Improving sustainability and cost efficiency for spare part allocation strategies by utilisation of additive manufacturing technologies

Karl Ott\textsuperscript{a,b,*}, Heimo Pascher\textsuperscript{a}, Wilfried Sihn\textsuperscript{a,b},

\textsuperscript{a}Fraunhofer Austria Research GmbH, Theresianumgasse 7, 1040 Vienna, Austria
\textsuperscript{b}Technical University of Vienna, Institute for Management Science, Theresianumgasse 27, 1040 Vienna, Austria

Abstract

Currently, no proper cost models are available to assist managers in selecting part-specific allocation strategies for spare parts under consideration of metal additive manufacturing (AM). Therefore, sustainability aspects and cost efficiency over a product lifecycle show potential for optimisation.

The aim of this paper is to propose a two-stage model as a basis for decision support in spare part allocation.

The first stage introduces a multi-criteria part classification regarding classical criteria as well as criteria referring to AM. The impacts on different spare part allocation strategies like final stockpiling, conventional spare part production or AM on demand will be focused.

Based on the first stage, a conceptual model for a comprehensive activity based cost assessment will be adopted to assess the arising costs that occur for each of the compared allocation strategies. Evaluating the relevant factors for the specific product, process, warehousing and capital issues, the basis for choosing the best suitable spare part allocation strategy will be presented.

The present document is a working paper, where the interim results of the intended concept model are introduced.

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* Corresponding author. Tel.: +43 676 888 616 12
E-mail address: karl.ott@fraunhofer.at
1. Introduction

When talking about sustainability, we focus on three pillars – namely ecology, economy and social issues. An important objective is to decouple economic growth with an accompanying environmental degradation. Furthermore, societal impacts like ensuring job security, respectively competitiveness in a globalised world are further factors. Economy and in particular companies play a central role in the integration of ecological, economic and social issues when deriving strategies or business models [1,2]. Challenges concerning sustainability may not be seen solitary; interdependencies between these areas play an important role when it comes to the strategic focus of a company.

Over different branches, there are highly diverse implications for sustainability aspects accompanied by AM. Holmström et al. [3] define sustainability as ability to combine manufacturing practice with operational practices in terms of design, distribution, use, product service and combinations of products and services.

An important advantage of AM can find application in spare parts management. The potential of AM to produce spare parts on demand gives companies the possibility to combine different spare part allocation strategies. By spare part allocation strategy, we understand the mode how different spare part items are provided to the plant operator especially after the End of Production (EOP). Due to diverse demand behavior of different part numbers, each specific item has a preferred strategy. We differentiate between the option of final stockpiling, where a specific part is produced in a sufficient quantity and the regarded parts are stored for a whole product lifecycle. Another possible option could be conventional manufacturing with a turning-milling centre or AM of a specific part on demand.

A mix of those different allocation strategies for a focused plant can lead to cost savings [4]. In addition, a possible reduction of transports and storage as well as reduction of the inherent consumption of resources and generated emissions are important factors regarding the positive implications on sustainability. In a survey, we asked 62 spare parts specialists how they see the potential of AM in the spare parts business [5]. Nearly half of the respondents answered that AM has very high (18 percent) or high (27 percent) potential in their own company. This issue shows that AM has high potential in the spare parts respectively after sales business. Nevertheless, several obstacles need to be overcome.

At present, companies in machinery and plant engineering do not have a decision support based on cost quantification of different spare part allocation strategies after EOP. Therefore, it is a difficult and subjective decision, which allocation strategy to choose and where to use the AM technology in an efficient way. There are different procedures for decision support for mere spare part allocation respectively mere AM production strategy. Deuse and Finke focused on post series supply of electronic components in the automotive sector based on spare parts classification [6]. Achillas et al. developed a framework for the selection of an effective portfolio of production strategies including AM [7]. Rickenbacher et al. developed a cost model for the estimation of the total cost per part for Selective Laser Melting [8]. Combined methodologies to assess AM and spare part allocation are existing only in a limited way. An existing methodology in form of a quick assessment, where potential spare parts undergo a process where knock-out criteria are applied was presented by Dombrowski et al. [9]. Furthermore, Lindemann et al. designed a three-phase workshop-concept, where potential spare parts for AM are identified while passing an Information-, Assessment- and Decision-Phase [10]. Jung proposed a generic guideline, where 6 characteristics of a focused spare part are assessed and recommendations on AM for specific spare parts are carried out [11].

In order to address this deficiency, the introduced concept is meant to develop a novel model for quantifying occurring part specific costs in spare parts management. AM is considered for part allocation as a basis for the derivation of new, hybrid spare part strategies. Therefore, a generic model for internal process and structural costs as support for decision makers is presented. This model should function as a fundament for deployment of new business models in spare parts management in machinery and plant engineering. A review on cost modelling is given to provide the required essentials. In the main part of the paper, a conceptual two-stage model for classification and assessment of spare part allocation in machinery and plant engineering is presented. Accompanying benefits concerning sustainability aspects like reduction of downtime or environmental optimisations like reduced greenhouse gas emissions in transport respectively decrease of energy consumption for warehousing and handling are considered.
2. Literature review

2.1. Potentials and challenges of AM in spare parts management – a starting point for new spare part strategies

AM offers a variety of opportunities in spare parts management: For instance, Lindemann et al. [12] describe the vision of shaping new business models. Companies in machinery and plant engineering will have the possibility to transform to digital development service providers. Parts of the supply chain could transform to a virtual basis. This leads to a reduction of transport efforts with thousands of transport kilometers and complicated logistics processes and therefore indicates positive impacts on resource consumption and costs [13]. AM for spare parts with sporadic demands, where no more tools are available (e.g. injection moulding) offers a high potential for companies to broaden their strategic options [7]. Holmström et al. [14] differentiate between two approaches: Central AM to replace inventory holding as well as distributed AM for replacement of inventory holding and conventional physical distribution. Centralisation offers the possibility to produce suitable slow moving B- and C-parts using AM on demand and to reduce warehousing efforts. Decentralisation of spare parts production using AM leads to reduced transport costs and resource-efficient provision of spare parts. Concerning possible issues like risks of downtime, higher potential for customer satisfaction or robustness against supply chain disruptions, decentral AM generates different advantages [15]. Furthermore, packaging material and costs can be reduced significantly. For and Despeisse [16] identified sustainability benefits across various life cycle stages examined by means of different use cases. Thomas [17] remarks the missing of a comprehensive cost model taking into account production as well as supply chain effects. Dombrowski et al. [9] emphasise the considerable effects occurring after the EOP of a considered system with its challenges like obsolescence or storability. Moreover, they point out the benefits strategy combination has on building spare parts supply scenarios.

2.2. Part-specific classification in terms of AM and spare part logistics

Barkawi et al. [18] point out that a part-specific parameterisation for spare parts and a combination and parallelism of the possible allocation strategies is a proper way to allow a flexible and efficient spare part allocation.

For classical spare parts management, Hu et al. [19] did a comprehensive literature review where they identified 37 approaches with prevalent focus on criticality, annual cost usage, unit price and lead time as well as on the used method and developed an multiple criteria ABC classification. In the reviewed literature, more other criteria like ordering cost, substitutability or durability were discussed. However, not only these factors are relevant for the structuring of spare parts. Barkawi considers the following spare part characteristics with their different manifestations: Product life cycle phase, spare part value and criticality or consumption behavior.

Summarising we can say, the conventional classification of spare parts is a topic, where authors lay their focus on different approaches. Classification of AM-specific criteria is another important factor that needs to be applied. The suitability for AM depends on many different criteria. Gebhardt [20] for instance states material, assembly, need for additional manual work, tools and CAD-compatibility as characteristic attributes. The process focus concerning issues like the need for generating a 3D model and inherent steps are presented by Breuninger et al. [21]. The potential for very small batch sizes, the elimination of tooling (especially when no more tools are available), the possibility for design and function integration are further characteristics which have to be taken into account when evaluating the suitability of AM for spare part allocation [22].

2.3. Existing cost models in spare parts management considering AM

By now, the focus on quantifying AM processes in the context of spare parts management was mainly lying on the mere AM process and the pre- and post processing activities and related costs. Currently, there is no comprehensive cost evaluation for the entire spare part allocation process with regard to AM.

Table 1 gives a chronological overview on existing cost models for the AM of parts. Especially the more recent literature covers the pre- and post processing costs as well as the build costs as such. Especially Lindemann et al. propose a detailed and well structured event driven cost model with detailed process steps but also ending with quality control and not taking into account spare part allocation. As shown in the last column, none of the presented models
considers logistical aspects. This circumstance implicates that there is no integrated cost model, which takes the spare part allocation process combined with the AM process into account. Furthermore, only Lindemann et al., Rickenbacher et al. and Fera et al. also consider an activity based costing approach for the quantification of metal AM costs. Beyond that, no costs regarding spare part allocation are considered. The missing focus on these logistics aspects makes it difficult to assess the complete spare part allocation process with its process and structural costs. The present paper contributes to assess the arising manufacturing as well as logistics costs of different allocation strategies, namely final stockpiling, conventional manufacturing, AM on demand or purchasing of spare parts.

Table 1: Overview on existing cost models ant their characteristics

<table>
<thead>
<tr>
<th>Authors</th>
<th>Pre processing costs</th>
<th>Build cost</th>
<th>Post processing costs</th>
<th>AM technology</th>
<th>Annotations</th>
<th>Logistical aspects considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexander et al. 1998 [23]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Fused deposition modeling (FDM)</td>
<td>First generic cost model</td>
<td>No</td>
</tr>
<tr>
<td>Hopkinson/Dickens 2003 [24]</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Stereolithography (SL)</td>
<td>Structured in machine-, labour- and material costs</td>
<td>No</td>
</tr>
<tr>
<td>Ruffo et al. 2006 [25]</td>
<td>Partly</td>
<td>Yes</td>
<td>Partly</td>
<td>Laser sintering (LS)</td>
<td>Structured in direct and indirect costs</td>
<td>No</td>
</tr>
<tr>
<td>Gibson et al. 2010 [26]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>SL</td>
<td>Machine costs, material costs and labour costs</td>
<td>No</td>
</tr>
<tr>
<td>Atzeni/Salmi 2012 [27]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>LS</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Rickenbacher et al. 2013 [8]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Selective laser melting (SLM)</td>
<td>Activity based costing</td>
<td>No</td>
</tr>
<tr>
<td>Fera et al. 2017 [28]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>SL, LS, Electron Beam Melting</td>
<td>Activity based costing</td>
<td>No</td>
</tr>
<tr>
<td>Lindemann et al. 2017 [29]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Powder bed fusion</td>
<td>Activity based costing, Life Cycle costs</td>
<td>No</td>
</tr>
<tr>
<td>Baumers et al. 2017 [30]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>LS</td>
<td>Structured in direct and indirect costs</td>
<td>No</td>
</tr>
</tbody>
</table>

2.4. Need for research of AM in the field of spare parts management

Weller et al. [31] point out that there is need for further research in the field development for AM technologies as well as business models and underline the fact that economic implications of such research could be potentially more significant than mere AM itself. Gausemeier and Kage [32] highlight the potential for change and effects from AM on the value chain, overall economy and society. Furthermore, they urge for the creation of future-orientated decision-making and AM-orientated strategic planning. Holmström and Partanen [33] see practice-orientated trial and error as very important but also design-orientated research for developing new solutions to shift spare parts to AM. Achillas et al. [7] underline that AM technologies should be focused in terms of the derivation of hybrid scenarios in spare part allocation. Because of the constant evolvement of the AM technology, it is necessary to revise existing conclusions periodically. Furthermore, existing research lacks in terms of quantification of the implications of AM for spare part supply chains [34]. Schröder et al. [35] underline that a process-based approach for the quantification of costs as well as the accompanying recycling and waste of material and other parameters is vital.

3. Two stage model for quantifying costs of spare part allocation strategies using AM

3.1. Part classification and structuring

The target of the actual elaborated conceptual approach is structured in two major stages. First, the identification and classification of input criteria concerning spare parts is carried out by literature research accompanied by expert
interviews. Subsequently, a part specific morphologic structuring of the regarded criteria with focus on the different ways of class formation (e.g. “yes/no”-criteria, grouping based on absolute figures like storability in time span etc.) will be carried out [36].

A multi-criteria decision-making analysis is carried out, where the Analytical Network Process (ANP) is chosen. This method is preferred because the present type of decision problem cannot be structured hierarchically due to the interaction and dependence of higher-level elements and lower-level elements. Not only the importance of the criteria determines the importance of the alternative as in a hierarchy, also the importance of the alternative itself determines the importance of the criteria. Inner dependencies also exist [37].

Target of the first major stage »part classification« is the part-specific prioritisation of the installed spare parts in a focused plant concerning suitability for AM. Two major criteria, namely, “part specific attributes” respectively “spare part management related” are established. A comprehensive collection of sub criteria concerning the two main criteria with their interdependencies is carried out subsequently.

Part specific attributes lay their focus on the spare part itself and all technological aspects, which are relevant for the suitability for AM [38]. A predestined example is given: When a focused spare part has its geometries (length, width, height) bigger than the building chamber of the 3D printer, the suitability for this focused part for AM is not given. Even if all other criteria can be fulfilled, the dependence on this constraint would eliminate the part from the next stage (see Figure 1).

Based on the identified (sub) criteria, identified data sources of a focused plant like bill of material, dynamic data like parts usage or inventory levels over time, purchasing data like minimum order quantity, delivery time etc. are processed and structured as exemplarily shown in Figure 2 with the big data integration tool “Pentaho”.

Induced by execution of the first methodical stage, a preselection is carried out, where unsuitable parts are eliminated from a closer consideration in major stage two and parts with evaluated high potential can be prioritised.

Figure 1: ANP Network structure with goal, criteria (sub criteria) and alternatives (own research based on Saaty/Vargas)

Figure 2: Data translation and interpretation via Pentaho Data Integration (Kettle) (own research)

3.2. Cost modeling for different spare part allocation strategies

The second stage of the model deals with a cost assessment for possible spare part allocation strategies: final stockpiling, purchasing of spare parts, conventional manufacturing of spare parts and – with a special focus – AM of spare parts on demand. Therefore, an activity-based costing model will be implemented [39].

In section 2.3, currently existing cost models for the mere AM process were presented. Formula (1) exemplarily shows a suitable approach for quantifying the costs for preprocessing, AM and post processing [8]. In particular, costs for preparation, building the job assembly, setup costs, costs for the actual building of the part, costs for removing the part from the machine, costs for separating the part from the substrate plate and post processing costs.

\[
C_{tot}(P_i) = C_{prop}(P_i) + C_{buildup}(P_i) + C_{setup}(P_i) \\
+ C_{build}(P_i) + C_{remove}(P_i) + C_{substrate}(P_i) \\
+ C_{post}(P_i)
\]
In contrast to this rather specific view on manufacturing costs and the related pre and post processing, we introduce a model with focus on all considerable steps in spare part allocation process as well as the accompanying structural costs. Starting with the triggering of a particular spare part order by a customer over the internal process chain considering the different possible strategies till goods issue. That means, each eventual allocation strategy gets quantified with cost modules, where some modules have a bigger impact in one strategy than in another. For example, in final stockpiling, the module storage costs will be much more important than in manufacturing parts on demand. Purchasing of spare parts has potentially higher cost positions in disposition than other allocation strategies. By conducting such a modular assessment, it is possible to compare the specific parts of the internal process chain as well as the occurring structural costs. Figure 3 gives an overview on the considered components for cost evaluation. The main focus is on 4 modules: The actual spare part costs with the material and manufacturing costs etc. and the process costs for the different possible allocation strategies like disposition or stock management are the first two modules taken into account. Additionally, the occurring storage costs for used facilities and inventory costs for the different strategies in the “Conventional path” and “Additive path” are examined.

Furthermore, the implications on the three pillars of sustainability will be evaluated. That means in particular the inherent social, environmental and economic effects when comparing the different possible allocation strategies. Based on these outcomes, part specific decisions concerning the most suitable allocation strategy can be made, which build the basis for the deployment of a machine or plant specific spare part strategy.

**Figure 3:** Process model for cost quantification of different spare part allocation strategies – top-level illustration (own research)

### 4. Conclusions and outlook

The present work represents a conceptual two-stage model for a comprehensive cost evaluation of spare part manufacturing and allocation regarding different spare part strategies and the emerging technology AM. The framework should act as an extension of existing cost models for AM, such as the activity based approach from Lindemann et al., where no logistical aspects are considered.

As a support tool for decision makers in machinery and plant engineering, the activity-based costing approach confronts different strategy options, such as final stockpiling, purchasing of spare parts or AM on demand as a basis for a profound decision for a part specific spare part allocation and the derivation of an overall plant spare part strategy. The approach leads to a simplification of the decision making for executives in spare parts management due to a structured cost quantification with fine granularity.

In a further step, implications on the overall supply chain costs and their implications on sustainability should be investigated. Especially the reduction of transport efforts and the inherent reduction of emissions and cost reduction as well as the reduction of traffic volume should not be underestimated issues in the context of sustainability. Therefore, the steadily development of the technology readiness level of AM is an important circumstance, especially when talking about decentralisation of production of spare parts, where technological obstacles still have to be overcome. One major challenge in the realisation of the concept is the issue of lacking and inconsistent data quality...
in the manufacturing industry. Master data has to available in a suitable quality as well as specific information on particular parts like 3D-models or mechanical requirements on the specific examined part.

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6. References