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Impact of Merging Components by Additive Manufacturing in Spare Parts Management

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Abstract

This paper investigates impacts of merging components and reduction of sub-assemblies by exploiting additive manufacturing (AM) capabilities to allow for production of various components forming the final part composition as just one single part. The analysis is performed by considering a base structure for part composition, and inclusion of final components currently produced with conventional methods, and then comparing this with a list of alternatives that consist of merged components realized through AM.

The comparative analysis among three main factors of reliability, logistics, and production cost and their impacts over average expected cost are the main aims of this study.

Keywords: Additive manufacturing; Spare parts management; Maintenance and reliability; Parametric analysis; Comonents merger

1. Introduction

As manufacturers and researchers continuously look for more appealing approaches towards improved applications and better integration of machinery based on Additive Manufacturing (AM) technologies in different fields of industry, spare parts sector has been demonstrating [1] more promising signs of progress for further implementation of AM [2]. One of these signs lies within merging components of maintenance spare parts. Part consolidation through AM is an interesting subject which has been widely studied [3]by researchers with respect to both sustainability [4] and structural design [5]. From an operational point of view, with AM-in contrast to conventional methods of production-functionality comes before and above complexity of the design, and so manufacturing functionally-enhanced parts characterized by the least possible number of assemblies whose design

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complexities can be matched with customers' desired requirements becomes feasible [6] and more accessible. From a strategic point of view, the just-in-time nature of AM-based productions eliminates the need for having large warehouses which are always accompanied with resource-demanding inventory keeping tasks.

Although some studies such as [7] have investigated technical guidelines of part consolidation and for instance in that case identified build direction and consideration of material properties as the main factors in such exercises, the approach in this paper is based on parametric analysis of the main factors that influence average incurred costs resulting from acquisition and management of the spare parts. These are the spares which are used to maintain and replace the failed parts that are used in the final product. A plausible classification of these factors is done to account for both manufacturing method, and product structure. While the primary set of factors accommodate effects of production cost, reliability effects, and logistics cost to account for the manufacturing method, the secondary set of factors comprise cost and reliability distribution of the components to incorporate the product specific features in the study. The main purpose of this contribution is to propose a parametric analysis and provide an overall view over the subject, and perform a comprehensive study which can extend beyond an individual case. This would help generalize the concept and make it more appealing to any industrial case, regardless of the product's structure and specific parameters value.

This study provides an evaluation of all alternatives through an enumeration process. In the meantime, a further investigation of maintenance implications resulting from AM usage in spare parts industry is provided. The main implication of this study is to understand how changing methods of production from a conventional process to an additive one for a multi-component product composition could alter the use-phase of components in medium to long terms. The remainder of this paper is organised as follows: section 2 provides the structure and modelling overview of the study, which is then followed by a numerical analysis and presentation of results for the parametric analysis in section 3. Section 4 provides maintenance implications of the analysis, and finally the paper is concluded in section 5.

Nomenclature

C_i	Cost of production for component i [€]
R_i	Reliability of component i [%]
λ_i	Failure rate of component i
T	Time period considered [hours]
$MTTF_i$	Expected mean time to failure for component i [hours]
Re_i	Expected number of replacements for component i
L	Logistics cost [%]
λ_{AJ}	Failure rate of merged components made by AM in alternative j
C_{BJ}	Cost of production of merged components made by AM in alternative j
α	Coefficient of production cost for merged components in AM
β	Coefficient of failure rate for merged components in AM
γ	Coefficient of logistics cost for merged components in AM
$TC(T)$	Average expected cost over the considered time period for base case [€]
$TC_j(T)$	Average expected cost over the considered time period for alternative j [€]

$i \in I = \{1, \dots, n\}$ denotes number of components
$j \in J = \{1, \dots, m\}$ denotes set of alternatives for merged components in AM

2. Model and structure

The study considers the main technical advantages provided by AM technologies as a platform that could practically offer a feasible solution to reduce the total number of components in the part composition. The choice behind AM as the enabler of this solution lies within the unique set of features that are realized by its dedicated machineries. One of the main features of AM is the ability to consolidate assembly parts and integrate them into single objects [8]. This capability can reduce the final weight of the part [9], boost its functionality [10], and provide high-customization opportunities [11]. These features alongside the supply chain simplifications and quick market responsiveness [12] as well as reductions in energy consumption and emissions [13] plus weight reduction opportunities [14] are what turn AM into a promising candidate for reaching the objective of this study. The issues with spare parts and their management become even more pressing in an area like advanced capital goods where demand variations, production and stock-out costs are high, while complexity of designs and remote service locations make the tasks only more challenging [15]. However, the dynamics of spare parts industry goes beyond capital goods. Accounting for the erratic demands which is an inherent characteristic of this sector could either lead to costly stock-outs or result in expensive piling up of inventories and thus, increasing total cost of stockholding. Although there have been several quantitative models like those mentioned in [16] and managerial approaches such as [17] in the literature to optimize and provide strategic solutions for inventories of spare parts, the financial implications of any decision in this field needs to be considered with respect to the whole supply chain.

As mentioned before, spare parts industry is the most significant area where AM characteristics can be attributed to. The fact that two of the most important aspects in management of spare parts inventory are number of working parts and their expected failure rates [18] provides more motivation to delve into this area. Although the evidence related to the AM's capabilities to increase the reliability of the parts and consequently decrease their failure rates are not still robust, reduction of the number of components can be viewed as an interesting starting point whose multiple instances of success can be found in literature [19] and industry [20]. However, despite the fact that inclusion of AM methods to increase complexity of components by integrating functionality of various parts, and reduction of the total number of assembled parts has already been introduced as a method to consolidate spare parts [21], this strategy requires a more careful assessment since the optimal solution in terms of cost may not always lie in outright removal of all sub-assembly stages. As it would be seen throughout this paper, an optimal solution depends on multiple factors whose impacts over the cost function could singularly or en masse vary and thus, necessitate proper decision-making. These decisions should not only consider design and technical feasibilities of mergers through AM, but also encompass a wider range of factors including but not limited to the reliabilities of components both before and after the merger, cost implications related to the procurement and productions, as well as inventory holding concepts.

2.1. Model

The mathematical model used in this paper is based on the basic series reliability model which can be found in literature [22], and the useful life period of the components is assumed to be based on exponential distribution where failure rates occur randomly. In the first step, by considering cost and reliability for component i where $i \in I = \{1, \dots, n\}$, the failure rate for each of them is obtained from (1):

$$\lambda_i = -\ln R_i / T \tag{1}$$

Then, considering that the components are assumed to be non-repairable and consequent quantification of reliability as MTTF, and by accounting for the specific period of interest during which the required replacements take place to substitute specific components, the expected mean time to failure for each of them in a constant failure rate system is attained from (2):

$$MTTF_i = 1/\lambda_i \tag{2}$$

The expected number of replacements for each component per specified period of interest is calculated in (3):

$$Re_i = T/MTTF_i \tag{3}$$

The average expected cost in the specific period, for the base case with no components merged with AM, can be calculated as follows.

$$TC(T) = (1 + L) \cdot \sum_{i \in I} C_i \cdot Re_i \tag{4}$$

For each merging scenario, a consistent method for calculation of the changes that take place is performed; i.e. for the components which are merged together, their respective individual λ_i values are summed up to account for the serial placement of the composition [22], while this value for the unmerged component remains intact. Having $s \in S = \{1, \dots, k\} \subseteq I$ as the set of components which are merged together for an alternative j. It is assumed that λ_{Aj} of the merged components can be obtained according to Eq. (5).

$$\lambda_{Aj} = \alpha \cdot \sum_{s \in S} (\lambda_s) \tag{5}$$

Having drawn failure rate of the merged component, value of reliability can be derived by inversing (1). Moreover, it is assumed that C_{Bj} can be calculated as follows:

$$C_{Bj} = \beta \cdot {}^{1}/_{k} \cdot \sum_{s \in S}(C_s) \quad (6)$$

Where k enumerates elements of I subset which are merged together in an alternative j. After deriving TC_j in (7), all alternatives are compared in terms of their average expected costs. The optimal j-th alternative is the one with $Min\, TC_j$.

$$TC_j(T) = (1 + L) \cdot \sum_{j \in J} C_{Bj} \cdot Re_{Aj} \quad (7)$$

2.2. Product structure

The current model can be applied to a general product structure with a bill of material (BOM) similar to the one depicted in Figure 1. By applying this model to the specific candidate components which can technically be merged together, an economic analysis is performed to ensure that reduction of the total number of assemblies is both technically and economically feasible.

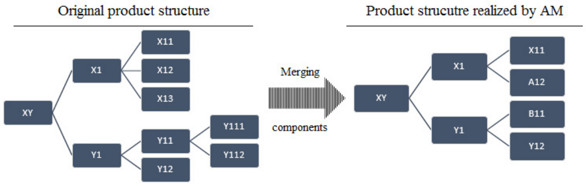

Figure 1. Reduction of number of assemblies by merging components through AM.

The main goal behind merging candidate components is to obtain a product whose final design could have the fewest possible number of assemblies similar to the air duct example mentioned in [23]. While with the original design made by conventional methods, the product is composed of 16 components and fasteners (on the left in Figure 2-a), the redesigned approach (on the right in Figure 2-b) realized through AM is made of only one single part with integrated functionalities and enhanced performance.

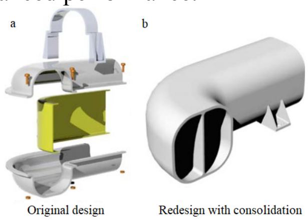

Figure 2. Aircraft duct example [23].

3. Analysis

3.1. Numerical example

The composition of the part which is used in this paper is made up of three components, each of which having its constant reliability rate that have been assumed to be different from each other. The structure of the composition is based on a serial model which can be seen in Figure 3.

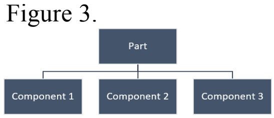

Figure 3. Schematic of the part composition.

All feasible alternatives resulting from merger of the components in the original composition that can be used to form the part are seen in Figure 4. Note that since scope of this paper is limited to the impacts arising from components' mergers, the technical feasibility of these mergers and the part design requirements have been assumed to be non-problematic.

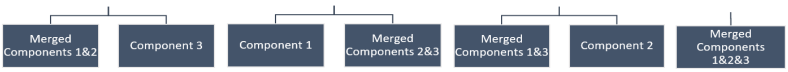

Figure 4. Schematic of all alternatives for merging components.

For a better analysis of a part's merger for the structure in Figure 3, the data in Table 1 is going to be used.

Table 1. Arbitrary data to be used to analyze impacts of merging components.

Parameter	Value	Unit
C_1	800	€
C_2	500	€
C_3	200	€
R_1	80	%
R_2	90	%
R_3	95	%
T	1000	Hours
L	50	% (of production cost)

As it can be seen in the table, it has been assumed that components with higher production costs have lower reliability, i.e. $C_1 > C_2 > C_3$ and $R_1 < R_2 < R_3$. A further elaboration of this aspect is discussed in 3.3. Logistics cost in this paper refers to the cost of storage, warehousing, and inventory, which is assumed to be a percentage of production cost. Also, the values assigned to α, β and γ are equal to 1. The average expected cost for each alternative as well as the base scenario can be seen in Figure 5.

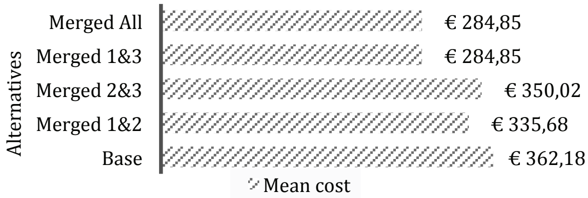

Figure 5. The average expected cost for all alternatives with no variations in factors.

As (4) suggests, the main factors impacting expected cost of each alternative are production cost, reliability, and logistics cost. From this part on for ease of understanding, the text is discussed based on the changes occurring to reliability rather than failure rate. A range of variations over three levels for each factor is performed. By generating a total permutation of 27 with the ranges specified in Table 2 for α, β and γ, a more detailed analysis of the factors is performed. It must be noted that the choice of three levels in this case is for demonstrative purposes, and that this level could assume any arbitrary value.

Table 2. Ranging coefficients of production cost, failure rate, and logistics cost.

α	β	γ
-50%	-50%	-50%
0	-25%	0
+50%	0	+50%

Having established a table of all alternatives (a total of five, including the base scenario in which no merger takes place), expanded over 27 permutations, the optimal option is derived from the solution with the minimum average expected cost. The optimal cost can be derived from any one (and in some cases two or more) of permutations.

3.2. Parametric analysis

In the next step, the results are subjected to a factorial analysis in the Minitab software. Although the design of experiment (DOE) in this case is balanced and so data means and fitted means are equal, the fitted means is preferred to assess response differences that result from the changes in factor levels. The results show that neither among L and C, nor between L and R can be seen any significant interactions, while the level of interaction between C and R is rather high. This impact becomes more evident once the main effects plot for the optimal values is drawn in Figure 6. As it can be seen, by varying C from -50% up to +50%, the average expected cost increases, while this effect for R is reversed. Also, it can be seen that the effect of L is not significant in comparison with that of other factors.

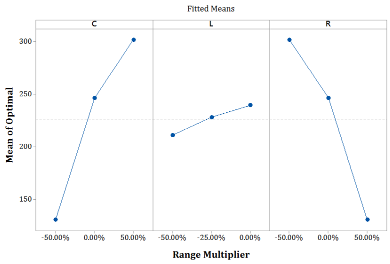

Figure 6. Main effects plot for the optimal values.

Having established cost and reliability as the most important factors standing out among the three factors, the analysis is moved back to the previous step where more detailed range of variations over coefficients which are incremented at smaller steps are introduced to C and R. The main objective in this step is to work out the active levels for both factors at which shifting towards a certain type of alternative (ranging from non-merged to all-merged) becomes optimal. To do so, the basic scenario is varied at different levels of the two main factors (C and R) by increments of 5%. While the calculations are globally the same as before for all alternatives and their permutations, the main difference arises from the fact that the logistics cost is kept constant. The total number of permutations for each alternative is 441 (for a range of -50%-+50%), plus the base case scenario whose values for all permutations remain the same. This is done to ensure that the base case scenario with no mergers can also be evaluated as an optimal alternative with respect to the other solution-scenarios simultaneously taking place. After generating permutations for all alternatives, the results (average expected cost for alternatives) are once again compared to each other to understand which alternative is producing the optimal result. Figure 7 illustrates distribution of mean cost for each alternative along its various permutations. As it can be seen, the mean cost for merged alternatives is almost always less compared with the base case scenario (non-merged). Although this suggests consolidation of components can generally lead to a reduction of average expected cost, the optimal situation needs to be monitored in more relative terms.

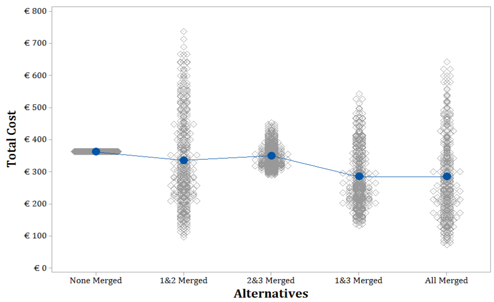

Figure 7. Individual Value Plot of different alternatives.

Looking at Figure 8 which demonstrates the outcomes of this procedure, the optimal alternative comes either from the non-merged, or partial merger of components 1 and 3, or the full-merger. Apart from the arbitrary values assigned to the parameters in the base scenario which is the main reason why the results are categorized among three alternatives out five, it is illustrated that increasing cost while decreasing reliability is a situation where the non-merger alternative almost always prevails the other choices. With increasing reliability, the optimal option shifts towards partial or full merger of components. Keeping at the high levels of reliability, the optimal options in case of lower costs tend towards full merger scenario, while by lowering levels of reliability, the optimal alternatives are once again dispersed over full and partial merger of components.

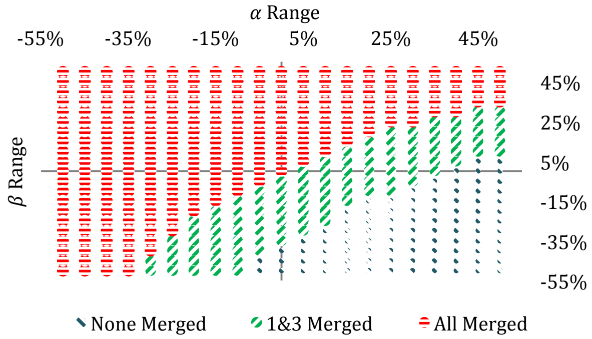

Figure 8. The impact of changing production cost and reliability on the average expected cost of different alternatives.

3.3. Reliability and cost outsets

By changing the outset of components' reliability rates, a different trend for the outcomes would be expected to emerge. As it can be seen in Figure 9, in the case where components with higher production costs have higher reliability rates ($C_1 > C_2 > C_3$ and $R_1 > R_2 > R_3$) the optimal alternative is widely dispersed among no-merger and partial merger of components 1 and 2, while full-merger of components becomes optimal for a handful of scenarios.

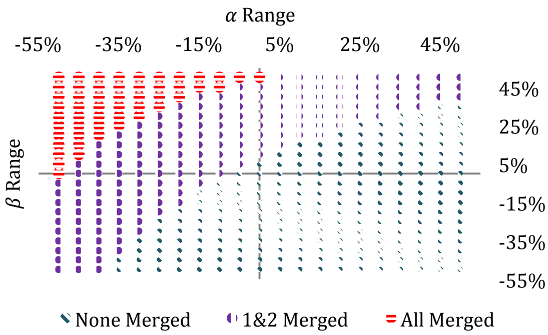

Figure 9. The impact of changing production cost and reliability on the average expected cost of alternatives for increasing reliability rates.

Another plausible outset for the reliability rates and production cost ($C_1 > C_2 > C_3$ and $R_1 = R_2 = R_3$), and the impacts of varying them over ranges can be seen in Figure 10. As illustrated, the optimal alternatives are almost equally divided between the choice of either full-merger of components or no-merger, leaving the only partial merge of components 1 and 2 for the center of the coordinate table where there are no variations in factors.

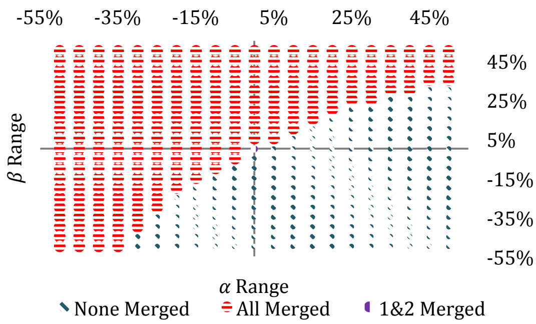

Figure 10. The impact of changing production cost and reliability on the average expected cost of alternatives for equal reliability rates.

4. Maintenance implications

The sensitivity analysis performed over the three main factors of production cost, logistics cost, and reliability of components reveals that depending on the situation, the optimal choice between no merger, partial merger or full merger of the components of a part could vary. Sticking to the original outsets of production costs and reliability rates ($C_1 > C_2 > C_3$ and $R_1 < R_2 < R_3$) and starting with the ideal situation [from manufacturer's perspective] in which reliability of the components is high and their production costs are low, the optimal option is always merging the components to the least possible number. This means considering that in such situations reliability of the components has already been secured, the optimality goes only in a way to minimize the associated costs. From both tactical and operational point of view, knowing that spending less on the procurement of the components would result in the same or higher level of reliability would certainly be an advantage for the manufacturer. Reduction of the number of replacements and increasing overall availability of the part/product are the results which can be expected to be obtained directly. Moving on diagonally to the opposite of the ideal situation where alongside increasing the costs, reliability decreases, the optimal situation in the worst-case scenarios tends towards the base alternative in which production of components separately and then assembling them later is preferred to other alternatives. This also makes sense, since if increasing the costs is adversely affecting the overall reliability of the part, the desirable choice is to either make the components separately, or opt for a partial solution where costs and reliability are in put in a trade-off. For the other situation in which reliability and cost act in harmony, i.e. the higher the cost of productions the higher the reliability of the components and vice versa, the outcomes are not conclusive. From what can be seen in the current study, the optimal options are divided almost half and half between full merger and partial merger of the components, and the instances where no merger is preferred is on border lines where the previously stated worst-case scenario is taking place. But apart from the values assigned to the factors and the increments made over ranges, the only firm suggestion for such scenarios can be that as long as manufacturers are willing to pay for the improvement of the quality of the components for the final products (consequently increasing their reliabilities), it would be a better and safer choice to opt for more assembly mergers and less separation of parts.

5. Conclusions

This study presents a parametric analysis of the most impactful factors in occasions where assembly of multiple components into the final spare part is taken as a case study for merging those components and reducing the total number of assemblies. By considering cost of production, logistics cost and reliability of the components, the analysis delves into the dynamics and interactions that they could have over each other as well as the overall performance in terms of expected costs. It is understood that depending on the values and trends assumed by production cost and reliability, the optimal alternative could vary among no merger, partial merger, or full merger of the components. In this study the logistics costs were assumed to be a percentage of the production cost which is one of the shortcomings of the paper. This assumption however, needs to be further broken down and analyzed in future studies to provide a more accurate picture about its impacts and interactions. Another factor whose more detailed analysis could improve the decision process is the production cost both in AM and conventional methods. The other shortcoming is the structure or in better words composition of the spare part: starting from this base structure, a more complex part composition (in terms of BOM levels and number of components) can be analyzed in future studies. Moreover, another limitation of the present study is related to the lack of experimentation data. Although this is a parametric analysis of the most impactful factors pertaining to a general structure, a set of experimentations over real case studies could yield significant results for the validation of the proposed model.

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