at this stage. Instead, the project team must obtain a clear picture about the resource requirement and the potential gains associated with digitizing each considered cluster. Otherwise, it will become difficult to engage in negotiations with internal and external stakeholders and to identify the most rewarding clusters.

By the end of Phase 3, the project team should have established proof of concept for using digital supply in various clusters. Furthermore, the project team should have gained the knowledge to define specific resource requirements to address the needs of different stakeholders and awareness of the business potential of digitizing certain clusters.

3.1.4 Phase 4: Scale-up

While the previous phases focused on building the foundation for a digital spare parts supply chain, Phase 4 follows the primary purpose of establishing digital spare parts supply as a standard approach within the organization. Therefore, it is important to systematically screen the the entire spare part population of each cluster for promising cases. As we will elaborate in Section 3.2.2, this task can be simplified using a data-driven approach.

Furthermore, new partnerships must be created to develop a digital ecosystem that allows the application of AM on a large scale. For example, relations with well-located AM factories must be established. Also, certification bodies must be identified with whom a standardized quality control process is developed. Lengthy and unstandardized quality control steps would reduce the logistical benefits of a digital spare parts supply chain and, more importantly, challenge the trust in the quality of AM-produced parts.

In addition, the project team must work-out a digital service model with IP rights holders at this stage. As we will elaborate in Section 3.2.2, through a data-driven approach, it becomes possible to challenge IP right holders not only punctually but with a larger spare parts population. Clearly, this approach improves the organization's negotiation position and thus provides ideal circumstances to define a digital service model in the organization's interest.

Roles in the project team familiar with sourcing, maintenance, and supply processes should analyze the potential role of a digital supply source. For instance, it is advisable that processes related to the procurement of new systems should explicitly prompt a consideration of digital supply. Similarly, for the obsolescence management of legacy systems, AM should be considered as an alternative supply source. The resulting options for process changes should be addressed within the project team and, if regarded relevant at this stage, proposed to the process owners. Overall, this action should ensure that AM is routinely considered as a supply option.

At the end of Phase 4, spare parts for which the application of AM is feasible and desirable should be available via a digital supply mode. Partnerships and agreements should be formed to achieve the implementation of AM on a large scale based on a new digital service model.

3.1.5 Phase 5: Knowledge Management

Phase 5 constitutes the final phase and should be used to increase transparency regarding the types of parts for which digital solutions are available across the organization. For example, this can be achieved by integrating a digital supply option into procurement systems.

Furthermore, feedback regarding the performance of digitally sourced spare parts should be systematically gathered to allow for continuous design improvement. For this, so-called digital twins may play an essential role. They provide access to information about the production setup, part utilization, and support track & trace access to the current installed base. Standardized routines should be developed to share the gathered data and to provide new incentives for suppliers to improve designs. For instance, IP owners should obtain visibility regarding the observed failure modes and should be compensated based on their willingness and ability to improve the design.

Additionally, it is advisable to explore the option of sharing digital infrastructure with other organizations. For instance, organizations may want to evaluate whether AM production capacities can be shared with other organizations. Likewise, it should be assessed whether it is viable to share designs or part performance records with other entities in the supply chain. At the end of Phase 5, the transition and continuous improvement of digital supply is ensured. Furthermore, the organization evaluated options with other organizations to share capacities and knowledge regarding the digital spare parts supply chain.

3.2 Tools and Methods

In Section 3.2.1, we will discuss a basic value estimation strategy that can be applied to perform scenario analysis. Next, in Section 3.2.2, we will elaborate a systematic screening method that allows the prioritization of the in-depth assessment of parts. Furthermore, we will explain how this method can be used to identify the most relevant part categories and OEMs of a cluster.

3.2.1 Basic Value Estimation Strategy

As elaborated in Section 3.1.4, sooner or later, it is important to quantify the business potential of digitizing certain clusters. A suitable method to address this need is conducting scenario analyses. For example, the project team may have gained insights into which percentage of spare parts can be digitized in a best-case scenario. Likewise, through pilot studies, the project team may have obtained information about potential lead time reductions or unit cost differences for certain clusters. These insights can be used to define scenarios – ideally in close collaboration with decision makers.

Using these scenarios, it is possible to estimate potential cost savings or other important performance indicators. In this section, we will elaborate how a model can be created to estimate potential cost savings with a digital spare parts supply chain. Of course, depending on the desired level of detail, such models can become quite complex. Here, we will focus on a simple value estimation strategy that can be further detailed as needed.

Before quantifying the business potential of digitizing an entire part cluster, first consider the situation in which an analyst wants to understand the value of replacing a single part. As we will discuss below, for such a situation, the analyst can compare the long-run average costs for both supply options. We will first elaborate the calculation of the long-run average cost for the situation with a conventionally produced spare part.

Conventional Supply Mode

Currently, the company orders the conventional part for a piece price c_C and pays a fixed cost K_C per order independent of the order size. Note that we use the subscript "C" to indicate that this value applies to the conventionally manufactured (CM) part. The order lead time is equal to L_C and, for simplicity, is modelled as deterministic (i.e., the lead time is constant). Furthermore, the system availability strategy of the company implies that in β percent of cases, the spare part should be available from the stock. This measure is also typically referred to as the fill rate. Demand that cannot be satisfied from the stock is backlogged, i.e., fulfilled as soon as resupply becomes available.

Here, for low-volume items, we make the common assumption that spare parts' demand occurs according to a Poisson process with rate λ_C. Usually, it is possible to estimate λ_C based on historic data. For example, if the company observed approximately 2 failures per year for the considered part, it is reasonable to use $\lambda_C = 2$. Furthermore, let us assume that the component order policy currently follows a continuous-review (s_C, Q_C) policy, i.e., each time the stock level drops below s_C, the company orders Q_C items. For inventory, the company incurs a holding cost rate h, which is commonly defined as the percentage of the piece price of an item. For example, given the cost of capital and storage cost, most organizations incur approximately 20% of the piece price as a typical holding cost per year. The notation is summarized in Table 2.

Tab. 2: *Notation conventional supply mode*

Notation	Example	Explanation
c_C	5k Euro	CM piece price
K_C	15k Euro	Fixed order cost for CM
L_C	0.4 years	CM reorder lead time
β	95% of items are used from stock	Fill rate
λ_C	2 items per year	CM demand rate
s_C	3 parts	CM reorder point
Q_C	7 parts	CM order quantity
h	20% of the piece price per year	Holding cost rate

A common approximation to determine a suitable order quantity Q_C is the so-called economic order quantity that is equal to

$$Q_C = \sqrt{\frac{2K_C\lambda_C}{hc_C}} \tag{1}$$

Given this setup, the long-run average cost can be estimated by the sum of the fixed and variable order costs and holding cost for in-transit stock, safety stock, and cycle stock. This is equal to

$$C_C(\lambda_C) = \frac{K_C\lambda_C}{Q_C} + \lambda_C c_C + hc_C(\lambda_C L_C + z\sqrt{\lambda_C L_C} + \frac{Q_C}{2}) \tag{2}$$

where z is defined as $\Phi^{-1}(z) = \beta$, with Φ denoting the standard normal cumulative density function. Note that assuming a normal distribution for calculating the safety stock is a common approach. Furthermore, Φ is initialized with the mean demand during the lead time $\lambda_C L_C$, the standard deviation $\sqrt{\lambda_C L_C}$, and the reorder point s_C. The reorder point should be determined such that the service level constraint β is met.

Digital Supply Mode

To calculate the long-run average costs for the digital supply mode, we adopt the same approach as for the CM supply mode. Hence, we must simply replace all parameters with the subscript "C" by the equivalent for the digital supply mode. In practice, this implies that we must estimate the average failure rate with the AM item λ_A, the replenishment lead time with AM L_A, and the fixed (K_A) and variable ordering costs (c_A). The remaining parameters are either independent of the supply mode or directly follow from the other AM input parameters.

In case the estimation of some parameters is difficult, it is advisable to consider these during the scenario analysis. For example, the analyst may consider a scenario in which the AM failure rate is X% higher compared to the CM item and a scenario in which the failure rates are identical. In the end, we will obtain a long-run average costs estimate for the digital supply mode denoted by $C_A(\lambda_A)$.

Cost Comparison

After the long-run average costs have been estimated for both supply modes, the analyst can determine the average cost savings $\Delta = C_C(\lambda_C) - C_A(\lambda_A)$ per time period, which can be achieved by shifting to a digital supply mode. Using these calculations across the spare parts population of a certain cluster, it is then possible to estimate the total cost savings potential depending on the chosen scenario.

3.2.2 Spare Parts Assortment Screening

The assessment of whether a spare part can be sourced digitally is expensive and time-consuming. Skilled (and expensive) personnel must assess various parts' characteristics to confirm the technical feasibility. Various agreements with stakeholder must be evaluated to obtain a full picture of the exact digitization costs, and finally, a suitable sourcing ecosystem must be identified to fully benefit from a digital sourcing mode.

To ensure that resources are spent on the most promising parts first, Knofius et al. (2016) developed a scoring procedure that primarily relies on data that are commonly used for supply chain optimization. Examples include historic demand, unit cost, and replenishment lead times or part criticality. Ultimately, the approach leads to a ranking of the considered spare parts population that allows focusing on the most promising parts first. In this section, we will outline the different steps of the approach and discuss various applications of the ranking to support the digitization initiative.

Ranking Approach

The ranking approach is shown in Figure 3. Next, we will discuss each step and refer to Knofius et al. (2016) for further details.

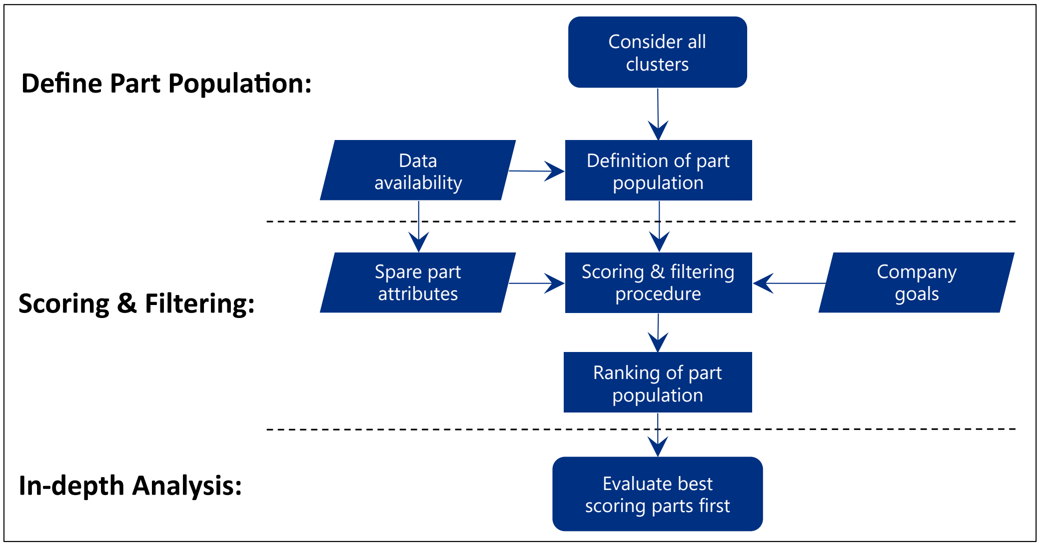

Fig. 3: *Outline ranking approach*

As shown, we begin the analysis by considering all clusters. In general, the more clusters that can be considered at ones, the more efficiently the analysis can be executed. However, in most cases, it is necessary to split the analysis and consider certain clusters separately.

For example, it can be necessary to separately consider spare parts from different assets since the goals associated with digitization may differ substantially. Moreover, one may want to focus on a certain part cluster first since they have been prioritized by the project team (cf. Section 3.1). Finally, separate analyses may become necessary if the data quality and availability substantially vary over sub-populations.

Next, we score the considered spare parts based on the values of spare part attributes that are retrievable from databases. For instance, if a spare part has a high demand rate, it may be of lesser interest than other spare parts since a conventional supply chain may allow the exploitation of economies of scale. On the other hand, if a spare part exhibits a long resupply lead time, it becomes relatively more interesting for a digitization initiative since likely substantial lead time reductions become possible.

By combining different spare parts attributes based on these relations, the analyst will be able to already generate a ranking. However, such a ranking would not reflect the goals of the digitization initiative since the importance of each relation would be determined arbitrarily by the analyst. For example, the digitization initiative may have determined that increasing supply chain flexibility is most interesting for the analyzed spare parts. Yet, spare part characteristics not indicative for improving supply chain flexibility (e.g., the remaining system usage period or the piece price) may have received the same importance in calculating the spare part rank as spare part characteristics highly indicative for improving supply chain flexibility with AM (e.g., the safety stock level and the demand rate). To avoid such shortcomings, it is advisable to define the relative importance of each spare part characteristic to achieve the desired goal with the digitization initiative. For this, the analyst may employ interviewing techniques, as discussed by Knofius et al. (2016).

Furthermore, it is possible to use part specific data to exclude spare parts that are certainly unsuitable for digitization. However, it should be noted that this step does not guarantee the technical feasibility of the remaining parts. This step simply represents a simple filtering process using constraints defined based on structurally available data.

After both the scoring and the filtering criteria have been defined, the ranking can be generated. However, before finalizing the ranking, it is advisable to execute 1 or 2 calibration steps. For this purpose, stakeholders are presented with a set of spare parts from the ranking and asked for their opinion. Ideally, the feedback obtained from different stakeholders is more or less reflected in the ranking. If this is not the case, this may indicate that the importance of certain spare part attributes must be reconsidered or that a filtering criterion needs revision. By repeating this procedure, the analyst ultimately arrives at the final ranking that can then be used to focus on the most promising spare parts for further analyses.

Applications

The ranking can be used for different means to support the digitization initiative. Here, we provide an overview of the different application options:

1. *Prioritize technical assessment*

   The ranking allows to focus the resource-intensive technical assessment on the most promising parts first. Note that the technical assessment should not focus on the question of whether AM technology is the best production method. Instead, it should focus on the question of whether AM technology is the best production method relative to the possible supply chain improvement. Results (both negative and positive) of the technical assessment should be structurally documented since these insights may become relevant at a later stage during the digitization initiative.

2. *Find promising parts for certain part categories*

   The ranking simplifies the identification of interesting cases for certain part categories. For instance, it may be desirable to digitalize as many parts in a certain category as possible. By searching through the part description, the ranking ensures that the most promising parts of this category are considered first. Likewise, it may be desirable to identify promising parts for a certain OEM or vendor.

3. *Challenge OEMs to further define digital service model*

   By analyzing the ranking, it may be identified that certain OEMs are associated with various parts that appear promising for a digital service model. Using the ranking, it then becomes possible to identify a larger set of promising, OEM-specific parts. Of course, this insight improves the interaction with the OEM. For example, the company may decide to engage in a discussion with a specific OEM to evaluate the possibility to share IP rights. Using the ranking and scenario analyses, the company can approach the OEM with a set of specific parts and can even estimate the expected savings with a digital service model. Both points strengthen the negotiation position of the company during the discussion with the OEM.

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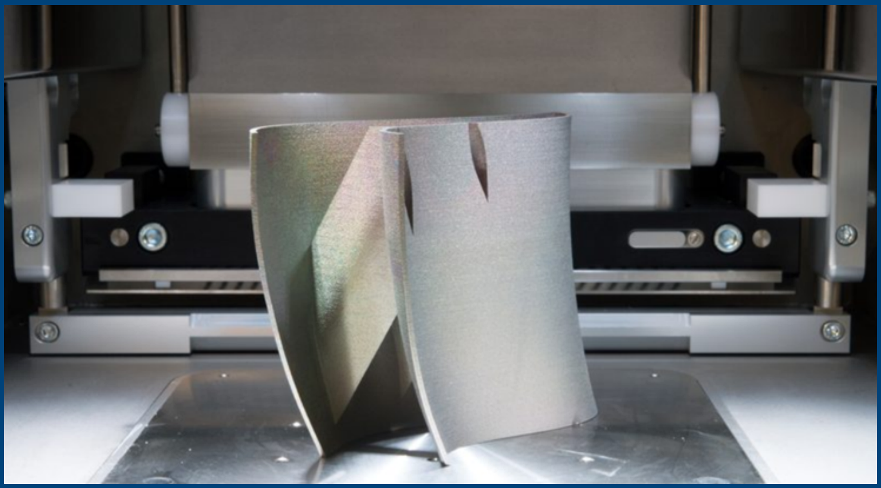

Towards a Digital Spare Parts Supply Chain

A Roadmap for Implementation

About the Author

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