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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 befits such as weight reductions. Consequences for asset maintenance, however, are not that well understood. For example, the spare part management may profit from potentially shorter resupply lead times of AM, but may suffer from more expensive consolidated parts having to be stocked in anticipation of random failures. Together with a different price and failure rate of AM components, this complicates the decision whether AM should be used to consolidate a spare part. 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, the repair of a component by replacing the defective sub-component only is no longer possible. Furthermore, short resupply lead times for the consolidated spare part turn out to be less beneficial than perceived and therefore relativize the benefit of consolidation with AM. Overall, these findings stress the necessity to adopt a total costs perspective when judging the effects of AM on spare parts management. Otherwise, consolidation may lead to unforeseen effects which may render its application debatable, even despite substantial functionality improvements.

Keywords: Consolidation, Capital Goods, Spare Parts, 3D printing

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1 Introduction

The lifecycle of expensive capital goods, such as manufacturing equipment for high-tech industries or health care and defense systems, often spans several decades. To remain operational during this period, a well-thought out maintenance and logistic support strategy is essential. In particular, spare parts are required to replace deteriorated and failed components. When system downtime has serious consequences, e.g. in case of a grounded aircraft or a stopped production line, short response times are essential. This condition necessitates that spare parts are available quickly, either by locating them close to the installed base or by means of emergency shipments. Both scenarios typically involve high costs. For instance, decentralized stocking of spare parts eliminates scale effects, and emergency shipments result in extra charges compared to regular shipments. An additional difficulty arises through the high variety of spare parts which are required to maintain a system. Tens of thousands or even hundreds of thousands spare parts used by a single company are not uncommon. As a consequence, in many applications, costs related to the spare part management of capital goods significantly exceed their acquisition costs (Öner et al., 2007). This prospect stimulated academia to propose models to optimize spare parts management and hence support decisions regarding how many spare parts to stock at which location in the supply chain, cf. Sherbrooke (2004), Muckstadt (2005) and Van Houtum and Kranenburg (2015). The emergence of additive manufacturing (AM) technology, however, might radically change such decisions in the medium to long run.

Characteristic for AM technology is that - contrary to conventional manufacturing (CM) processes - materials are added layer upon layer to manufacture complete parts. This approach allows a substantial reduction of tooling requirements and setup costs, and thus enables more flexible production of various parts with the same machinery. Based on this characteristic, the production of parts close to the customer sites may become economically reasonable as well (Mellor et al., 2014). Another characteristic is that manufacturing costs are independent of the geometric complexity of the produced part (Hague, 2006). Therefore, design options that were previously infeasible due to Design for Manufacturing (DFM) conventions now become feasible and may allow a usage-driven design. Likewise, the use of raw materials might become more efficient compared to subtractive production processes.

These novel process characteristics have led to high expectations for the application of AM technology. For instance, a survey of the industry showed that about 60% of all respondents foresee the possibility of more than 50% of US manufactures adopting AM technology within 3 to 5 years (PwC, 2014). This expectation might also be a consequence of the rapid advancement of AM technology. In general, AM technology is becoming faster, cheaper, safer, more reliable, and environmentally friendly (Gibson et al., 2010).

The low-volume, high-variety spare parts business is often identified as a potential beneficiary of AM technology. For example, Walter et al. (2004) describe how AM technology may increase the responsiveness of spare part supply chains. They elaborate how safety stock costs can be reduced while response times are kept short by producing spare parts on demand. Additionally, the obsolescence risk of stored spare parts decreases. In the same publication, Walter et al. discuss the concept of producing spare parts close to the customer site. They explain that this concept may offer an alternative to decentralized stocking and emergency shipments. In the latter case, the investment in the required infrastructure is justified by the flexibility of being able to produce different parts with the same AM machinery. Also relevant for the spare parts business might be the option to repair parts with AM technology. For instance, consider a worn out spare part that can be repaired with AM. This may increase the usage period considerably and thus may offer substantial cost savings. The potential is demonstrated by means of a burner tip used in gas turbines at Siemens. Siemens (2014) was able to reduce the repair lead time by 90% and the associated repair cost by 30%.

The spare part management, however, might also be affected by new spare part designs that become feasible with AM technology. According to the Wohlers Associates (2014), the most promising application of the new design freedom 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 and Kirchain (2009) and Wits et al. (2016). For instance, couplings between parts, and thus the cause for several failure modes, can be removed. Furthermore, the performance of the consolidated part may be improved. In this context, performance refers to aspects like 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). Finally, the general benefits of AM technology apply, which we elaborated on earlier. In Appendix 1, we illustrate a typical case of consolidation that was realized with AM technology.

Despite the potentials of consolidation, it would be incorrect to assume that consolidation is always preferable. Instead, 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 might remove the option to repair a defective component by the replacement of sub-components and 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 are lost because of the higher customization of the consolidated part. Consider for example commonality effects that can be achieved by stock pooling among low level parts. Also, higher purchasing costs are likely 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 productions steps. For instance, current AM processes typically require support materials which have to be removed in separate production steps. The same holds true for post-processing steps which are required to increase the surface quality or to reduce residual stress. Finally, consolidation may change spare part characteristics negatively. For example, metal based AM technologies often result in parts that suffer from porosity despite post-processing. As a consequence, mechanical properties are compromised because pores act as a possible origin for cracks. In conclusion, it is not surprising that Thomas (2016) criticizes that studies about consolidation tend to adopt a perspective that is too narrow. Opportunities and drawbacks of consolidation are summarized in Table 1.

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	

Tab. 1. Characteristics of consolidation with AM technology

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 methods for spare part optimization. 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 lifecycle costs of capital goods in Section 3. In Section 4, we explain the model and clarify our assumptions. Afterwards, in Section 5 we conduct different experiments in order to quantify the effects of consolidation. The results reveal under which conditions consolidation appears profitable. We conclude with Section 6, where we summarize the results and provide guidelines as to when consolidation may be worthwhile.

2 Literature review

In this section, we discuss two streams of literature. First, we consider theories for the optimization of spare part inventories in order to set the ground for the methodology applied in this paper. Second, we review literature that quantifies possible effects of AM technology on supply chains.

2.1 Spare part literature

A seminal paper in the field of spare part 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 part 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. For a more extensive overview on this stream of literature, we would like to refer to Sherbrooke (2004), Muckstadt (2005) and Van Houtum and Kranenburg (2015).

2.2 Quantitative models AM literature

The consequences of AM technology for the supply chain are not well understood yet (Holmström et al., 2016). Accordingly, we mostly find conceptual and visionary considerations for the use of AM technology in supply chains, e.g. Pérès and Noyes (2006), Holmström et al. (2010), Waller and Fawcett (2014), Sasson and Johnson (2016). Here, we review the quantitative results.

Barz et al. (2016) study the impact of a more efficient raw material utilization of AM technology 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 technology. 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. It needs to be mentioned, however, 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 about the consequences of a more uniform requirement of raw material with AM technology which is not addressed in their paper.

Liu et al. (2014) analyze the effect of using AM technology instead of CM for a spare parts supply chain of aircrafts. They compare central and decentral deployment of AM equipment with different demand characteristics and service level requirements. The spare part design is considered to be identical for both production methods. In all experiments, the safety stock requirements are lower with AM technology and exemplify the benefit of AM technology of being able to produce on demand. 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 technology 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 cost of AM equipment can be further reduced. Likewise, they identify a higher automation of AM equipment as crucial to reduce the required personnel cost in a decentralized AM supply chain. Finally, they demonstrate that a short production lead time of AM technology 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 technology.

Sirichakwal and Conner (2016) study the consequences of reduced holding costs and replenishment lead times for spare parts which result from the application of AM technology. For this purpose, 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 costs 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 are identical. As a result, potential differences in failure behavior or different spare part configurations are not regarded.

Westerweel et al. (2017) investigates under which conditions an AM part yields lower total lifecycle costs than the CM version. Therefore, 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 MTBF 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 lifecycle length. In case AM technology requires higher investment costs which cannot be offset by performance improvements, this may be ameliorated by spreading out the cost over a large installed base size and long lifecycle. Effects arising from consolidation are assumed to be known upfront and serve as an input to the model.

Overall, we find that literature in this field does not quantify the consequences of consolidation even though consolidation is perceived as the most important application of AM technology for operations (Wohlers Associates, 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 technology cf. Wits et al. (2016) and Lindemann et al. (2015). Second, the value of consolidation tends to be misinterpreted (Thomas, 2016). Third, consolidation may significantly influence the lifecycle costs of capital goods (cf. Section 1). These aspects motivate the study in this paper, wherein we evaluate under which circumstances consolidation with AM technology is advisable from an economical perspective.

3 Effects of consolidation on lifecycle costs

During the lifecycle of expensive capital goods, different cost factors must be considered. Elmakis and Lisnianski (2006) differentiate between 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 model.

Both the development and the production cost category are largely influenced by the manufacturing processes. 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 parts produced with AM, which increases the production costs. We encapsulate these considerations with the difference in purchasing costs between the AM part and the CM assembly. Note that depending on the supply chain layout, one may interpret the purchasing costs as production costs as well.

Often the operation and service cost category is the main contributor to the total lifecycle costs of expensive capital goods (Öner et al., 2007). We subdivide this cost category into operational costs, maintenance costs, and downtime costs. Operational costs arise during the direct usage of the capital good. Typical representatives of this category are electricity, personnel and fuel costs. Some of these cost factors may be affected by consolidation. For example, consider the burner tip business case as specified 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 costs savings. However, in general these cost savings heavily depend on the specific business case and are not suitable for a generic assessment of the effects of consolidation with AM. Consequently, we will exclude the operational costs from the analysis. Nevertheless, note that it is possible to incorporate operational cost differences as input for the analysis of a specific case.

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 part management are likely to be affected by consolidation. As mentioned in Section 1, the failure behavior of consolidated and printed parts usually differs from CM parts. Therefore, the frequency of maintenance activities varies, and the required stock levels of the associated spare parts are different. Also, we often observe shorter replenishment lead times for printed parts, which is a consequence of having less complex supply chains and fewer assembly steps. Hence, we may encounter lower stock levels. Conversely, consolidation of parts constrains the repair options. For instance, repair by replacement of sub-components is no longer possible, and thus may lead to higher repair costs. In order to capture the described differences in maintenance costs, we consider the different failure rates, replenishment lead times, holding costs and repair costs.

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, there exists a relation between downtime costs and target availability, that is, higher downtime costs induce a higher target availability (Houtum and Zijm, 2000). Second, the target availability is typically easier to assess intuitively and thus is more often specified in service contracts or functional specification documents than downtime costs. We therefore compare the total life cycle costs of the AM part with the CM assembly, subject to a mutual availability constraint in our analysis.

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 lifecycle. Often this situation leads to a depreciation of the value of the remaining stock. Consolidation may worsen this effect, as parts are more complex and specific, and hence more valuable. 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, it is difficult to predict during the design phase which of the two effects will eventually have a more significant impact, as aspects like decreasing demand and learning effects during the lifecycle 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 lifecycle of the capital good. For these reasons, we decided to exclude the disposal costs from the analysis. In an actual case where 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. Afterwards, we list the resulting assumptions before we construct the mathematical model in the next sub-section. 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. In case no stock is available, demand is backordered until a spare part becomes available. The failed component enters a repair process (if possible), which always results in a ready-for-use spare part with a similar failure pattern as an entirely new item. Inventories are controlled according to a base stock policy.

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 costs 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 processes. 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.

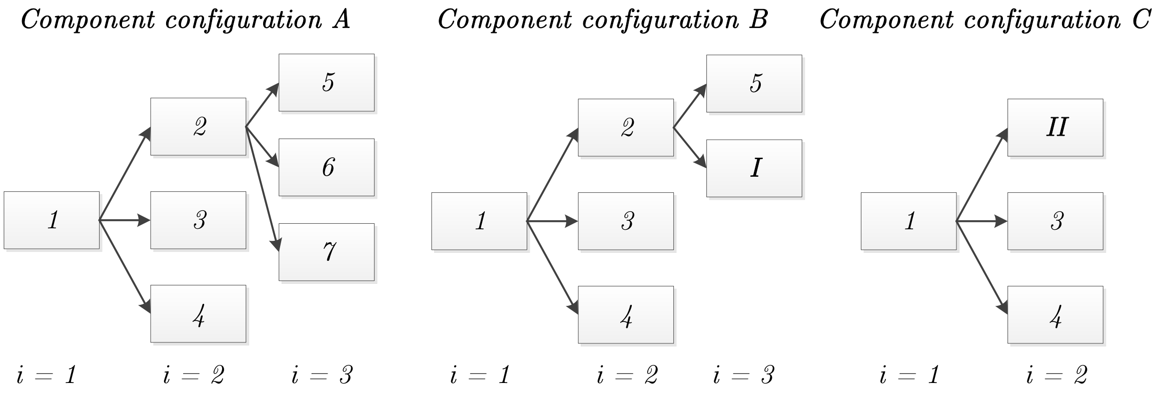

Fig. 1. Possible configurations of component

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 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 the lowest indenture parts; 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.
11. Holding costs are encountered during the repair and ordering process.
12. No condemnation occurs, i.e. each repair is successful.

4.3 Notation and mathematical model

In this paragraph, we explain the mathematical model. Notations are introduced in the text and summarized in Table 2. For the evaluation of functions introduced in this sub-section, we refer to 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, $i = 1, 2, \ldots I$, 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 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 per 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. 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 by replacing the failed part $z \in Z_{k1}$ with r_z being the cost rate of replacement. In case $\Gamma_k(z) \neq \emptyset$, the part $z \in Z_{k1}$ 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 costs 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 costs 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 costs rate a_z plus the total piece price of all its lower level parts included in $\Gamma_k(u)$. The average replenishment ($z \in Z_{kI}$) or repair lead time ($z \in Z_k \setminus Z_{kI}$) of $z \in Z_k$ is denoted by l_z.

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 $z \epsilon Z_{kI}$
r_z	Replacement cost rate of part $z \epsilon Z_k$
p_z	Purchasing cost rate of a lowest indenture part $z \epsilon Z_{kI}$
a_z	Assembly cost rate of a higher indenture level part $z \epsilon Z_k \setminus Z_{kI}$
$P_k(z)$	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
$EBO(.)$	Expected number of backorders
$VBO(.)$	Variance of backorders
$R_k(z)$	Parts in replenishment of part z in configuration k

Tab. 2. Notation overview

We define the following decision variables:

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

$\mathbf{S_k} = \{s_k(z) | \forall z \in Z_k\}$ for $\forall k \in K$, where $s_k(z)$ denotes 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 the next sub-section.

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

4.4 Model evaluation

As clarified in Section 2, we use VARI-METRIC to evaluate our model (Sherbrooke, 1986). 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 each lowest indenture level part $z \in Z_{kI}$ with $m_k(z) = IB\lambda_z$. For a higher indenture part $u \in Z_k \setminus Z_{kI}$, we use $m_k(u) = \sum_{z \in \Gamma_k(u)} m_k(z)$. Next, we determine for part $z \in Z_k$ the expected number of backorders $EBO(s_k(z), .)$ and the variance of backorders $VBO(s_k(z), .)$. At the lowest indenture-level, 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 $R_k(y)$ for part $y \in \Psi_k(z)$:

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

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

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

$$A_k(\mathbf{S_k}) \approx Max\{1 - \frac{EBO(\mathbf{S_k})}{IB}, 0\}. \tag{4}$$

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 the lowest indenture part $z \in Z_{kI}$, we have $P_k(z) = p_z$. For a higher indenture part $u \in Z_k \setminus Z_{kI}$ we use $P_k(u) = a_u + \sum_{y \in \Gamma_k(u)} P_k(y)$. 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:

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

Finally, we obtain the total costs with

$$TC_k(\mathbf{S_k}) = \sum_{z \in Z_{k1}} C_z(s_k(z)). \tag{6}$$

4.5 Model optimization

To optimize the formulated model, we follow the marginal analysis of Sherbrooke, cf. Sherbrooke (2004). The underlying idea of Sherbrooke's 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 $\mathbf{S_{k_{new}}} := \mathbf{S_k} + \mathbf{e_z}$ ;
    Calculate $\Delta_z = \frac{EBO(\mathbf{S_k}) - EBO(\mathbf{S_{k_{new}}})}{TC_k(\mathbf{S_{k_{new}}}) - TC_k(\mathbf{S_k})}, \forall z$ ;
    Let $u := argmax_z \Delta_z$ and set $\mathbf{S_k} := \mathbf{S_k} + \mathbf{e_u}$ ;
    Store efficient point $(EBO(\mathbf{S_k}), TC_k(\mathbf{S_k}))$;
    Evaluate $A_k(\mathbf{S_k})$;
end
```

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 $\tilde{A}$.

5 Experimental section

In this section, we will conduct numerical experiments in order to gain insights about the effects of consolidation with AM. For this purpose, we will consider two setups: consolidation at the same indenture level ($I = 1$), and consolidation over two indenture levels ($I = 2$). 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 **B**%.
2. The average costs savings 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 $\mathbf{\Delta TC[B]}$%.

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 $\mathbf{\Delta ln(TC)}$.

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.

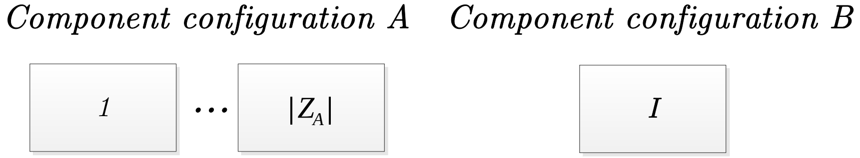

Fig. 2. Possible configurations of component

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 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 $\boldsymbol{\alpha}$ 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 $\boldsymbol{\beta}$ describing the ratio between the average failure rates of both configurations. The purchasing costs rate of Part I is related to the purchasing costs rate of Configuration A (i.e. $p_A = \sum_{z \in Z_A} p_z$) with $p_I = \gamma p_A$, where $\boldsymbol{\gamma}$ models the ratio between the purchasing costs rate of both configurations. Therefore, if either of the factors (α, β, γ) is smaller than 1, consolidation offers a more favorable part characteristic.

In Table 3 we list the parameter values of the first experiment, 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.

Parameters	**Values**
l_z	$U[0.2, 1]$
λ_z	$U[0.2/\lvert Z_k\rvert, 5/\lvert Z_k\rvert]$
p_z	$U[100/\lvert Z_k\rvert, 20000/Z_k]$
κ	0.15, 0.3
$\tilde{A}$	0.95, 0.995
$\lvert Z_A\rvert$	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

Tab. 3. Parameter values

As a first step, we study the significance and the effect of changing input parameters with linear regression. As the dependent variable we use $\Delta ln(TC)$. The regression analysis revealed the following standardized relation with an $R^2 = 0.92$:

$$\begin{aligned} \Delta ln(TC) = -0.9 - 0.02\tilde{l}_A - 0.01p_A - 0.05\tilde{A} - 0.07\kappa \\ +0.02\lambda_A + 0.58|Z_A| + 0.13\alpha + 0.5\beta + 0.55\gamma \end{aligned} \tag{7}$$

Based on a t-test, each of the applied predictors is significant with a confidence level of more than 99%. Furthermore, the predictors are not significantly correlated. Therefore, the linear regression is suitable to deducing several characteristics of consolidation: the holding costs fraction (κ), the target availability ($\tilde{A}$), the weighted average replenishment lead time ($\tilde{l}_A$) and the purchasing costs 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 costs 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 costs 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 specific instances, the cost saving potentials of consolidation are high. For example, consider the scenario where the purchasing costs rate is 1.6 higher for Configuration B than for Configuration A ($\gamma = 1.6$). On average, the higher purchasing costs 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 costs savings on average ($\Delta TC[B]\% = -11\%$). This finding clarifies that assessing the value of consolidation by a single characteristic like the purchasing costs rate is not advisable. Instead, a total costs perspective is required to evaluate the possible benefit of consolidation.

Parameter	**Value**	**B%**	**ΔTC[B]%**	**Δln(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

Tab. 4. Impact of changing parameters

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 consolidation than a lower failure rate (β) or purchasing costs rate (γ). Accordingly, $B\%$ changes

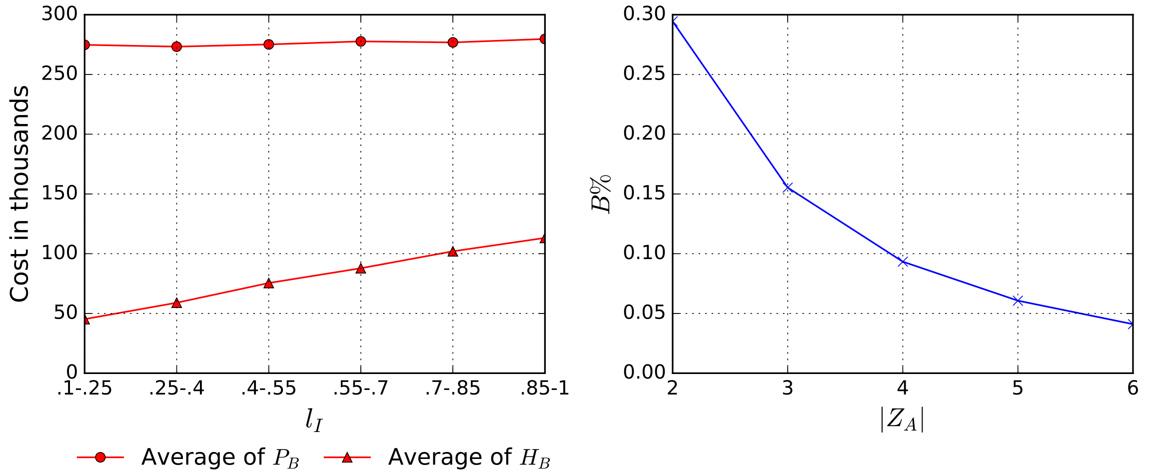

Fig. 3. Effect of average replenishment lead time (left) and effect of $|Z_A|$ (right)

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 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 (left) 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 costs fraction (κ), a long weighted average lead time ($\tilde{l}_A$) or a high purchasing costs rate of Configuration A (p_A). Therefore, this result also offers an interpretation for results 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 costs saving with consolidation, which we deduced from the regression analysis. On the right side of Figure 3, 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 costs savings eventually. Given that this flexibility increases with $|Z_A|$, the result of the regression analysis appears reasonable.

To further elaborate on this aspect, 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 4 , 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 costs rate and the average replenishment lead time.

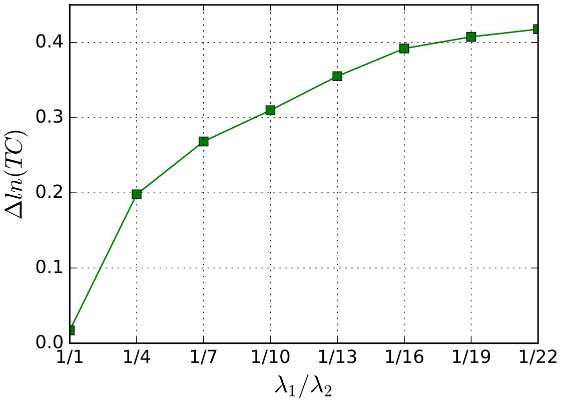

Fig. 4. Consequence of different failure rates

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 5. 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.

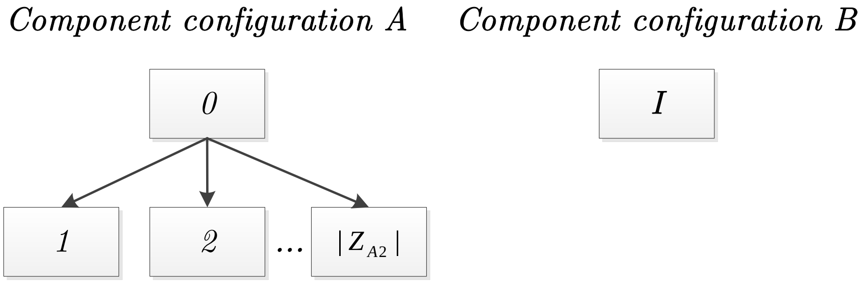
Component configuration A *Component configuration B*

Fig. 5. 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 $\boldsymbol{\xi}$ 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 $\boldsymbol{\pi}$ denotes the ratio between the repair costs rate and total piece price of Part 0.

Parameters	**Values**
l_z with $z \in Z_{k2}$	$U[0.5/\lvert Z_{A2}\rvert, 1/\lvert Z_{A2}\rvert]$
λ_z with $z \in Z_{k2}$	$U[0.2/\lvert Z_{A2}\rvert, 5/\lvert Z_{A2}\rvert]$
p_z with $z \in Z_{k2}$	$U[2000/\lvert Z_{A2}\rvert, 20000/\lvert Z_{A2}\rvert]$
κ	0.15, 0.3
$\tilde{A}$	0.95, 0.995
$\lvert Z_{A2}\rvert$	1, 2, 3, 4, 5
α	0.8, 1, 1.2
β	0.2, 0.6, 1
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	$\gamma P_A(0)$

Tab. 5. Parameter values

In Table 5 we show the experimental settings. Given that we sample 25 times from each uniform distribution, the experimental setup results in 270.000 problem instances.

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. Afterward, we evaluate the impact of the lead time ratio ξ.

In Figure 6, 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.

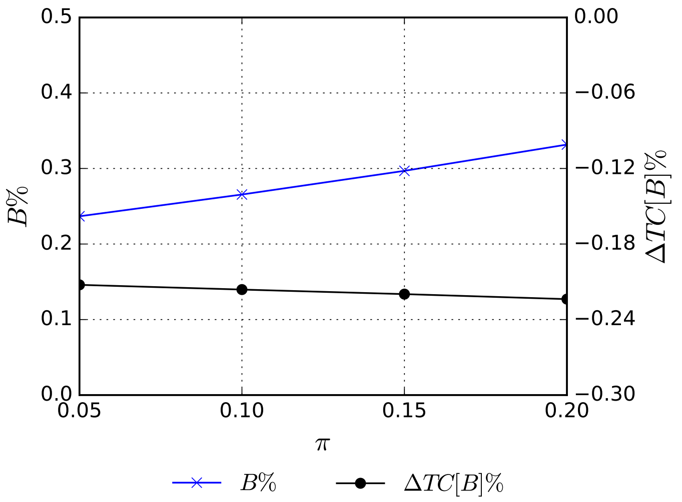

Fig. 6. Effect of changing repair costs

While Configuration A allows for solving a failure by purchasing a new sub-component only, consolidation requires the purchase of the entire Configuration. Next to the purchasing costs savings, the repair process may reduce the holding costs as well. This potential is illustrated in Figure 7, 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 costs saving potential decreases slightly ($\Delta TC[B]\%$). These effects are a consequence of the possibility to resupply

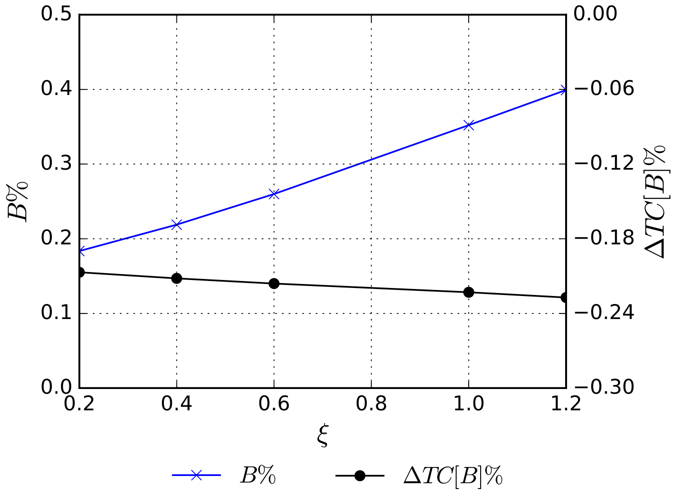

Fig. 7. Effect of changing repair lead time

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 8 (left). 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.

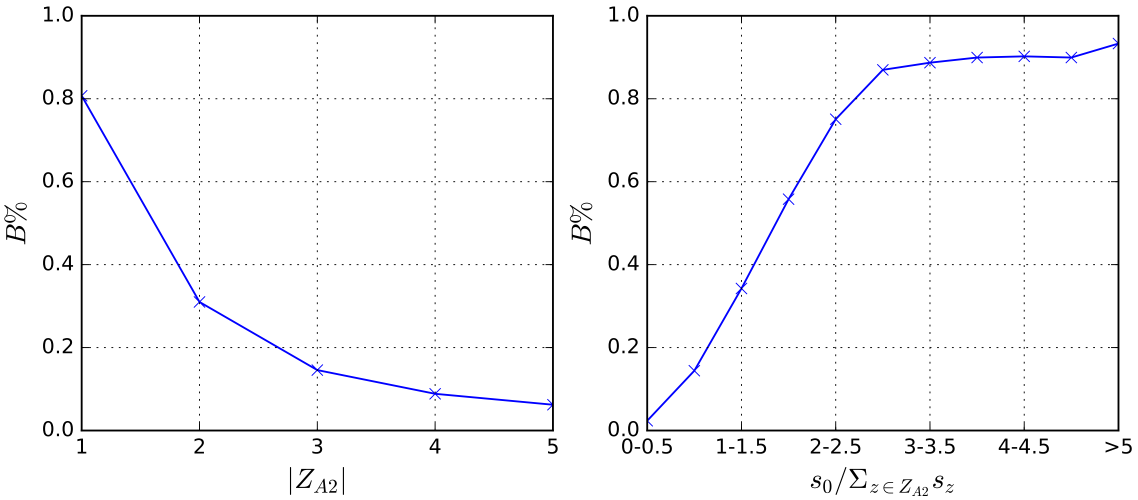

Fig. 8. Impact of $|Z_{A2}|$ (left) and stock allocation (right)

Finally, in Figure 8 (right), we show that the allocation of stock among indenture levels in Configuration 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 subcomponents (i.e. $s_0/\sum_{z\in Z_{A2}} s_z > 2.5$), 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. This assessment is based on the following observations:

1. Typically, a combination of higher reliability, reduced replenishment lead 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.

Overall, these findings should not be misunderstood as a statement against consolidation through AM technology. We merely wish to stress the need to adopt a total costs perspective when judging the impact of AM-based consolidation of spare parts. Should this be neglected, the consequences of consolidation may be underestimated due to different logistics, manufacturing and repair processes and thus may lead to higher total costs even despite substantial functionality improvements. Furthermore, the total costs perspective is useful to justify consolidation 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.

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Appendix

Example of consolidation

One of the more popular business cases of consolidation is a fuel nozzle used in General Electric's CFM LEAP engines. Using AM technology it was possible to reduce the part count from 18 to 1 and, as a consequence, to decrease weight by 25%, as well as increasing the estimated life time by a factor of 5 (GE Aviation, 2015).

Fig. 9. Printed fuel nozzle used in CFM LEAP engines of General Electric