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Consolidating spare parts for asset maintenance with additive manufacturing

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Abstract

Consolidation of parts is the redesign of an assembled component with fewer, but therefore more complex parts. While complex parts are often difficult to produce with conventional manufacturing (CM) technologies, the high degree of design freedom of additive manufacturing (AM) facilitates consolidation. Typically, consolidation with AM is chosen because of its functional benefits such as weight reductions. Consequences for asset maintenance, however, are not that well understood. For example, the spare parts management may profit from potentially shorter AM resupply lead times, but may suffer from more expensive consolidated parts having to be stocked in anticipation of random failures.

In this paper, we analyze the total costs of consolidation with AM, including logistics, manufacturing and repair costs. Our results suggest that consolidation with AM often leads to higher total costs. This finding mainly stems from loss of flexibility. For example, in case of a failure, a consolidated component has to be replaced entirely whereas the conventional assembled component might only require replacement of a defective sub-component. Furthermore, short resupply lead times for the consolidated spare part turn out to have little impact and therefore relativize the benefit of consolidation with AM. Overall, these findings stress the necessity to adopt a total costs perspective when assessing the effects of design changes with AM. Otherwise, design changes may lead to unforeseen effects which may render its application debatable, even despite substantial functionality improvements.

Keywords: Consolidation, Capital Goods, Spare parts, Digital manufacturing, 3D printing

1. Introduction

Characteristic for additive manufacturing (AM) technologies is that, contrary to conventional manufacturing (CM) processes, materials are added layer by layer during the manufacture of complete parts. This approach allows a substantial reduction of dedicated tooling requirements and setup costs, and thus enables more flexible production of various parts with the same machinery. Based on this characteristic, design options that were previously (economically) infeasible due to Design for Manufacturing (DFM) conventions now become viable and may allow a usage-driven design. Likewise, the use of raw materials might become more efficient compared to subtractive production processes. However, as we will exemplify in this paper, design changes have a substantial influence on the total life cycle costs of capital goods. The underlying effects have to be understood upfront to allow for a successful application of AM.

According to the Wohlers Report (2014), the most promising application of the new design freedom with AM for operations is the integration of parts, i.e. the redesign of an assembled component with fewer, but therefore more complex parts. This concept is referred to as consolidation. Next to reducing the number of assembly steps, and thereby production lead time and costs, consolidation may improve the reliability of assembled components, see Johnson & Kirchain (2009) and Wits et al. (2016). For instance, couplings between parts, often the cause of several failure modes, can be removed. Furthermore, the performance of the consolidated part may be improved. Examples are reduced weight while fulfilling the same functionality, less flow resistance or improved heat dissipation. Moreover, the supply chain might be simplified because the number of distinct parts that need to be sourced, tracked and inspected decreases. Hence, operational complexities and long lead times are reduced (Yang et al., 2015). In Appendix 1, we illustrate a typical case of consolidation which demonstrates the technological feasibility of consolidating parts with AM and its associated potential for operational cost savings.

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Despite the potentials of consolidation, it would be incorrect to assume that consolidation is always preferable. In fact, it is unclear under which conditions a consolidated part is more valuable than its CM and assembled counterpart. This is due to several potential disadvantages of consolidation. For instance, consolidation removes the option to repair a defective system via the replacement of sub-components. In particular, the disassembly of the component would no longer be possible and thus force the replacement of the entire component. This constraint may lead to additional acquisition costs and stocking of more complex parts compared to the assembly case. Similarly, possible commonality effects, achieved by pooling stocks of common low level components, are lost because of the higher level of customization of the consolidated part. On the other hand, the design freedom of AM may allow to change the characteristics of a component such that it fits more connections than in the past and thus may compensate for this drawback.

Another shortcoming may arise from potentially higher purchasing costs because of more specific parts as well as the general novelty of industrial AM processes. Weller et al. (2015) point out that the latter may also increase the number of required production steps. For instance, current AM processes typically require support materials which have to be removed in separate production steps. The same is true for post-processing steps which are required to increase the surface quality or to reduce residual stress. Additionally, process setup and calibration demand close cooperation between producer and user. These inherent dependencies limit supply options and may increase consolidation costs. In the future, however, it is likely that the number of suitable suppliers may rise significantly. Generic AM processes support the production of a wide product range with the same equipment while conventional suppliers are often limited to fewer products or dependent on suppliers themselves. Hence, costs associated with supplier dependencies are likely to decrease for consolidation but also for AM production in general. A final drawback of consolidation with AM concerns part characteristics which may be affected negatively. For example, metal based AM technologies often result in parts that suffer from porosity despite post-processing, cf. Cunningham et al. (2017). As a consequence, mechanical properties are compromised because pores act as a possible origin for cracks. In conclusion, Thomas (2016) rightfully criticizes the tendency of

studies about consolidation to adopt a perspective which is too narrow. Opportunities and drawbacks of consolidation are summarized in Table 1.

Table 1: Characteristics of consolidation with AM technology

Opportunities	Drawbacks
+ Less assembly steps	- No replacement of sub-components
+ Shorter lead times	- Lost commonality effects
+ Simplified supply chain	- Potentially higher purchasing costs
+ Potentially higher reliability	- Potentially lower reliability
+ Performance improvements	- Stocking of more complex parts
+ Reduced tooling and setup effort	- Post-processing
+ Lower raw material usage	- Currently high supplier dependencies
+ Future low supplier dependencies	

In this paper, we investigate under which circumstances consolidation with AM technology is advisable from an economic perspective. Therefore, we identify and study the root causes which are responsible for the economic value of consolidation with AM technology using existing models from the spare parts literature. In doing so, we deliberately focus on cost factors that often go unattended in the general debate about consolidation with AM technology. As our results will show, the value of consolidation with AM strongly depends on aspects other than just design improvements and its associated operational cost savings.

The remainder of the paper is organized as follows: In Section 2, we discuss related literature and elaborate the contribution of this paper. We continue with an overview how consolidation may influence the life cycle costs of capital goods in Section 3. In Section 4, we explain the model that we use to analyze the economic value of consolidation with AM. Next, in Section 5 we motivate and conduct numerical experiments. The results reveal under which conditions consolidation appears profitable. We conclude with Section 6, where we summarize the results and suggest directions for future research.

2. Literature review

In this section, we discuss two streams of literature. First, we consider theories for the optimization of spare parts inventories in order to set the ground for the methodology

applied in this paper. Second, we review literature that quantifies possible effects of AM technologies on supply chains.

2.1. Spare parts literature

A seminal paper in the field of spare parts management has been written by Sherbrooke (1968) who introduces the METRIC methodology. In this paper, Sherbrooke considers a multi-item, two-echelon distribution network, which he evaluates with an approximation for the number of items in resupply. Based on convexity properties, Sherbrooke developed a marginal approach to optimize the inventory positions of each item. Later, this work was extended to more complex network structures and more accurate approximations for the number of items in resupply. A first contribution on spare parts stocking decisions for assemblies was made by Sherbrooke (1971), who introduced the indenture level concept. The purpose of this concept is to categorize the material breakdown structure of an assembled spare part, more or less similar to a Bill of Material structure: a first indenture level part consists of second indenture level parts, etc. This categorization is used to organize the optimization of inventories across different product or system hierarchy levels. A key assumption is that a failed first indenture level part can be repaired by detecting the failed second indenture level part(s), and either replacing them or continuing to search for the cause on the third level, etc. Sherbrooke's work was extended by Muckstadt (1973) to the MOD-METRIC model which considers a two-echelon, two-indenture system. Based on the approach of Graves (1985), Sherbrooke (1986) improved the MOD-METRIC model with a more accurate two-moment approximation for the number of items in resupply. The resulting approach is referred to as VARI-METRIC, and applicable to multi-echelon, multi-indenture systems with backordering. We base our analysis on the VARI-METRIC approach by Sherbrooke. We refer to Sherbrooke (2004), Muckstadt (2005) and Van Houtum & Kranenburg (2015) for a more complete overview.

2.2. Quantitative models AM literature

The consequences of AM technologies for the supply chain are not well understood yet (Holmström et al., 2016). Accordingly, we mostly find conceptual and visionary considera-

tions for the use of AM technologies in supply chains, e.g. Pérès & Noyes (2006), Holmström et al. (2010), Waller & Fawcett (2014), Sasson & Johnson (2016). Here, we review the quantitative results.

Barz et al. (2016) study the impact of a more efficient raw material utilization of AM technologies on the supply chain layout using mixed-integer programming to analyze a two-stage supply network. In the first stage, raw materials are delivered to production sites. In the second stage, the finished product is delivered to customer sites. Decision variables are the location of the production sites, the production site/customer site relations and the transportation quantities. They find that transportation costs decrease with the use of AM technologies. This result is explained by a lower requirement of raw materials and thus less transportation costs from the raw material source to the production site. Also, production sites tend to be located closer to customer sites due to this property. As a final observation they report that the number of opened production sites is rather independent of the raw material utilization. Note that some crucial assumptions are made: demand is deterministic and independent of the production technology, production capacity costs are independent of the production technology and no inventory is allowed. Also, it would be interesting to obtain insights in the consequences of a more uniform requirement of raw material with AM technologies, a topic not addressed in their paper.

Liu et al. (2014) analyze the effect of using AM technologies instead of CM for a spare parts supply chain of aircraft. They compare central and decentral deployment of AM equipment with different demand characteristics and service level requirements. The spare parts design is assumed to be identical for both production methods. In all experiments, the safety stock requirements are lower with AM technologies. Furthermore, they find that a central deployment of AM capacity is favorable for slow moving spare parts, with high demand variability and long AM production times. Otherwise, a distributed utilization of AM technologies appears favorable. The investment costs for AM equipment or personnel costs are not considered and therefore bias the analysis in favor of a decentralized deployment. This critique is confirmed by the findings of Khajavi et al. (2014). They show that a decentralized layout only becomes attractive if the acquisition costs of AM equipment can

be further reduced. Likewise, they identify a higher automation of AM equipment as crucial to reduce the required personnel costs in a decentralized AM supply chain. Finally, they demonstrate that a short production lead time of AM technologies is important – especially if short customer order lead times are demanded. Long production lead times would enforce inventories and thus would gradually reduce one of the key benefits of AM technologies.

Sirichakwal & Conner (2016) study the consequences of reduced holding costs and replenishment lead times for spare parts which result from the application of AM technologies. They assume a single stock point where they apply a continuous review base stock policy with emergency shipments. In general, they find that holding costs and replenishment lead time reductions have positive effects on the total inventory costs. Furthermore, they argue that holding cost reductions decrease the stock-out probability because companies are incentivized to keep more stock. In particular, this finding holds for parts with low demand rates. Apart from differences in holding costs and replenishment lead times, however, they assume that the AM and CM part behave identical. As a result, potential differences in failure behavior or different spare part configurations are not regarded.

Westerweel et al. (2018) investigate under which conditions an AM part yields lower total life cycle costs than the CM version. To this end, they model a single stock point that follows a continuous review base stock policy with emergency shipments. Their model reveals that even if the reliability of the AM part is lower than that of the CM part, the AM version yields lower total costs under the assumption that the production costs of both design options are identical. Conversely, if the production costs are different but the MTBFs are identical, the AM version is still preferable for cases with higher production costs. These findings are a consequence of the key assumption that AM always requires a shorter production lead time. Furthermore, they provide insights into the consequences of a large installed base size and the life cycle length. In case AM technologies require higher investment costs which cannot be offset by performance improvements, this may be compensated by spreading the costs over a large installed base size and long life cycle. Effects arising from consolidation are assumed to be known upfront and serve as an input to their model.

Overall, we find that the literature in this field does not quantify the consequences of

consolidation even though consolidation is perceived as the most important application of AM technologies for operations (Wohlers Report, 2014). Instead, it is assumed that no design changes occur or that the effects of design changes are known a priori. This type of assumption is problematic for three reasons: First, design changes are imposed by AM technologies cf. Wits et al. (2016) and Lindemann et al. (2015). Second, consolidation may significantly influence the life cycle costs of capital goods (we further elaborate on this take in Section 3). Third, the value of consolidation tends to be misinterpreted (Thomas, 2016). These aspects motivate the study in this paper, in which we evaluate under what circumstances consolidation with AM technology is advisable from an economic perspective.

3. Effects of consolidation on life cycle costs

During the life cycle of expensive capital goods, different cost factors must be considered. Elmakis & Lisnianski (2006) distinguish the following cost categories: development costs, production costs, operation and service costs, and disposal costs. In this section, we describe how consolidation with AM may change these cost categories and explain how these changes are regarded in our analysis.

3.1. Development and production costs

Both the development and the production costs are largely influenced by the manufacturing process choice. Thus, the decision to use AM for the purpose of consolidation is likely to affect these cost categories. We justify this claim by the following observations: AM parts typically do not require tooling and less setup activities compared to CM. Additionally, assembly steps are fewer and in most cases we require less raw materials for the production of AM parts. The latter aspect decreases sourcing costs and supply chain complexity. On the other hand, industrial AM processes have not matured yet. Hence, the acquisition of AM machinery represents an expensive and risky investment which may lead to high piece prices of AM parts.

Moreover, quality constraints may demand extensive post-processing or rework of AM parts, which increases the production costs. However, developments in the field of process

monitoring may reduce the need for post-processing in the future. An example is in-situ process monitoring for which features like temperature and size of the melt pool are measured with the goal to enable closed-loop control mechanisms; see Craeghs et al. (2012), Tapia & Elwany (2014) or Everton et al. (2016). These control mechanisms are able to reduce the high AM process variability and thus may decrease the number of post-processing steps required in the future. Also, various metal printing equipment producers incorporate automated post-processing functions in their machines. For instance, the MetalFab1 by Additive Industries supports automated heat treatment, part removal from the build plate and build plate storage Additive Industries. While it seems probable that post-processing steps, in particular for metal prints, remain necessary in the foreseeable future, the time dedicated to post-processing activities is likely to decrease. Furthermore, such advancements may simplify standardization and qualification, which have been identified as major challenges for the adoption of AM technologies in industry and significantly contribute to the typically high AM piece price (Frazier, 2014).

In our analysis, we encapsulate these considerations with the difference in unit costs between the AM part and the CM assembly. Depending on the supply chain layout, the unit costs may either be interpreted as purchasing or as production costs. In the following we focus our discussion on the situation of an external AM supplier. However, our results are similarly representative for the scenario in which AM production is carried out in-house. In this case, we would use the average AM throughput time instead of the contractually agreed AM replenishment lead times (cf. Section 4.1) for our analysis, as is common in the METRIC-type of models. In fact, the assumption is that the inventory policy does not change the utilization of repair and resupply processes, so that it is sufficient to measure waiting times in these processes. Finite capacity models (e.g. Sleptchenko et al. (2003)) exist to facilitate the trade-off between investing in repair and production capacity or investing in spare part inventories. However, Song & Zhang (2016) find that in-house AM equipment utilization typically remains low in a multi-item, multi-source spare parts setting.

In either case, we do not regard fixed purchasing/production costs explicitly. AM parts typically do not require tooling and less setup since both the design and the manufacturing

process are highly digitalized. To that end, low production quantities or even one-for-one production (no batching) becomes economically feasible and allows to incorporate setup costs in the unit costs. Of course, such a modeling decision does not appear appropriate in the presence of high fixed costs. For instance, consider the case in which tooling for the CM part was discarded and has to be rebuilt. Alternatively, a supplier may stop the support for a CM part. Today, these situations are often solved with expensive final orders, see e.g. Kleber et al. (2012). In both cases the low AM preparation costs may favor the application of AM technologies. In this paper we do not regard these extreme cases, but note that future research is necessary to gain quantitative insights in the value of AM technologies under these circumstances.

The same holds for production technologies other than AM with which consolidation may be feasible. Examples are CNC processes and Flexible Manufacturing Systems (FMS). Although indeed the cutting tools exploited in CNC machinery and FMS are versatile (but constrained by their stand times), a part manufactured on a CNC machine does require special fixtures and clamping devices, often even build up or constructed for that particular part. In FMS, the combination of pallets and fixtures may be specific for particular products, and requires a setup performed outside the CNC machines (i.e. at the I/O station of the FMS). As a result, to extend our results for consolidation with other production technologies, it is perhaps more suitable to allow for batch production to account for fixed production costs explicitly. Since we focus on consolidation with AM exclusively, we defer these consideration to future research.

3.2. Operation and service costs

Often the operation and service cost category is the main contributor to the total life cycle costs of expensive capital goods (Öner et al., 2007). We separate this cost category into operational costs, maintenance costs, and downtime costs.

Operational costs arise during, and as a result of, the direct operation of a system, such as electricity, personnel and fuel costs. Some of these cost factors may be affected by consolidation since the design change may cause different operational costs of the focal part.

For example, consider the fuel nozzle discussed in Appendix 1. In this case, GE achieved a weight reduction through consolidation, and thus was able to reduce fuel consumption, which ultimately led to operational cost savings. However, in general these cost savings heavily depend on the specific case and are often difficult to measure exactly. To that end, we exclude the operational costs from the numerical experiments but note that, if for a specific case operational cost savings estimates were available, they can be easily incorporated as input to the model. As we show in Section 4.4 (Equation 4), the expected number of backorders is closely related to the expected number of operating parts. Hence by multiplying the expected number of operating parts with the average operational cost savings per part per period, we obtain an estimate for the associated operational cost savings per period.

Maintenance costs arise due to preventive and corrective maintenance activities and are required for the upkeep of capital goods. Maintenance activities and associated support functions like spare parts management are likely to be affected by consolidation. As mentioned in Section 1, the failure behavior of consolidated and printed parts usually differs from those of CM parts. Failures of expensive capital goods caused by a dysfunctional part are typically solved by a repair-by-replacement policy in which entire units are replaced to limit a system's downtime. Next, the removed units are sent to a specialized repair shop where the fault is diagnosed and solved by replacing a (typically far cheaper) sub-component. Even though this practice may lead to stocking of more expensive/complex parts, downtime and repair costs are typically reduced significantly. Furthermore, the stocking of lower-level items may reduce the repair lead time and thus decrease the necessity for a high base stock level of the higher-level items. Consolidation of parts may obstruct the repair process, given that sub-components are not replaceable anymore. Instead, a new complex consolidated part has to be procured or manufactured. Hence, repair costs are likely to increase. On the other hand, if the consolidated part is replaced with a new version upon failure, part deterioration or repair process induced failures are avoided. For critical parts the consequences are limited, though, as detailed quality checks typically warrant a certain quality level for repaired items. Finally, shorter AM lead times may reduce stock levels and stock-out risks with consolidation even though the option to stock high level items only may increase the inventory

costs again. As explained in Section 1, the lead time reductions are mainly achieved through a simplified supply chain and assembly process, and a (usually) shorter AM production lead time.

In order to capture the described differences in maintenance costs, we study the effects of different failure rates, replenishment lead times, holding costs and repair costs. Note that we focus on the corrective maintenance case in this paper. For preventive maintenance, spare parts inventories are sometimes not required and thus the analysis is simplified. Alternatively, for example in case of condition-based monitoring, a more specific analysis becomes necessary that does not relate to the characteristics of consolidation specifically, but rather to the short AM replenishment lead times in general. To elaborate, it may become possible to postpone the repair decision without additional requirement for spare parts inventories and thus to collect further data about the condition of the monitored part. Future research should reveal if more evidence about the part condition justifies the application of AM technologies even despite possible drawbacks. Likewise, in our analysis we do not account for cost associated with the setup of possible repair shop infrastructure, but restrict ourselves to the case for which repairs are carried out by external service providers.

Downtime costs arise if the capital good is non-operational; they are typically difficult to quantify because they relate to soft factors such as customer satisfaction and company image. We express the downtime costs in terms of an availability target for the system. This decision is justified by two observations. First, target availability is typically easier to assess intuitively than downtime costs and thus is more often specified in service contracts or functional specification documents. Second, there exists a relation between downtime costs and target availability, that is, higher downtime costs cause a higher target availability. In fact, it has been shown that in many cases a one to one relationship between downtime costs and service level constraint holds (Van Houtum & Zijm, 2000). Hence, if a company has insights in downtime costs, these are usable for determining a corresponding availability target. Such situations may for instance occur if the service provider reacts to a stock-out with an emergency supply that offers a suitable but more expensive substitute. Here we will compare the total life cycle costs of the AM part with the CM assembly, subject to a

mutual availability constraint.

3.3. Disposal costs

The last cost category are the disposal costs which arise during the phase out of the capital good. Consolidation may influence these costs due to differences in over- and underage costs. Overage costs refer to costs that arise if too many spare parts remain unused at the end of the life cycle. Often this situation leads to a depreciation of the value of the remaining stock. In case stock is remaining, consolidation may worsen this effect, as parts are more complex and specific, and hence more valuable. On the other hand, short AM replenishment lead times may permit smaller safety stocks which may compensate for this disadvantage. Underage costs arise due to insufficient stock during the final phase of the product or system when regular resupply is discontinued. This condition leads to downtime costs or additional charges to purchase spare parts during this final phase. Here, consolidation with AM technology may decrease the underage costs given that replenishment lead times are typically short and setup costs are low. As a consequence, the impact of supply discontinuations decreases.

Unfortunately, during the design phase, it is difficult to predict which of the two effects will eventually have a more significant impact, as aspects such as decreasing demand and learning effects during the life cycle are difficult to foresee. Furthermore, potential over- or underage costs heavily depend on operational decisions, such as how to deplete the stock levels at the end of the life cycle of the capital good. For these reasons, we decided to exclude the disposal costs from the analysis. In an actual case for which this insight is available however, one may include disposal cost differences between the AM part and the CM assembly as input into the analysis.

4. Model

In this section, we present the model that we will use to quantify the effects of consolidation. Therefore, we first present an outline of the model before we construct the mathematical model in the next section. Key assumptions are discussed in the text and

are summarized in Section 4.3. We close this section with the description of the model evaluation and optimization.

4.1. Model outline

Consider a single stock point which serves an installed base of systems with a critical component, i.e. once the component of a particular system fails, the entire system has to stop operation. The component is a multi-indenture item and may appear multiple times in each system. For ease of presentation, however, we assume that each component occurs only once in each system. Upon failure, the entire component is replaced by a stocked spare part to keep the downtime of the system short. Recall that for high-value assets, a repair-by-replacement is common practice in industry, see Section 3. In case no stock is available, demand is backordered until a spare part becomes available. The failed component enters an uncapacitated repair process (if possible), which will return a ready-for-use spare part with a similar failure pattern as an entirely new item. We justify the modeling choice of an uncapacitated repair process with the common practice where throughput times are the subject of contractual agreements with the repair shop. This also means that the modeled repair times are in fact lead times in the repair shop, covering net processing times as well as waiting times for resources. In our model, inventories are controlled according to a base stock policy. This modeling decision is justified by the fact that we focus on expensive, slow-moving items where batching independent of the replenishment process generally does not occur because the focus is on meeting tight service level requirements.

Depending on manufacturability constraints, different configurations of the component are feasible. Figure 1 illustrates a possible set of configurations of a component. Configuration A represents the design with the highest segmentation. That is, no consolidation of parts took place. In Configuration B, Parts 6 and 7 are consolidated with AM technology which results in a Part I with a specific failure rate, average replenishment lead time, holding and replenishment cost rate. Also, consolidation across indenture-levels is possible. This situation occurs for Configuration C where the functions of Parts 5, 6, 7 and 2 are replaced by Part II. Finally, each component configuration may demand different replenishment pro-

cesses. For instance, a consolidated part, like Part I and II in Figure 1, cannot be repaired by replacement of sub-components because these do not exist. Thus, a purchase takes place to obtain a substitute for Part I and II. In contrast, a failure of Part 2 can be solved by replacing the dysfunctional sub-component.

Figure 1: Possible configurations of component

The goal of the model is to evaluate which component configuration minimizes the total costs subject to an availability constraint. Therefore, we jointly optimize the base stock level(s) and the component configuration.

4.2. Notation and mathematical model

In this paragraph, we explain the mathematical model. Notations are introduced in the text and summarized in Table 2. The evaluation of the functions introduced in this subsection, is presented in Section 4.4. We consider an installed base of IB systems where we focus on one critical component. The set of feasible configurations of that component is denoted by K . Each component configuration $k \in K$ is characterized by a multi-indenture structure and consists of a set of parts Z_k . For example, the set of parts of Configuration C in Figure 1 is represented by $Z_C = \{1, II, 3, 4\}$. Indenture levels are specified with i , $i = 1, 2, \dots, I$, where the set of parts at indenture level i is denoted by $Z_{ki} \subseteq Z_k$. Thus $Z_{C2} = \{II, 3, 4\}$. The set of children of part $z \in Z_k$ is denoted by $\Gamma_k(z)$. Accordingly, in

Table 2: Notation overview

Notation	Explanation
IB	Installed base size
K	Set of feasible configurations
k	Specific component configuration
Z_k	Set of parts in configuration k
i	Indenture level, where I denotes the lowest hierarchy level
Z_{ki}	Set of parts in configuration k at indenture level i
$\Gamma_k(z)$	Set of children of part z in configuration k
$\Psi_k(z)$	Parents of part z in configuration k
λ_z	Failure rate of a lowest indenture part $z \in Z_{kI}$
r_z	Replacement cost rate of part $z \in Z_k$
p_z	Purchasing cost rate of a lowest indenture part $z \in Z_{kI}$
a_z	Assembly cost rate of a higher indenture level part $z \in Z_k \setminus Z_{kI}$
$P_k(z)$	Total piece price of part z in configuration k
κ	Holding costs fraction
l_z	Average replenishment lead time/repair lead time of part z
x_k	Binary variable which indicates if configuration k is used
$\mathbf{S}_k$	Vector describing all base stock levels for configuration k
$s_k(z)$	Base stock level of part z in configuration k
$TC_k(\mathbf{S}_k)$	Average total costs of configuration k given $\mathbf{S}_k$
$\tilde{A}$	Target availability of the installed base
$A_k(\mathbf{S}_k)$	Average availability for configuration k given $\mathbf{S}_k$
$m_k(z)$	Demand rate of part z
$EBO(\cdot)$	Expected number of backorders
$VBO(\cdot)$	Variance of backorders
$R_k(z)$	Parts in replenishment of part z in configuration k

Figure 1, the set of children of Part 2 in Configuration B is represented by $\Gamma_B(2) = \{5, I\}$. The set of parents of part $z \in Z_k$ is denoted by $\Psi_k(z)$ (note that since we assume that each component occurs only once in each system, $\Psi_k(z)$ consists of a single element, but we keep the set notation for the purpose of generalization). The failure rate of the lowest indenture part $z \in Z_{kI}$ is described by λ_z . We assume that failures occur according to a Poisson process. For our purposes the Poisson demand assumption seems most appropriate, given that we consider a low-demand environment with mechanical parts that are dimensioned to outlast the intended maintenance interval or lifetime of the capital good (common practice for downtime critical mechanical components of capital goods). Accordingly, failures are random in nature and may, for instance, be caused by unintended stress levels, imprudence

during maintenance/shipping activities or unobservable quality issues during the production. The failure rate of a higher indenture level part $z \in Z_k \setminus Z_{kI}$ is equal to the accumulated failure rate of its children. If component configuration $k \in K$ is an assembly, i.e. $|Z_k| > 1$, the component can be repaired in the repair shop by replacing the failed part $z \in Z_{k2}$ with r_z being the cost rate of replacement. In case $\Gamma_k(z) \neq \emptyset$, the part $z \in Z_{k2}$ can be repaired by replacing the failed child $y \in \Gamma_k(z)$ with r_y being the cost rate of replacement, etc.

Otherwise, if part $z \in Z_k$ has no children, i.e. $\Gamma_k(z) = \emptyset$, we discard the failed part and order a new part at a purchasing cost rate p_z . The holding costs per period (e.g. per year) of part $z \in Z_k$ are a fraction κ of the total piece price $P_k(z)$. In case we consider a part $z \in Z_{kI}$ on the lowest hierarchy level the total piece price is equal to the purchasing cost rate. For a part $u \in Z_k \setminus Z_{kI}$ on a higher hierarchy level the total piece price is equal to the assembly cost rate a_z plus the total piece price of all its lower level parts included in $\Gamma_k(u)$. The average replenishment ($\Gamma_k(z) = \emptyset$) or repair lead time ($\Gamma_k(z) \neq \emptyset$) of $z \in Z_k$ is denoted by l_z .

We define the following decision variables:

$$x_k \forall k \in K, \text{ where } x_k = \begin{cases} 1, & \text{if configuration } k \text{ is used} \\ 0, & \text{otherwise.} \end{cases}$$

$\mathbf{S}_k = \{s_k(z) | \forall z \in Z_k\} \forall k \in K$, where $s_k(z)$ is the base stock level of part $z \in Z_k$.

The average total costs of configuration $k \in K$, given $\mathbf{S}_k$, are denoted by $TC_k(\mathbf{S}_k)$. The target availability for the installed base is given by $\tilde{A}$, while the average availability for a certain component configuration $k \in K$ and base stock policy $\mathbf{S}_k$ is denoted by $A_k(\mathbf{S}_k)$. Consequently, we have to solve the following non-linear integer optimization problem in order to find the minimum cost configuration. The evaluation of the functions in the optimization

problem is discussed in Section 4.4.

$$\begin{aligned}
 & \underset{x_k, s_k(z)}{\text{minimize}} && \sum_{k \in K} x_k TC_k(\mathbf{S}_k) \\
 & \text{subject to} && \sum_{k \in K} x_k = 1 \\
 & && A_k(\mathbf{S}_k) \geq \tilde{A} \\
 & && s_k(z) \in \mathbb{N}_0 \\
 & && x_k \in \{0, 1\}
 \end{aligned} \tag{1}$$

4.3. Assumptions

1. The critical component we study is used only once in each system. Also, each part occurs only once in the component.
2. For each part, a one-for-one replenishment policy (S-1,S) is applied.
3. Failures of parts occur according to a stationary Poisson process and are caused by a failure of a lower indenture part (if any).
4. The configuration of the component does not influence the failure rate of the lowest indenture parts.
5. Each part in the multi-indenture structure is critical, i.e. the entire component does not function if one part is defective and thus leads to a non-operational system.
6. If a failure occurs, it is always the entire component that is replaced.
7. Each component is repaired by replacement of a lower indenture part, except for parts without children; they are discarded upon failure, and a new part is purchased.
8. Lead times are independent and identically distributed for each part.
9. The repair lead time does not depend on lower-indenture parts. Thus, it captures the time to diagnose and replace a failed part if a spare part is in stock.
10. Repair capacity is not constrained; instead, we consider the contracted repair lead time.
11. Holding costs are encountered during the repair and ordering process.
12. No condemnation occurs, i.e. each repair is successful.

4.4. Model evaluation

As clarified in Section 2, we use VARI-METRIC to evaluate our model (Sherbrooke, 1968). In this section, we will review the essential steps for our problem setting:

To compute $A_k(\mathbf{S}_k)$, we must derive the demand rate for each part $z \in Z_k$ first. We begin with computing the demand rate for parts without children ($\Gamma_k(z) = \emptyset$) with $m_k(z) = IB\lambda_z$. For an assembled part ($\Gamma_k(z) \neq \emptyset$), we use $m_k(z) = \sum_{y \in \Gamma_k(z)} m_k(y)$. Next, we determine for each part the expected number of backorders $EBO(s_k(z), \cdot)$ and the variance of backorders $VBO(s_k(z), \cdot)$. For parts without children, we obtain these measures using a single site model, cf. Sherbrooke (2004). Next, we determine the mean and variance of the number of parts in the replenishment process $R_k(z)$ for parts with children:

$$E[R_k(z)] = m_k(z)l_z + \sum_{y \in \Gamma_k(z)} EBO(s_k(y)) \quad (2)$$

$$Var[R_k(z)] = m_k(z)l_z + \sum_{y \in \Gamma_k(z)} VBO(s_k(y)) \quad (3)$$

To obtain the expected number of backorders $EBO(s_k(z), \cdot)$ and the variance of the backorders $VBO(s_k(z), \cdot)$ for these parts, we use a two moment approximation. That is, we fit a negative binominal distribution to the mean and the variance of R_z as given above. Analogously, we proceed with the higher indenture level parts until the expected number of backorders of the component, $EBO(\mathbf{S}_k)$, is obtained. Finally, to derive the average availability $A_k(\mathbf{S}_k)$, we use the following approximation:

$$A_k(\mathbf{S}_k) \approx \text{Max}\{1 - \frac{EBO(\mathbf{S}_k)}{IB}, 0\}. \quad (4)$$

In order to compute $TC_k(\mathbf{S}_k)$ we determine the total piece price $P_k(z)$ for every part $z \in Z_k$ first. For parts without children, we have $P_k(z) = p_z$. For assembled parts, we use $P_k(z) = a_z + \sum_{y \in \Gamma_k(z)} P_k(y)$. Next, we determine $C_z(s_k(z))$, i.e. the average total costs for each part

$z \in Z_{k1}$ and all its lower indenture parts. We have:

$$C_z(s_k(z)) = \begin{cases} m_k(z)(r_z + p_z) + s_k(z)\kappa p_z, & \text{if } \Gamma_k(z) = \emptyset \text{ or } |Z_k| = 1; \\ m_k(z)r_z + s_k(z)\kappa P_k(z) + \sum_{y \in \Gamma_k(z)} C_y(s_k(y)), & \text{otherwise.} \end{cases} \quad (5)$$

Finally, we obtain the total costs with

$$TC_k(\mathbf{S}_k) = \sum_{z \in Z_{k1}} C_z(s_k(z)). \quad (6)$$

4.5. Model optimization

To optimize the formulated model, we follow the marginal analysis of Sherbrooke, cf. Sherbrooke (2004). The underlying idea of Sherbrookes approach is to construct solutions by successively increasing the stock level of the most cost effective item, where cost effectiveness is captured by the backorder reduction per unit of capital (e.g per dollar) invested. This procedure leads to a convex EBO-costs curve. Algorithm 1 formalizes this approach for component configuration $k \in K$.

Algorithm 1: Marginal analysis for component configuration $k \in K$

Set $s_k(z) := 0, z \in Z_k$ and define $\mathbf{e}_z$ as a $|Z_k|$ -dimensional unit vector with the position of Part z equal to 1;

while $\tilde{A} > A_k(\mathbf{S}_k)$ **do**

 Set $\mathbf{S}_{k_{\text{new}}} := \mathbf{S}_k + \mathbf{e}_z$;

 Calculate $\Delta_z = \frac{EBO(\mathbf{S}_k) - EBO(\mathbf{S}_{k_{\text{new}}})}{TC_k(\mathbf{S}_{k_{\text{new}}}) - TC_k(\mathbf{S}_k)}, \forall z$;

 Let $u := \text{argmax}_z \Delta_z$ and set $\mathbf{S}_k := \mathbf{S}_k + \mathbf{e}_u$;

 Store efficient point $(EBO(\mathbf{S}_k), TC_k(\mathbf{S}_k))$;

 Evaluate $A_k(\mathbf{S}_k)$;

Following Algorithm 1 for each configuration $k \in K$, we obtain a set of convex EBO-costs curves. The convexity property allows us to easily find the convex frontier of the EBO-costs curves, for example with the Graham scan (Graham, 1972). As a result, we can approximate which configuration leads to the most cost-efficient results given a desired availability $\tilde{A}$.

Also, the resulting convex-frontier may lend itself to be utilized in more practical multi-item analyses, see e.g. Van Houtum & Kranenburg (2015). Here, however, we restrict ourselves to the single-item, single-location setup in order to evaluate the influence of consolidation with AM technology.

5. Experimental section

In this section, we will conduct numerical experiments in order to gain insights in the effects of consolidation with AM. For this purpose, we will consider two setups: consolidation at the same indenture level ($I = 1$) in Section 5.1, and consolidation over two indenture levels ($I = 2$) in Section 5.2. For both setups, we will compare a CM non-integrated Configuration A with an AM integrated Configuration B. Throughout the experiments we will use three different performance indicators to measure the value of consolidation:

1. The percentage of instances where Configuration B has lower average total costs than Configuration A. This performance indicator is denoted by $\mathbf{B}\%$.
2. The average costs reduction with consolidation in case Configuration B has lower average total costs $\Delta TC[B] = \frac{TC_B(S_B) - TC_A(S_A)}{TC_A(S_A)}$, where the average of $\Delta TC[B]$ over several instances in percentage is denoted by $\Delta \mathbf{TC}[\mathbf{B}]\%$.
3. The log difference between the total costs of both configurations, defined as $\ln \frac{TC_B(S_B)}{TC_A(S_A)}$, see Törnqvist et al. (1985). This measure has the advantage of being symmetric, i.e. $\ln(a/b) = -\ln(b/a)$. Thus, the average log difference is a suitable indicator of the relative costs difference over several instances. We denote the average by $\Delta \mathbf{ln}(\mathbf{TC})$.

5.1. Consolidation of single-indenture components

In Figure 2, we illustrate possible component configuration structures in this section. Configuration A represents the CM manufactured component which consist of $|Z_A|$ parts. Configuration B is produced with AM and fulfills the same function with one part only. To simplify the presentation of the model input and results, we relate the characteristics of parts in Configuration A to the characteristics of Part I. Thus, we derive the average

Figure 2: Possible configurations of component

replenishment lead time of Part I from the weighted average replenishment lead time incurred with Configuration A, i.e. $\tilde{l}_A = \sum_{z \in Z_A} \frac{m_A(z)}{m_A(A)} l_z$, with $m_A(A) = \sum_{z \in Z_A} m_A(z)$. The measure $\tilde{l}_A$ has the useful property of returning the same average replenishment lead time for both configurations if it holds that $l_I = \tilde{l}_A$. To experiment with differences in the average replenishment lead times as well, we introduce the factor α and define $l_I = \alpha \tilde{l}_A$. Following the same logic, we use the average failure rate experienced with Configuration A (i.e. $\lambda_A = \sum_{z \in Z_A} \lambda_z$) to compute the average failure rate of Part I and therefore have $\lambda_I = \beta \lambda_A$, with β describing the ratio between the average failure rates of both configurations. The purchasing cost rate of Part I is related to the purchasing cost rate of Configuration A (i.e. $p_A = \sum_{z \in Z_A} p_z$) with $p_I = \gamma p_A$, where γ models the ratio between the purchasing cost rate of both configurations. Therefore, if either of the factors (α, β, γ) is smaller than 1, consolidation offers a more favorable part characteristic.

The parameter ranges analyzed in the numerical experiments are based on the situation described in Section 3. Accordingly, we assume a component that is operated in expensive capital goods. For such components (and its subcomponents), repair and replenishment lead times often range in the order of magnitude of months, see Basten & van Houtum (2014). Also, for components operating in expensive capital goods, the availability target is usually high, therefore we aim for 95% and 99.5% demand fulfillment from stock, respectively. For the holding cost fraction, we evaluate scenarios with low ($\kappa = 0.15$) and with high holding costs ($\kappa = 0.3$). Following results that suggest that AM technologies are valuable for low-demand rates in particular, see e.g. Khajavi et al. (2014) or Liu et al. (2014), we focus on low-demand environments. Also, we note that low-demand environments are more common for expensive capital goods.

For the lead time difference between both configurations, we typically find the assumption

of a significantly shorter AM than CM lead time (i.e., $\alpha < 1$) in the literature. For example, Liu et al. (2014) report on data from the aerospace industry. For CM items they find lead times between 1.5 and 8 month, whereas, for AM parts, they typically assume lead times of less than a month. Another example are the case studies discussed by Westerweel et al. (2018). They observe AM resupply lead times of about two weeks while for the CM source, they find lead times of about 2 to 5 months. However, for the situation considered in this paper, there are also arguments against such extreme lead time advantages. For example consolidated AM items typically exhibit a rather high geometric complexity which may cause additional processing times. In this context Löber et al. (2013) elaborate that complex structures often require more advanced post-processing procedures. To accommodate these findings in our numerical experiments, we primarily focus on lead time reduction ($\alpha < 1$) but also regard cases where the expected lead time increases ($\alpha > 1$). The piece price for AM items is typically higher than for CM parts. Not only does this situation relate to the novelty of industrial AM processes, but also to the high raw material costs. Additionally, AM processes remain labor and skill intensive (Weller et al., 2015). Yet, as we discussed in Section 3, consolidation may also reduce the total piece price. For instance, costs associated with the assembly process no longer apply. Also, inefficiencies caused by sourcing sub-components from various suppliers can be reduced with consolidation. Accordingly, we analyze scenarios where the piece price decreases ($\gamma < 1$) but also scenarios where the piece price increases ($\gamma > 1$) due to consolidation with AM. For the reliability, we adopt a similar approach since, following our discussion in Section 1 and 3, it is possible that consolidation influences the reliability positively ($\beta > 1$) or negatively ($\beta < 1$).

In Table 3 we summarize the resulting parameter values, where $U[a, b]$ represents a continuous uniform distribution between the values a and b . Given that we can model arbitrary demand rates with λ_z , we set the installed base size equal to 1 (i.e. $IB = 1$). For each parameter combination, we sample 25 values from the uniform distributions, which results in 196,000 problem instances.

As a first step, we study the significance and the effect of changing input parameters with multiple linear regression. As the dependent variable we use the performance indicator

Parameters	Values
l_z	$U[0.2, 1]$
λ_z	$U[0.2/ Z_k , 5/ Z_k]$
p_z	$U[100/ Z_k , 20000/ Z_k]$
κ	0.15, 0.3
$\tilde{A}$	0.95, 0.995
$ Z_A $	2, 3, 4, 5, 6
α	0.05, 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4
β	0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6
γ	0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6

Table 3: Parameter values

$\Delta \ln(TC)$. The regression analysis revealed the following standardized relation with log-transformed independent variables:

$$\begin{aligned} \Delta \ln(TC) = & -0.9 - 0.02 \ln(\tilde{l}_A) - 0.002 \ln(p_A) - 0.05 \ln(\tilde{A}) - 0.07 \ln(\kappa) \\ & + 0.02 \ln(\lambda_A) + 0.6 \ln(|Z_A|) + 0.13 \ln(\alpha) + 0.51 \ln(\beta) + 0.57 \ln(\gamma) \end{aligned} \quad (7)$$

In the Appendix, we provide the full regression report and further diagnostic tests that qualify the model to be suitable for explanatory purposes. We deduce several characteristics of consolidation from the regression model: the holding costs fraction (κ), the target availability ($\tilde{A}$), the weighted average replenishment lead time ($\tilde{l}_A$) and the purchasing cost rate of Configuration A (p_A) have a positive effect on the cost saving potential with consolidation (i.e. $\Delta \ln(TC)$ decreases). On the contrary, an increase of the other factor reduces the cost saving potential with consolidation. Also, it appears that β and γ have a considerably higher effect on $\Delta \ln(TC)$ than α . Finally, the number of integrated parts ($|Z_A|$) is the most important predictor for the value of consolidation. We will establish an interpretation of these findings in the remainder of this sub-section.

In Table 4 we present the effect of differences in replenishment lead time, failure rate and purchasing cost rate by varying α , β and γ . Overall, we find that the costs saving potential with consolidation is limited in the evaluated parameter range. Accordingly, the performance indicator $\Delta \ln(TC)$ is positive for most parameter values in Table 4. Nevertheless, the

results for $\Delta TC[B]\%$ clarify that, in case consolidation is superior, the cost saving potentials of consolidation are high. For example, consider the scenario where the purchasing cost rate is 1.6 higher for Configuration B than for Configuration A ($\gamma = 1.6$). On average, the higher purchasing cost rate leads to significantly higher total costs with consolidation ($\Delta \ln(TC) = 1.22$). However, for the few instances where Configuration B is preferable ($B\% = 1\%$), consolidation offers major cost savings on average ($\Delta TC[B]\% = -11\%$). This finding clarifies that assessing the value of consolidation by a single characteristic like the purchasing cost rate is not advisable. Instead, a total costs perspective is required to evaluate the possible benefit of consolidation.

Table 4: Impact of changing parameters

Parameter	Value	B%	$\Delta TC[B]\%$	$\Delta \ln(TC)$
α	0.05	20%	-32%	0.46
	0.2	16%	-30%	0.54
	0.4	14%	-29%	0.60
	0.6	13%	-28%	0.65
	0.8	11%	-27%	0.70
	1	10%	-27%	0.74
	1.2	10%	-26%	0.77
	1.4	9%	-26%	0.80
β	0.4	41%	-34%	-0.8
	0.6	22%	-28%	0.28
	0.8	12%	-24%	0.53
	1	7%	-21%	0.74
	1.2	4%	-18%	0.91
	1.4	2%	-15%	1.05
	1.6	1%	-12%	1.18
γ	0.4	46%	-34%	-0.16
	0.6	22%	-26%	0.24
	0.8	11%	-22%	0.53
	1	5%	-19%	0.75
	1.2	3%	-15%	0.93
	1.4	1%	-13%	1.09
	1.6	1%	-11%	1.22

Furthermore, the results presented in Table 4 replicate the findings in the regression analysis: A short replenishment lead time (α) provides less incentive to make use of consoli-

dation than a lower failure rate (β) or purchasing cost rate (γ). Accordingly, $B\%$ changes by only 11% points if we compare $\alpha = 0.05$ and $\alpha = 1.4$. This effect is significantly smaller than effects resulting from changes in β and γ . The relation between costs and replenishment

Figure 3: Effect of replenishment lead time changes on the average purchasing and the average holding costs

Figure 4: Effect of the number of functional integrated parts on the percentage of instances where Configuration B yields lower costs ($B\%$) and the average cost reduction if Configuration B yields lower cost in percentage ($\Delta TC[B]\%$)

lead time allows us to deduce an explanation for this finding. The average purchasing costs defined by $P_B = m_B(I)p_I$ are independent of the replenishment lead time. Thus, changes in α affect the average holding costs ($H_B = s_B(I)\kappa p_I$) only, which limits the impact on the total costs. We illustrate this relation in Figure 3 for different values of l_I . On the contrary, β and γ affect both costs (P_B and H_B) and thus have a higher influence on the value of consolidation on average.

Considering the fact that short lead times are a key benefit of AM, this finding may partially explain why consolidation does not appear recommendable for most test instances. Conversely, we may reason that consolidation through AM becomes more valuable in cases where the average holding costs of a conventional configuration are high. This situation is more likely in cases with a high target availability ($\tilde{A}$), a high holding cost fraction (κ), a long weighted average lead time ($\tilde{l}_A$) or a high purchasing cost rate of Configuration A (p_A). Therefore, this result also offers an interpretation for findings from the regression analysis

where the negative coefficients of $\tilde{A}$, κ , $\tilde{l}_A$ and p_A indicate a positive correlation with the value of consolidation.

Next, we investigate the negative effect of the number of parts (i.e. $|Z_A|$) on the potential cost saving with consolidation, which we deduced from the regression analysis. In Figure 4, we illustrate this effect by plotting $B\%$ as a function of $|Z_A|$. As expected $B\%$ decreases with the number of consolidated parts.

We hypothesize that this effect is related to the additional flexibility to fulfill the availability target ($\tilde{A}$). For instance, one may obtain the option to allocate stock unevenly among parts which leads to cost savings eventually. Given that this flexibility increases with $|Z_A|$, the result of the regression analysis appears reasonable. To further elaborate on this aspect,

Figure 5: Increase in failure rate differences favors segmented configuration illustrated by the increasing average log difference between the total costs of both configurations ($\Delta \ln(TC)$)

we conducted a small sub-experiment with $|Z_A| = 2$ where we chose $\lambda_1 = 0.5$ while varying λ_2 . Other parameter values are chosen as they were in the previous experiment (cf. Table 3). In Figure 5, we show that $\Delta \ln(TC)$ is close to 0% if Part 1 and Part 2 have the same failure rate ($\lambda_1 = \lambda_2$). The more the failure rates deviate, the larger $\Delta \ln(TC)$ becomes. The results exemplify the value of flexibility: In case both parts have a rather similar failure rate, the benefit of allocating stock unevenly between both parts is low. If, however, the difference is high, the benefit of allocating stock unevenly increases. Given that such differences are more

likely to occur with a higher number of parts, $|Z_A|$ is a negative predictor for the benefit of consolidation. This hypothesis is further supported by comparable results in experiments where we varied the purchasing cost rate and the average replenishment lead time.

5.2. Consolidation of two-indenture components

In this sub-section, we focus on the effect of consolidation over two-indenture levels. The possible component configurations are illustrated in Figure 6. To simplify the presentation of the model input and results, we follow an approach comparable to the one in Section 5.1 and relate several input parameters to each other. For parameter relations that do not follow from the explanations in Section 5.1 immediately, we give a short outline subsequently. The remaining parameter relations are listed in Table 5.

Figure 6: Possible configurations of component

We chose the weighted average replenishment lead time of parts at the lowest indenture level ($\tilde{l}_{A2}$) as orientation for the average repair lead time of Part 0, where $\tilde{l}_{A2} = \sum_{z \in Z_{A2}} \frac{m_A(z)}{m_A(A)} l_z$, with $m_A(A) = \sum_{z \in Z_{A2}} m_A(z)$. Accordingly, we obtain the average repair lead time for Part 0 by $l_0 = \xi \tilde{l}_{A2}$, where ξ models the relative deviation of the average repair lead time from $\tilde{l}_{A2}$. Likewise, we define the repair cost rate of Part 0 relative to the total piece price of Part 0 and therefore obtain $r_0 = \pi P_A(0)$, where π denotes the ratio between the repair costs rate and total piece price of Part 0.

In Table 5 we show the experimental settings. In case of the replenishment lead time factor (α), we restrict the parameter range to the case where the average replenishment lead time of the segmented configuration is at least as long as it is for the consolidated configuration. This restriction seems justified given that a shorter replenishment lead time

Table 5: Parameter values

Parameters	Values
l_z with $z \in Z_{k2}$	$U[0.5/ Z_{A2} , 1/ Z_{A2}]$
λ_z with $z \in Z_{k2}$	$U[0.2/ Z_{A2} , 5/ Z_{A2}]$
p_z with $z \in Z_{k2}$	$U[2000/ Z_{A2} , 20000/ Z_{A2}]$
κ	0.15, 0.3
$\tilde{A}$	0.95, 0.995
$ Z_{A2} $	1, 2, 3, 4, 5
α	0.2, 0.6, 1
β	0.8, 1, 1.2
γ	0.8, 1, 1.2
ξ	0.2, 0.4, 0.6, 1, 1.2
π	0.05, 0.1, 0.15, 0.2
p_0	$U[0, 2000]$
l_I	$\alpha \tilde{l}_{A2}$
λ_I	$\beta \lambda_A$
p_I	$\gamma P_A(0)$

for the AM produced component is more likely in practice, and we already observed that α has less impact on the value of consolidation (Section 5.1). In case of β and γ , we reduced the parameter range as well, disregarding the most extreme values which allows us to put higher emphasis on the impact of the factors ξ and π . The experimental setup results in 270,000 problem instances because we sample from each uniform distribution 25 times.

As elaborated in Section 1, consolidation of assembly structures may eliminate a repair option. While an assembly structure can be repaired by replacing defective sub-components, this flexibility is lost with consolidation. To obtain further insights on this aspect we study the effect of the repair cost rate ratio π first. Next, we evaluate the impact of the lead time ratio ξ .

In Figure 7, we depict $B\%$ and $\Delta TC[B]\%$ as a function of the repair cost ratio π . The results indicate that in case of low repair costs compared to the total piece price of Part 0, consolidation is typically not advisable. Accordingly, $B\%$ and $\Delta TC[B]\%$ decrease with decreasing π . This observation relates to lower average purchasing costs with Configuration A in case π is small. While Configuration A allows for solving a failure by purchasing a new sub-component only, consolidation requires the purchase of the entire configuration.

Figure 7: Effect of changing repair costs on the percentage of instances where Configuration B yields lower costs ($B\%$) and the average cost reduction if Configuration B yields lower cost in percentage ($\Delta TC[B]\%$)

Figure 8: Effect of changing repair lead time on the percentage of instances where Configuration B yields lower costs ($B\%$) and the average cost reduction if Configuration B yields lower cost in percentage ($\Delta TC[B]\%$)

Next to the purchasing cost savings, the repair process may reduce the holding costs as well. This potential is illustrated in Figure 8, where we show $B\%$ and $\Delta TC[B]\%$ as a function of the repair lead time ratio ξ . As we observe, the shorter the repair lead time, the less instances lead to consolidation as the preferred configuration ($B\%$). Also, the cost saving potential decreases slightly ($\Delta TC[B]\%$). These effects are a consequence of the possibility to resupply Part 0 quickly in case ξ is small. Accordingly, one may decrease the stock level of Part 0 while fulfilling the same availability target and thus decrease the average holding costs. If an assembly structure can be repaired by replacing sub-components only, the value of consolidation is limited. In particular, this conclusion holds if the repair cost rate is low compared to the purchasing costs of a new component and if the average repair lead time is short.

Next, we address the question of how the number of consolidated parts at the second indenture level influences the value of consolidation. Therefore, we illustrate the percentage of instances where consolidation is preferable ($B\%$) depending on the number of sub-components ($|Z_{A2}|$) in Figure 9. We observe that $B\%$ decreases with increasing $|Z_{A2}|$. This finding appears reasonable, as nearly the same logic as in Section 5.1 applies: The higher

the number of sub-components, the higher the flexibility to allocate stock unevenly among the parts to fulfill the required availability of the repair shop. One particularly noteworthy outcome can be observed when $|Z_{A2}|$ is equal to 1, because in this case more than 80% of instances favor consolidation. However, this finding further strengthens the flexibility argument given in Section 5.1. In case $|Z_{A2}|$ is equal to 1, Configuration A does not offer additional flexibility compared to Configuration B. Therefore, the benefit of keeping a segmented design needs to be justified by other aspects.

Finally, in Figure 10, we show that the allocation of stock among indenture levels in Con-

Figure 9: Effect of the number of functional integrated parts on the percentage of instances where Configuration B yields lower costs ($B\%$) and the average cost reduction if Configuration B yields lower cost in percentage ($\Delta TC[B]\%$)

Figure 10: Effect of changing stock allocation on the percentage of instances where Configuration B yields lower costs ($B\%$) and the average cost reduction if Configuration B yields lower cost in percentage ($\Delta TC[B]\%$)

figuration A gives a good approximation whether consolidation is valuable. For instance, in case the stock level of Part 0 is high compared to the total stock of the sub-components (i.e. $s_0 / \sum_{z \in Z_{A2}} s_z > 2$), consolidation appears more interesting. As a result, the stock allocation in a multi-indenture structure may give a first indicator for which parts consolidation might be worthwhile from a total costs perspective.

6. Conclusion

In this paper we have investigated the consequences of consolidation through AM technology. Therefore, we have quantified the total costs differences between a CM assembly and a consolidated AM part for different scenarios. Our results show that consolidation using AM often leads to higher total costs than the CM design. The key reason is that replacing a consolidated AM part is often more expensive than repairing a conventional part by replacing a subcomponent. This may easily wipe out the advantages of a shorter lead time or a lower failure rate of the consolidated AM part. This assessment is based on the following observations:

1. Typically, a combination of higher reliability, reduced replenishment lead time and lower price is required to achieve cost reductions with consolidation. The improvement of one characteristic alone was found to be insufficient in most cases.
2. The benefit of a shorter replenishment lead time through consolidation is less valuable than a lower price or higher reliability, whereas a shorter lead time is often pointed out as a major advantage of AM.
3. The more parts are consolidated into a single one, the less likely consolidation is to be beneficial due to restrictions on possible stock allocation.
4. The higher the difference in part characteristics such as failure rate or purchasing costs, the less likely consolidation of these parts is to be beneficial.
5. The option of repairing a CM assembly by replacing failed sub-components leads to a lower benefit of consolidation, especially when the repair lead time is short and/or the repair costs are low.

As a consequence, even though pointed out as a major opportunity for operations, consolidation with AM technology comes along with a number of hidden costs - in particular for the service business. We argue that, in the light of these findings, industry has to be convinced that the adoption of AM technologies is not only a task for the design department, but also for logistics and maintenance engineers. By disregarding this perspective in the early stages of AM adoption, unexpected costs may arise that in the long run may

damage the perceived value of AM technologies. On the other hand, by including service costs in the analysis, the application of AM technologies may become justifiable also in less obvious cases. For instance, we found that even if the failure rate of a consolidated AM configuration is 1.6 times higher than that of a CM configuration, consolidation may still lead to significantly lowered total costs.

Future research may further substantiate the value of a more holistic perspective and is very much needed considering numerous unanswered questions. As we have discussed, AM technologies may prove valuable for cases where CM methods yield high startup costs, caused for instance by discarded tooling or in case of discontinued supply. Moreover, during our investigations in practice we realized that the transition from CM to AM methods holds major difficulties for companies. Several questions may arise. How do we cope with two significantly different item versions in the field? How do we value the experience and data availability about the CM part version? When do we discontinue the CM supply source and how do we cope with remaining CM stock? Finally, as we have elaborated, assessing the value of AM technologies in combination with condition based monitoring, where short replenishment lead times are essential, appears to be a promising direction for further investigation.

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Appendix A. Example of consolidation

One of the more popular business cases of consolidation is a fuel nozzle used in General Electrics CFM LEAP engines. Using AM technology it was possible to reduce the part count from 18 to 1 and, as a consequence, to decrease the weight by 25%, as well as increasing the estimated life time by a factor of 5. By 2020, GE expects to have printed 100,000 fuel nozzles. An aircraft equipped with the new LEAP engine unlocks savings of around US \$3 million per year compared to an engine that does not use the printed fuel nozzles (GE Aviation, 2015). Unfortunately, it is unclear how these cost savings are exactly attributed to the weight reduction and durability improvement.

Appendix B. Regression analysis

Table 6 shows the results of the multiple regression for the dependent variable $\Delta \ln(TC)$ where the independent variables are log-transformed.

The R-squared for this model is 0.97. Furthermore, based on a t-test, each regressor is significant with a confidence level of more than 99% while White standard errors are consistent in the presence of heteroskedasticity. Finally, a Ramsey RESET test revealed

Figure A.11: Printed fuel nozzle used in CFM LEAP engines of General Electric

Table B.6: Results multiple regression

	Unstandardized coefficient	White standard errors	Standardized coefficient	t	Sig.
Intercept	.3303	.0103		-32.1776	.0000
$\ln(\lambda_A)$	.0532	.0016	.023	33.8593	.0000
$\ln(\tilde{l}_A)$	-.0526	.0021	-.018	-25.0332	.0000
$\ln(p_A)$	-.0031	.0011	-.002	-2.9321	.0034
$\ln(\alpha)$	.1016	.0006	.132	170.6034	.0000
$\ln(\beta)$	.9051	.0013	.511	698.4365	.0000
$\ln(\gamma)$	1.0013	.0013	.565	793.7871	.0000
$\ln(Z_A)$	.8056	.0008	.603	984.5423	.0000
$\ln(\kappa)$	-.1699	.0017	-.073	-102.6065	.0000
$\ln(\tilde{A})$	-1.5557	.0248	-.045	-62.6956	.0000

that the model is sufficiently specified ($P = 0.37$) and thus supports the choice of linear regression model for our purposes.