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N. Knofius, M.C. van der Heijden, W.H.M. Zijm

University of Twente, Drienerlolaan 5, P.O. Box 217, 7522NB Enschede, The Netherlands

Abstract

Purpose – For more than ten years, the value of additive manufacturing (AM) for after-sales service logistics has been propagated. Today, however, only few applications are observed in practice. In this paper, possible reasons for this discrepancy are discussed and a method is developed to simplify the identification of economically valuable and technologically feasible business cases.

Design/methodology/approach – The approach is based on the Analytic Hierarchy Process (AHP) and relies on spare part information that is easily retrievable from the company databases. This has two advantages: first, the approach can be customized towards specific company characteristics, and second, a very large number of spare parts may be assessed simultaneously. A field study is discussed in order to demonstrate and validate the approach in practice. Furthermore, sensitivity analyses are performed to evaluate the robustness of the method.

Findings – Results provide evidence that the method allows a valid prioritization of a large spare part assortment. Also, sensitivity analyses clarify the robustness of the approach and illustrate the flexibility of applying the method in practice. More than 1000 positive business cases of AM for after-sales service logistics have been identified based on the method.

Originality/value – The developed method enables companies to rank spare parts according to their potential value when produced with AM. As a result, companies can evaluate the most promising spare parts first. This increases the effectiveness and efficiency of identifying business cases and thus may support the adoption of AM in after-sales service supply chains.

Keywords Rapid manufacturing, 3D printing, spare parts, after-sales supply chains

Paper type Research paper

1. Introduction

Additive Manufacturing (AM) is a computer-controlled production process, in which a complete item is built up layer by layer from basic materials. In contrast, subtractive manufacturing processes remove materials from a larger workpiece to obtain the item. While applications were usually related to prototyping, today applications are more diverse. In this paper, the focus lies on the application of AM in after-sales service supply chains which support the maintenance of advanced capital goods during their life cycle of, typically, several decades. This support consists of providing all resources needed for system upkeep, such as service engineers, tools, and spare parts. Spare parts management is usually demanding because of the combination of the large variety of parts, the presence of many expensive slow movers, a geographically dispersed installed base, and the often high costs of system downtime, leading to strict customer service levels. Examples of advanced capital goods can be found in manufacturing equipment for the high-tech industry, health care and communication systems, and defense equipment.

Despite the early recognition of the potential of AM for after-sales service supply chains, see e.g. Walter et al. (2004), only a limited amount of applications can be found in the real world. This is surprising, as many spare part characteristics for advanced capital goods appear to be tailor-made for AM technology: high demand variability, high production costs, long order lead-times, low demand rates, complex designs, high out-of-stock costs, and remote service locations, cf. Cohen et al. (2006).

In contrast, applications of AM which improve *part design* are increasingly put into practice: In the aerospace industry, substantial efforts are made to achieve *weight reductions* through AM. For instance, Deloitte (2014) reports a weight reduction of 67% for a part used in the Airbus A320 while fulfilling the same function as the conventionally manufactured part. Another application emerges in the production of molds where engineers exploit the *design freedom* of AM to integrate cooling channels which optimize the heat dispersion. This allows shorter production cycles and thus increases productivity (Leandri, 2015). Also, the functional integration of components into one piece part (monolithic design) is becoming more popular. Apart from eliminating assembly times, functional integration often improves part characteristics such as failure behavior or weight. For instance, GE Aviation (2015) reduced the part count of a fuel nozzle from 18 to 1, while the weight was decreased by 25% and the estimated life duration increased by a factor of 5. Most noticeable are the changes in the healthcare industry, where entire markets are transforming because *mass customization* enabled by AM supports an individual fitting of hearing aids, dental crowns, surgical implants etc.

These applications clarify the technological readiness of AM to produce functional parts. The question remains why AM is less commonly found in after-sales service logistics. In general, this cannot be explained due to a lack of benefits. As such, concepts like printing on demand and location may have a large effect on the total life cycle costs, as will be reviewed in Section 2.2. More realistic seems the explanation that logisticians are less aware of the capabilities of AM technology than design engineers. Conversely, design engineers may not be aware which logistical characteristics are important in order to improve after-sales service supply chains. This unfamiliarity on both sides may lead to an underestimation of the benefits of AM.

In this paper, a scoring method is developed to identify eligible spare parts for the application of AM technology. Based on the discussed observations, such support appears necessary to realize the potentials of AM technology for after-sales service logistics in practice. The method is designed to rank hundreds of thousands of spare parts according to their possible benefit when produced by AM. The output enables practitioners to prioritize and, therefore, to focus on the most promising parts first. As a result, this approach increases the effectiveness and efficiency of selecting promising business cases in after-sales service logistics. This finding is demonstrated by means of a field study conducted at a part supplier in the aviation industry. Next to obtaining more than 1000 positive business cases, a validity and robustness study provides evidence that the method offers a suitable approach to prioritize a large spare part assortment.

The paper is organized as follows: In Section 2, related literature is reviewed. Next, Section 3, describes the scoring method. In Section 4, the results of the field study are discussed, as well as the validation of the ranking method. In Section 5, sensitivity analyses are performed in order to evaluate the robustness and to demonstrate the flexibility of the approach. Finally, Section 6 states the conclusions to be drawn from this study.

2. Literature review

The literature review is divided into three parts. In Section 2.1, literature about advanced capital goods will be discussed to recap the specific characteristics of spare parts. In Section 2.2, these spare part characteristics will be contextualized with the debate about potential applications of AM technology in after-sales service logistics. Finally, Section 2.3 will review methods of identifying parts that benefit from the application of AM technology, and will expose their limitations when utilized in the spare part domain.

2.1. Spare parts for advanced capital goods

The lifecycles of advanced capital goods, e.g. manufacturing equipment for high-tech industries as well as health care and defense systems, often last decades. To remain operational during this period, a well thought maintenance and logistic support strategy is essential. This necessity is clarified by Öner et al. (2007) who reveal that more than 60% of the total lifecycle costs of capital goods may relate to the spare parts management. Downtime costs are the main contributor; they can potentially exceed tens of thousands of Euros per hour (Kranenburg, 2006). Additional complexity is added through the high variety of spare parts which are required to maintain capital goods. Hundreds or even thousands of spare parts being used in a single system is not uncommon (Van Jaarsveld, 2013). In combination with low demand rates and uncertain failure behavior, this situation typically yields high inventory costs. Furthermore, fast transportation modes and decentral stocking locations are required to keep response times for the globally dispersed installed base short. As a consequence, stock pooling effects are limited and high expenses for transportation arise. Moreover, low demand rates may result in a weak position compared to spare part suppliers, especially if the sourcing options are limited. This situation often causes long resupply lead times and high procurement costs (Roda et al., 2014). Additionally, supply disruptions become more likely because the spare part supplier may decide that the low-volume business is no longer economical. As a response, the asset owner (or service provider) typically has to invest in additional spare part inventories to fulfill the demand during the remaining usage period of the capital good. Due to high uncertainties, this frequently leads to substantial costs (in the millions) as also noted by Behfard et al. (2015).

This challenging environment stimulated academia to propose models to optimize the spare parts management and thus support decisions regarding how many spare parts to stock at which location in the supply chain, see e.g. Sherbrooke (2004), Muckstadt (2005) and Van Houtum and Kranenburg (2015). Moreover, it is observable that asset owners increasingly outsource maintenance activities to service providers or OEMs with strict service level requirements (Oliva & Kallenberg, 2003). One may interpret this trend as an acknowledgement of the high effort required to efficiently organizing the maintenance of capital goods. Finally, a new manufacturing technology – namely AM – may give rise to novel solutions in the spare parts management (Bennett, 2012). These opportunities are reviewed in the next subsection.

2.2. Potential of additive manufacturing for spare parts management

AM offers several opportunities for improvement in spare parts management. The most apparent potential is the *reduction of manufacturing costs*. For example, Gibson et al. (2010) report that it is likely for low-volume parts that the production costs can be reduced because of lower setup and tooling costs. Additionally, *direct part usage costs* can be decreased when AM is utilized. For instance, consider a worn out spare part which can be repaired with AM. This may increase the usage period considerably and thus may offer substantial cost savings. In particular, this appears to be valuable if the broken spare part has a relatively long resupply lead time and/or is expensive. The potential is illustrated by means of a burner tip used in gas turbines: Siemens (2015) was able to reduce the repair lead time by 90% and the associated repair cost by 30%. Another scenario for the reduction of usage costs may be an increased reliability of the part. As such, replacement intervals increase and therefore may reduce the total lifecycle costs.

In addition, Walter et al. (2004) describe how AM may *increase the responsiveness of a supply chain*. For example, they elaborate how safety stock costs can be avoided while response times are kept short by printing on demand. Additionally, the obsolescence risk of stored spare parts decreases because of order driven production. In the same publication, Walter et al. discuss the concept of printing on location. It is argued that this practice offers benefits if demand occurs at remote locations or if customer response times have to be short. So far, this could only be achieved by (emergency-)shipments or by holding inventory close to the installed base as discussed in Section 2.1. Next to Walter et al. other authors discuss the potential to increase the responsiveness of a supply chain with AM. Articles referring to this aspect include: Holmström et al. (2010), Liu et al. (2013), Khajavi et al. (2014), Sirichakwal and Conner (2016) and Thomas (2016).

Another application arises if spare part *supply is discontinued.* As elaborated in Section 2.1, this event typically causes high costs and is more likely for low-volume parts. With AM technology, it may be possible to reestablish the supply continuity in a relatively cheap way as mentioned by Sasson and Johnson (2016).

Also, it is conceivable to create a *temporary fix* with AM if a replaceable is unavailable in the short run. That is, the printed part would bridge the period until the intended replaceable becomes available. This application of AM represents an alternative to keeping expensive safety inventories or risking long downtimes. Note that a temporary fix might still be valuable, even if it yields lower performance rates. Today, first consideration for this type of applications can be found in the military, which often uses highly advanced equipment at remote locations (McLearen, 2015). In the next subsection, methods which support the identification of parts for the application of AM technology are discussed.

2.3. Identifying promising parts for additive manufacturing

Typically, a bottom-up approach is employed for the identification of promising parts for AM. That is, a practitioner realizes that AM technology might improve characteristics of a specific part. This encourages an assessment of the benefits and technological feasibility to print the part. In the literature, several methods are proposed to support such a bottom-up approach.

One example is the two-stage method suggested by Simkin and Wang (2014): In the first phase, it is examined whether the part suggested by the practitioner falls in at least one category of a defined list of potential benefits of AM technology. Examples from this list are *improved functionality*, *lower sourcing costs*, and *lower import/export costs*. If this is not the case, it is argued that it is almost certain that it is not worthwhile to print the suggested part. In the second phase, it is examined which AM production methods can be used to manufacture the part. Unfortunately, the details of this assessment are not specified. Afterwards, cost-benefit analyses are performed with Monte Carlo simulation. For instance, Simkin and Wang compare the total lifecycle costs of AM production methods with the costs of a conventional manufacturing process. Also, the impact of in-house manufacturing and outsourcing is compared. Again, it is not stated explicitly which factors are included in the lifecycle costs, and how they are calculated.

Another method is proposed by Lindemann et al. (2015). They structure the entire bottom-up procedure with a workshop concept: During a first workshop, company representatives are informed about the advantages and limitations of AM technology. The purpose of this step is to qualify and inspire company representatives to independently identify parts for further analysis. During a second workshop, the resulting part candidates are evaluated by AM experts and the company representatives. To this end, Lindemann et al. have developed a scoring method which assesses different part characteristics - primarily concerning technological constraints of AM such as part size and materials. Afterwards, economic aspects and possibilities for redesign of the best scoring parts are considered in more detail. This requires additional data collection and evaluation. The assessment is carried out by AM experts, though the details are not specified.

For the spare part environment, however, the described bottom-up procedures may entail disadvantages: First, they rely on the expertise of practitioners, which might be limited in after-sales service logistics and thus may lead to unsatisfactory results. Second, the evaluation only takes a limited number of parts into account, as practitioners can consider only a relatively small part of the overall assortment. As a consequence, it is likely that promising parts are overlooked. In particular, this applies if the business case appears less intuitive. For example, consider a case where it is likely that the manufacturing costs increase, but the resupply lead time decreases. At first, such a case might be ignored. If the entire lifecycle costs are considered however, the positive effects of a shorter lead time may outweigh the negative effects of higher costs (Van der Heijden et al., 2013). That is, the lower requirement for safety stocks may decrease holding costs and obsolescence risks to such an extent that the higher manufacturing costs are more than compensated.

This type of problems can be avoided by using a top-down approach that can be initiated with a large part population. For instance, it is possible to prioritize the analysis based upon potential economic benefit. This mitigates the risk of disregarding promising parts and additionally increases the efficiency. Furthermore, dependency on the expertise of practitioners can be decreased and thus the chance of underestimating logistical improvements is reduced. However, no reports on a top-down approach were found in the literature.

The key contribution of this paper to the existing literature is to develop and validate a top-down approach to identify promising spare parts from a large assortment using information that is typically available in standard information systems. With this method, promising parts can be identified that may have been overlooked otherwise.

Note that the reference for the value to print a spare part is its current functionality. New functionalities that may be added using AM, are not considered in the analysis, as this corrupts the efficiency of the top-down approach. That is, each part would have to be analyzed extensively, which is often time consuming. Instead, the opportunity to add new functionalities should be addressed separately. For example, it may be worthwhile to combine the top-down method with a procedure as proposed by Lindemann et al. (2015). Specifically, the output of the top-down procedure could be used as input for the second workshop. This has the advantage that a large part population is considered, while the attention of company representatives and AM experts is directed to the most promising parts.

3. Ranking method

The objective of the top-down approach is to obtain a ranking which specifies the potential of AM for a spare part relative to the other analysed spare parts from the perspective of supply chain management. In this section, an overview of the method is presented. Afterwards, the details will be elaborated in separate subsections.

At first, the spare part assortment for the analysis is selected. As will be clarified in Section 3.1, it is not recommended to always take the entire spare part population into account. Next, the resulting spare parts are scored based on values of *spare part attributes*, which can be retrieved from the company databases. Table 1 gives an overview of relevant spare part attributes. These are linked to the potential of AM for spare parts management as described in Section 2.2. For this purpose, Table 1, shows which value level of a spare part attribute may indicate an improvement potential with AM. The underlying logic of the assignment is explained in Appendix 1.

Tab. 1. Value range of spare part attributes that indicate improvement potential with AM technology

		Improvement potential						
		Reduce manufacturing/ order costs	Reduce direct part usage costs	Reduce safety stock costs	Improve supply chain responsiveness	Postponement	Temporary fix	Reduce effect of supply disruptions
Spare part attributes	Demand rate	Low		Low		Low		
	Resupply lead time			Long	Long	Long	Long	
	Agreed response time			Short	Short		Short	
	Remaining usage period		Long					
	Manufacturing/ order costs	High						
	Safety stock costs			High		High		
	Number of supply options	Few			Few			Few
	Supply risk				High			High

Read: If spare part attribute 'x' belongs to value level 'y' then this indicates improvement potential 'z'.

Furthermore, an assessment is made in the method whether the spare part complies with technological constraints that are enforced by the current advancement of AM technology. These constraints are referred to as *Go/No-Go attributes.* For the ranking method, the rather basic attributes *material type* and *part size* are used. Other constraints, for example associated with the geometric shape and tolerances for manufacturing, are usually more difficult to assess based solely on information that is easily obtainable from databases. In addition, such requirements may not be adequately represented by the conventionally manufactured part. For instance, it may be that the conventional manufacturing process may yield over-dimensioned technical solutions.

The suggested Go/No-Go and spare part attributes have to be understood as an orientation, because company-specific data availability may require adaptations: It is possible that not all aspects can be considered or that only secondary data is available. For example, in the field study of Section 4, it was difficult to obtain data about the part size. Instead, the part identification number was used, which gave a good approximation for the part size in this company. Moreover, company-specific attributes may be available. For instance, in one company where this method was applied a keyword indicated whether the company held the design rights for a spare part. This company-specific attribute was taken into account by assuming that holding the design rights is an indicator of lower setup costs for an AM process and therefore reduces the manufacturing costs.

Next to considering Go/No-Go and spare part attributes, also *company goals* are taken into account. This is motivated by different objectives of companies which may influence the preference to print specific spare parts. As such, some companies may focus on cost reductions, while others may prefer to improve their service despite higher costs. In the method, these insights are used to derive a *weight* for each spare part attribute, where weight describes the influence a spare part attribute can have on the overall score of a spare part. Section 3.2, will explain how these weights are derived from company goals.

Finally, based on the attribute weights and values, weighted average scores are computed for each spare part, and the analysed spare part assortment is ranked accordingly. The ranking reveals which spare parts are more promising than others for the specific company. The scoring procedure will be discussed in Section 3.3.

3.1. Determining the spare part assortment

In order to allow the ranking of a large spare part assortment, the retrieval of data is limited to database queries or in-house analysis tools. Furthermore, to facilitate a proper comparison, one needs to have information on an attribute for a large portion of the analyzed spare parts. To achieve this may appear challenging if spare parts of different types of assets are considered. This holds even more if the company is operating in different supply chains. For example, an asset user or service provider may have more information about operational data than an OEM. As a consequence, in some companies only a subset of the entire spare part population may be selected. Also, separate analyses may become necessary if the data quality and availability varies over subpopulations. These decisions constitute the first step of the ranking method, and should be taken in close collaboration with company representatives.

The output of this step is an overview of the selected spare part assortment, the Go/No-Go attributes, the spare part attributes and the associated values. An example can be seen in Table 2. Note that only a subset of the relevant spare part attributes (cf. Table 1) is shown for illustrative purposes. This subset is used in the graphics throughout the remainder of this paper.

Tab.2. Result first phase

Part ID	**1**	**2**	**3**	**…**
Material type (***E***lectronic, ***M***etal, ***P***lastic)	E	P	M	…
Part size (dm³)	1	3	4	…
Supply risk (%)	21	50	35	…
Remaining usage period (month)	21	56	12	…
Supply options (***#***)	1	14	3	…
Manufacturing/ order costs (10.000 Euro)	5	15	1	…
⋮	⋮	⋮	⋮	⋮

3.2. Obtaining the weight for the spare part attributes

In this section, the company-specific attribute weights are derived from the company goals. To define suitable company goals, the classification scheme of Chopra and Meindl (2016) is used. They differentiate between responsive and efficient supply chains: one focusing on increasing flexibility and one focusing on reducing costs. To allow for more precision, this is further distinguished into operational flexibility and strategic flexibility. While operational flexibility refers to the ability to match supply and demand, strategic flexibility here means the ability to handle potential supply disruptions in the future. Using a more practical terminology, this results in three company goals: *secure supply, reduce downtime and reduce costs*.

To evaluate the company-specific importance of each company goal, a pairwise comparison approach following the logic of the *analytic hierarchy process* (AHP) is used. In the first stage, decision makers of the company give a score for each pair of company goals that indicates which company goal has a higher priority. These scores allow for an approximation of an importance measure of each company goal relative to the other company goals. Due to the pairwise comparison, inconsistency becomes controllable and decision complexity is prevented. For a review of the AHP method, see Saaty (2008).

Afterwards, the spare part attributes are assigned to the company goals. Given that the spare part attributes have already been allocated to improvement potentials (cf. Table 1), the relation between spare part attributes and company goals is established by assessing improvement potentials to company goals. This results in the allocation shown in Table 3. The motivation for this allocation is given in Appendix 2. Note that Go/No-Go attributes are not assigned to any company goal. They describe the technological feasibility of printing the spare part and are therefore independent of the company.

Tab. 3. Spare part attributes assigned to company goals

		Company goals		
		Secure supply	Reduce downtime	Reduce costs
Spare part attributes	Demand rate		X	X
	Resupply lead time		X	X
	Agreed response time		X	X
	Remaining usage period			X
	Manufacturing/ order costs			X
	Safety stock costs		X	X
	Number of supply options	X	X	X
	Supply risk	X	X	

In the second stage of the AHP method, pairwise-comparisons between the assigned spare part attributes for each company goal are performed. Accordingly, practitioners were asked the following type of question: *"If we improve both attribute values for the entire spare part assortment, which attribute does support the achievement of the company goal X better?"* This results in importance measures of the attributes.

Finally, to obtain the spare part attribute weights, importance measures of the attributes are multiplied by the importance measures of the associated company goal. Figure 1 provides an example of a typical result. Note that in case an attribute is allocated to more than one company goal, the weight equals the sum of all partial weights (cf. Figure 1: For example, the attribute *supply risk* obtains a weight of 0.22 + 0.105 = 0.325).

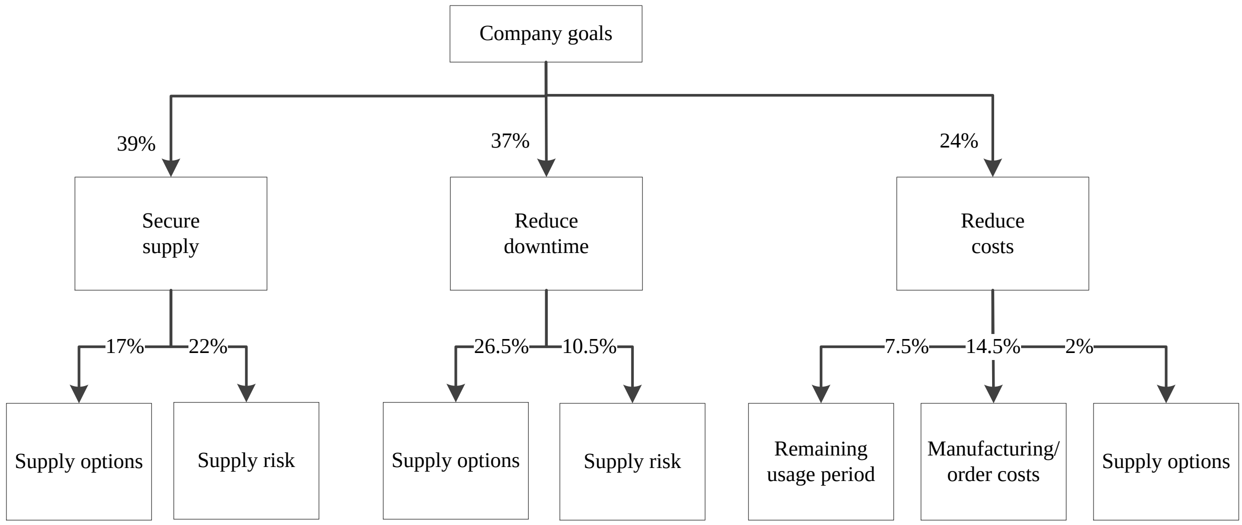

Fig. 1. Example attribute weighting

It has to be stressed that the resulting weights have to be understood as estimates. Even though the AHP method represents a well-established scientific approach, subjectivity in decision-making may lead to inaccuracies. In Section 6.1, sensitivity analyses will be used to quantify the consequences of these inaccuracies for the ranking.

3.3. Calculate the overall score of a spare part

After the spare part attribute weights have been computed, scores for each attribute value are calculated. For Go/No-Go attributes, a binary scoring is applied, i.e., if the attribute value is located in the technologically feasible range, it is assigned a “1”, otherwise a “0”. A good estimation of the feasible range can be obtained through technical data sheets of recent AM machine releases.

For other spare part attributes, a linear scoring approach is used. That is, the value range of all spare parts is normalized: the best value receives a score of “1”, and the worst value a score of “0”. Values in-between receive a proportional score. Alternatively, one may use the 95% percentiles instead of the extreme values to protect against data pollution. In this case, all values exceeding the 95% percentiles obtain the score of the corresponding extreme value.

Afterwards, the weighted score for each spare part attribute is calculated by multiplying the score with the attribute weight. In a final step, the following procedure is applied in order to obtain the overall score for a spare part:

1) Multiply the scores of the Go/No-Go attributes.
2) Sum the scores of the spare part attributes.
3) Multiply the results of 1) and 2). Note that already one “No-Go” results in a score of “0”.

The final score for a spare part can range from “0” to “1”, where “1” represents the highest possible score. An example for one spare part can be seen in Table 4.

Tab. 4. Example final data of a spare part

Attribute	**Value**	**Weight**	**Score**	**Weighted score**
Material type	Metal	-	1	1
Part size	0.5	-	1	1
Supply risk	20	32.5%	0.21	0.06825
Remaining usage period	15	7.5%	0.31	0.02325
Supply options	5	45.5%	0.48	0.2184
Manufacturing/order costs	48	14.5%	0.24	0.0348
			Overall score	**0.3447**

Next to linear scoring of spare part attributes, other scoring methods might be employed. For example, consider a five or two point scale where the scale thresholds are determined by the value distribution of all spare parts. That is, for a two point scale, the worst 50% receives a score of “0”, and the other 50% a score of “1”. It needs to be guaranteed, however, that the scoring approach provides a sufficient differentiation between the analyzed spare parts. To clarify, it would be undesirable if nearly all spare parts obtain the same score, as this would prohibit sufficient prioritization. Section 5.2, will provide an overview of the resulting differentiation for several scoring methods and study the impact on the final ranking.

4. Field study

The ranking method outlined above was tested during a field study at a part supplier in the aviation industry, with more than 400.000 spare parts. Section 4.1, will elaborate on the application of the approach and highlight the key findings. In Section 4.2, the prioritization mechanism of the model is validated. For this purpose, a stratified sample of parts was selected from the ranking, and compared to the opinion of the implementation manager for AM technology at the company.

4.1. Application and findings

After an evaluation of data availability and data cleaning, it was decided together with company representatives to base the analysis on 40.330 spare parts. The analysis was initiated with the eight spare part attributes as specified in Table 1 and the two Go/No-Go attributes. As no suitable data source for the a*greed response time* was available, however, this attribute had to be dropped. Furthermore, the *part number* was used as a substitute for *part size*. This replacement was chosen because direct information about the part size was often not accessible. Fortunately, the company-specific numbering system relates part size to the part number and thus is a good proxy.

In addition, the attribute *airplane type* was used instead of *number of supply options*. It was found that for spare parts which are exclusively used in specific airplane types, demand can be fulfilled by dismantling phased-out airplanes. Other information about the number of supply options was not easily retrievable.

Finally, the attribute *supply risk* was substituted by the attribute *survival probability*, where the survival probability defines the chance that a spare part supplier will be available within one year. This measure was available in this company for most of the analyzed spare parts and was once calculated based on the model by Li et al. (2016). Table 5 gives an overview of all attributes associated with the weights derived from the AHP method.

Tab. 5. Spare part attributes used in first case study

Attribute	Weight	Explanation
Part number	-	The part number gives insights about spare part size
Material type	-	Indicates the material type e.g. electronic, composite or metal
Safety stock costs	18%	High safety stock may be reduced with AM
Manufacturing/order costs	17%	High sourcing costs may be reduced with AM technology
Demand rate	16%	For low volume production AM may reduce order costs
Survival probability	13%	Spare parts with high supply risk could be obtained with AM
Remaining usage period	13%	An early lifecycle phase may indicate high saving potentials of operational costs
Resupply lead time	13%	AM may reduce long resupply lead time and thus decrease safety stocks
Airplane type	10%	Specific airplanes obtain less spare parts from dismantling

Due to the Go/No-Go attributes, 34.140 of the analyzed spare parts were classified as not feasible to print from a technological perspective (in the near future). The remaining 6.190 spare parts were ranked, which resulted in a score distribution as shown in Figure 2 (left).

Based on the ranking, the case company could already identify 1.141 technologically feasible and economically beneficial business cases. A typical example is a fitting stud used for the attachment of a safety belt as illustrated in Figure 2 (right). For this case, it is estimated that it will be possible to reduce the resupply lead time by about 40% and the order costs by about 70% with AM. The prospect of this improvement potential stimulated a reengineering project for the fitting stud despite high costs for certification. This outcome demonstrates the benefit of the developed top-down approach: Practitioners probably would have disregarded the fitting stud due to the high certification costs. In comparison, the ranking method typically exposes promising characteristics for high scoring items and thus justifies an assessment of the part in more detail.

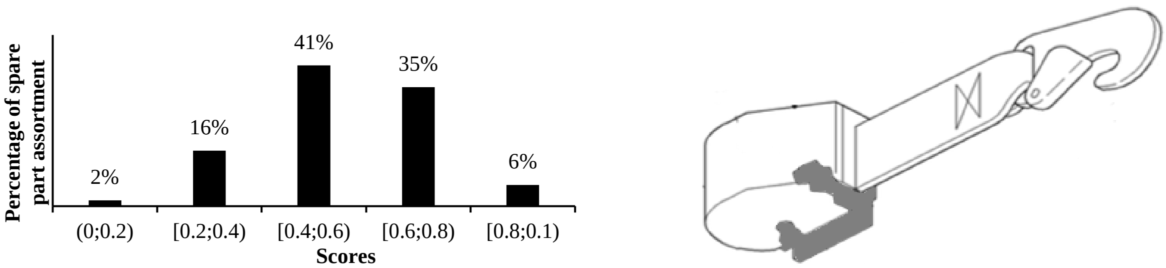

Fig. 2. Score distribution first field study and safety belt with fitting stud (gray)

4.2. Validation

The obtained ranking was compared with the opinion of the implementation manager for AM technology at the company in order to validate the prioritization mechanism. For this purpose, a stratified sample of 18 spare parts was selected from the ranking. The sample is divided in three subgroups: parts with scores larger than 0.8 (1), parts with scores between 0.4 and 0.6 (2) and parts between 0.01 and 0.4 (3), respectively. Note that a score of 0 indicates that the spare part is not printable. Therefore these cases are not considered in this analysis. Next, without knowledge about the rank, the AM manager was asked to assign a priority to each of the 18 spare parts – namely, most interesting (1), maybe interesting (2) and least interesting (3) for AM. The results are shown in Table 6.

Tab. 6. Categorization of selected spare parts by company representatives

Spare part number	Rank method	AM manager	Spare part number	Rank method	AM manager
1	2	3	10	2	2
2	2	3	11	1	2
3	2	2	12	3	3
4	3	3	13	1	1
5	1	3	14	1	2
6	1	1	15	2	3
7	1	2	16	2	3
8	2	3	17	3	3
9	3	3	18	1	2

As observable from Table 6, the judgement of the AM manager appears more critical than the ranking method, i.e. the AM manager assigned each of the 18 spare parts in the same or a lower priority class than the method. This finding appears reasonable because part specific information that is difficult to include in a generic top-down approach may be available to a company representative.

Spare part number 5 exemplifies this situation. In the scoring method, spare part number 5 obtained the second best score of all 6.190 items, yet the AM manager assigned it to the least interesting category. In this case, he took into account that the supply of the spare part is about to be discontinued, but a cheap offer for a final order is available because the supplier of this spare part wants to sell the remaining inventory of this item. As a result, it does not appear interesting for the company to invest in an AM manufactured substitute, because the remaining demand can be covered economically.

Another example is spare part number 18. In the scoring method, it received a score of 0.89. The AM manager, however, only judged the part to be "maybe interesting". He argues that the spare part has a demand rate of less than one part per year. Thus, the spare part would not be suitable for an "engaging" proof of concept to higher management. Instead, he prefers a part with a higher demand rate in order to demonstrate the benefits of AM on a more regular basis. From a political point of view this argument is reasonable, though it is rather questionable from an economical point of view. By adapting the scoring method, however, this political aspect could be taken into account. For instance, one may truncate the linear score for the demand rate and assign a score of "0" if the demand rate is below a certain threshold.

Both examples demonstrate that specific information or personal preferences have to be taken into account in order to identify the right spare parts for the problem owner. Nevertheless, based on the stratified sample of 18 spare parts, no evidence was found that a structurally retrievable spare part attribute was omitted, nor that the scoring method has to be adapted. This conclusion is supported by the significant correlation between ranking method and company judgment of several aspects: All 4 items belonging to the worst scoring group in the model were assigned to the least interesting category by the AM manager as well. Furthermore, those items that were indicated as most interesting by the AM manager were scored highest by the model as well.

These findings lead to the conclusion that the ranking model appears to offer a valid prioritization mechanism and thus makes an evaluation of a large spare part assortment more effective and efficient.

5. Sensitivity analyses

As explained in Section 3.2, estimating the attribute weights may incur inaccuracies because of the subjectivity of decision-making. In Section 5.1, sensitivity analyses will be carried out to assess the consequences for the ranking. In Section 5.2, different scoring methods will be assessed with regard to their applicability. Also, the impact on the ranking will be evaluated.

5.1. Consequences of inaccurate weights

Inaccuracies are less worrisome if the ranking is rather insensitive to spare part attribute weight changes. Hence, the robustness of the ranking towards weight changes is assessed in this section. The following analysis is based on data from the field study carried out in the aerospace industry (cf. Section 4).

To evaluate the robustness, sensitivity analyses are performed on the spare part attribute weights where the change in the ranking is measured. This is achieved by computing the correlation between the actual ranking of the field study and the new ranking obtained by varying one weight. Note that varying one weight leads to change in all other weights because the relative importance of all weights changes. To measure the correlation, Spearman's rho is applied (Kornbrot, 2005). As a matter of course, Spearman’s rho is equal to 1 for the weights used in the field study. Furthermore, a correlation of more than 0.5 is referred to as significant (ibid.). The results are illustrated in Figure 4.

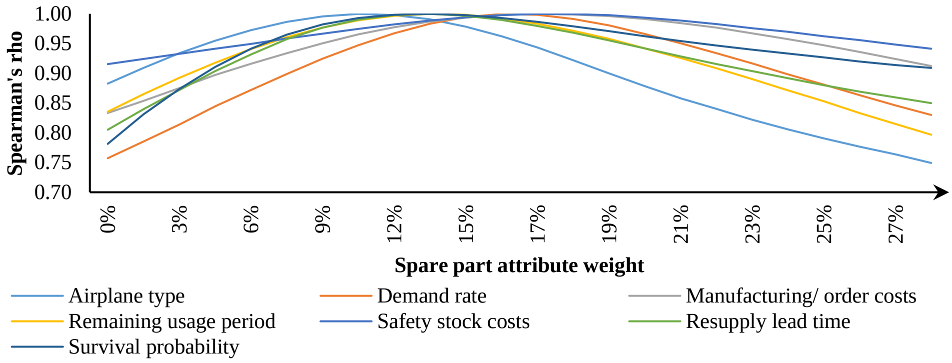

Fig. 4. Sensitivity of attribute weights

As can be seen, the correlation between the rankings remains significant even if a spare part attribute weight is changed by more than 15%. Comparable behavior can be observed if the analysis is limited to the 10% top scoring spare parts. It can be concluded that the ranking appears robust against inaccuracies resulting from the AHP method.

5.2. Consequences of different scoring methods

In Section 3.2, a linear scoring approach was proposed to evaluate the spare part attribute values. This has the advantage that most of the available information is considered, and therefore high differentiation among the spare parts can be achieved. In a practical setting however, it may appear useful to deviate from the linear scoring approach. Generally, this does not cause problems, as long as sufficient differentiation among the scores can be guaranteed. To clarify, if nearly all spare parts obtain the same score, the ranking is less useful.

Subsequently, it will be demonstrated that this requirement can be fulfilled with several scoring procedures. Also, it will be shown that the effect on the ranking is acceptable and does not yield considerable deviations. For both analyses, data from the field study carried out in the aerospace industry are used (cf. Section 4).

Of course, it is impossible to conceive all possible scoring methods. Subsequently, the analyses will be limited to the comparison of linear scoring to scoring with a two point and a five point scale (cf. explanations in Section 3.2). Other scoring methods however, may be analyzed in the same manner.

First, the degree of differentiation of the overall scores is assessed by determining the number of unique scores for the 6.190 spare parts considered in the aerospace field study. As shown in Table 7, the two point scale approach yields the lowest differentiation with 143 unique scores. Even though this is substantially less than what can be achieved using the linear scoring approach (5753), this degree of differentiation should be sufficient to prioritize further analyses for most applications.

Second, the effect of different scoring procedures on the ranking is evaluated. Using the same approach as in Section 5.1, Spearman’s rho was computed between all three rankings using the linear scoring approach as a benchmark. Thus, the Spearman’s rho is equal to 1 for this procedure. As can be found in Table 7, all three scoring methods are significantly correlated. This indicates that it is acceptable to deviate from the proposed linear scoring approach and thus gives additional flexibility for the application in practice.

Tab. 7. Unique scores depending on approach and ranking correlation

Scoring type	Unique scores	Unique scores [%]	Spearman's rho
Two point scale	143	5%	0.75
Five point scale	628	10%	0.81
Linear scoring	5753	94%	1

6. Conclusion

In this paper, a method was developed to increase the transparency in the decision-making process of which spare parts may benefit from AM. An argument was made that such a method is required, as available concepts may underestimate the potential of AM, in particular for after-sales service supply chains.

A field study demonstrates the value of this method, as it facilitated the identification of more than 1000 technologically feasible and economically beneficial business cases. Simultaneously, this result shows the practical benefit of AM for after-sales service supply chains. A validation study gives evidence that the prioritization mechanism underlying the method is in accordance with practical opinion. Accordingly, the method appears suitable to the task of prioritizing a large spare part assortment and thus makes the selection of spare parts more effective and efficient. The method was further shown to be robust against possible inaccuracies of spare part attribute weights that may result from subjectivity of decision-making. Moreover, different scoring procedures were studied and found to be eligible for the ranking method, thus providing flexibility in terms of practical application. In conclusion, companies may be encouraged to use this approach in order to simplify the identification of promising spare parts for AM.

For future research efforts, it might be worthwhile to extend the proposed method by considering possible design improvements. For example, one might try to identify indicators that relate to the probability with which an assembled spare part can be printed as a single part and use these indicators as additional spare part attributes in the method.

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Appendix 1: Relation of spare part attributes to improvement potentials

A *low demand rate* often indicates high demand variability. This may lead to inefficiencies in the manufacturing process due to high tooling and setup costs (and thus incurring higher purchasing costs in case a supplier manufactures the spare part). Additionally, high demand variability results in relatively high safety stock costs to fulfil service level agreements. This may be reduced by decreasing the resupply lead time with AM. Furthermore, countermeasures against high uncertainties like emergency shipments or supplier dedicated stock can be replaced, for example by printing on demand and therefore postponing the production decision. Note that the demand rate was chosen instead of the demand variability, because data about demand variability is typically difficult to obtain – particularly for slow moving items.

A *long resupply lead time* may result in high safety stock costs or high system downtime, because the variability of the lead time demand is usually high. By reducing the resupply lead time with AM, one may therefore reduce the safety stock costs or downtime. Simultaneously, countermeasures against high safety stocks or long downtimes like emergency shipments or supplier dedicated stock can be avoided because of an increased responsiveness. In a best case scenario, it is possible to print on demand and therefore transform the supply chain from a make-to-stock to a make-to-order setup. Finally, long resupply lead times may offer potential to use a temporary fix in order to reduce the safety stocks or downtime.

If the *agreed response time is short*, safety stocks are often located close to the customer site. This reduces pooling effects and therefore may lead to relatively high safety stock costs. AM technology may enable production on location or shorter resupply lead times, and thus decrease safety stock costs. Furthermore, printing on location or obtaining the spare part within a shorter resupply lead time yields a higher responsiveness of the supply chain. Accordingly, concepts like emergency shipments and supplier dedicated stock may become obsolete or may be replaced by a more efficient temporary fix.

If the *remaining usage period* of a spare part is *long*, the recurring direct usage costs of the spare part may be reduced more often and thus this situation offers the highest potential. For example, repair costs and assembly costs may be lower with an AM manufactured part.

If the *manufacturing/order costs* are *high*, AM technology may offer a cheaper way to produce a spare part that can fulfil the same function.

If the *current safety stock costs* are *high*, AM technology may reduce the resupply lead time and thus lead to lower safety stock costs. Also, service efforts like emergency shipments and supplier dedicated stock may be avoided. For example, it may be possible to print on demand (i.e. postpone the production decision) and therefore avoid safety stock costs.

If there are only a *few supply options* for a spare part, AM may offer a chance to reduce order costs because an additional supply option improves the negotiation position. Furthermore, AM might increase the flexibility, for example by employing a Dual Sourcing concept. Finally, the additional option to print the spare part may become important if the regular supply is discontinued.

If the *supply risk* is *high*, i.e. suppliers may permanently discontinue the production of the spare part soon, AM may be useful to obtain a more reliable supply source. Furthermore, a high supply risk implies less flexibility to deal with demand and supply variations. AM could increase this flexibility.

Appendix 2: Assignment spare part attributes to company goals

In order to obtain an importance measure, i.e. weight, for each spare part attribute, each spare part attribute needs to be assigned to a company goal. Given that the spare part attributes have already been allocated to improvement potentials (cf. Table 1), the relation between spare part attributes and company goals can be established by assessing which improvement potential is associated with which company goal.

The improvement potentials *reduce manufacturing/order costs, reduce direct part usage costs* and *reduce safety stock costs* describe the chance to improve the efficiency with AM. This aligns with the company goal to reduce costs. The remaining improvement potentials describe the ability to increase the flexibility with which a certain service function can be fulfilled. This affects both the company goal *reduce downtime* and the company goal to *secure supply*. As is explained in Section 3.2, however, the company goal *secure supply* is associated with the ability to handle potential supply disruptions in the future. This is represented by the improvement potential *reduce effect of supply disruptions*. The other improvement potentials describe the operational flexibility, i.e. the ability to match supply and demand. The assignment is visualized in Table A1.

Tab. A1. Spare part attributes assigned to company goals

		Improvement potential						
		Reduce manufacturing/ order costs	Reduce direct part usage costs	Reduce safety stock costs	Improve supply chain responsiveness	Postponement	Temporary fix	Reduce effect of supply disruptions
Spare part attributes	Demand rate	Low		Low		Low		
	Resupply lead time			Long	Long	Long	Long	
	Agreed response time			Short	Short		Short	
	Remaining usage period		Long					
	Manufacturing/ order costs	High						
	Safety stock costs			High		High		
	Number of supply options	Few			Few			Few
	Supply risk				High			High

= Reduce costs = Reduce downtime = Secure supply

After assigning the improvement potentials to company goals, the relation between spare part attributes and company goals can be established. That is, each spare part attribute which is assigned to a particular improvement potential is assigned to the respective company goal. This results in Table 3.

Nr.	Year	Title	Author(s)
515	2016	Selecting parts for additive manufacturing in service logistics	N. Knofius, M.C. van der Heijden, W.H.M. Zijm
514	2016	Solving Routing Problems by Exploiting the Dual of a master LP Formulation	M. Firat, N.P. Dellaert, W.P.M. Nuijten
513	2016	Single-Item Models with Minimal Repair for Multi-Item Maintenance Optimization	J.J. Arts, R.J.I. Basten
512	2016	Using Imperfect Advance Demand Information in Lost-Sales Inventory Systems	E.Topan, T. Tan, G.J.J.A.N. Van Houtum, R.Dekker
511	2016	Integrated Resource Planning in Maintenance Logistics with Spare Parts Emergency Shipment and Service Engineers Backlogging	S. Rahimi Ghahroodi, A. Al Hanbali, W.H.M. Zijm, J.K.W. van Ommeren, A. Sleptchenko
510	2016	A note on Maximal Covering Location Games	L.P.J. Schlicher, M. Slikker, G.J.J.A.N. van Houtum
509	2016	Spare parts pooling games under a critical level policy	LP.J. Schlicher, M. Slikker, G.J.J.A.N van Houtum
508	2016	A note on "Linear programming models for a stochastic dynamic capacitated lot sizing problem"	T.D. van Pelt, J. C. Fransoo
507	2016	Multi-hop driver-parcel matching problem with time windows	W.Chen, M.K.R. Mes, J.M.J. Schutten
506	2016	Constrained maintenance optimization under non-constant probabilities of imperfect inspections	J.P.C. Driessen, H. Peng, G.J.J.A.N. van Houtum
505	2016	Awareness Initiative for Agile Business Models in the Dutch Mobility Sector: An Experience Report	P.W.P.J. Grefen, O.Turetken, M. Razavian
504	2016	Service and transfer selection for freights in a synchromodal network	A.S. Pérez Rivera, M.K.R. Mes
503	2016	Simulation of a multi-agent system for autonomous trailer docking	B. Gerrits, M.K.R. Mes, P.C. Schuur
502	2016	Integral optimization of spare parts inventories in systems with redundancies	A. Sleptchenko, M.C. van der Heijden
501	2016	An agent-based simulation framework to evaluate urban logistics scheme	W.J.A. van Heeswijk, M.K.R. Mes, J.M.J. Schutten
500	2016	Integrated Maintenance and Spare Part Optimization for Moving Assets	A.S. Eruguz, T. Tan, G.J.J.A.N. van Houtum
499	2016	A Condition-Based Maintenance Model for a Single Component in a System with Scheduled and Unscheduled Downs	Q. Zhu, H. Peng, B. Timmermans, G.J.J.A.N. van Houtum
498	2016	An age-based maintenance policy using the opportunities of scheduled and unscheduled system downs	Q. Zhu, H. Peng, G.J.J.A.N. van Houtum
497	2016	Dynamism in Inter-Organizational Service Orchestration - An Analysis of the State of the Art	P.W.P.J. Grefen, S. Rinderle-Ma
496	2016	Service-Dominant Business Modeling in Transport Logistics	O.Turetken, P.W.P.J. Grefen
495	2016	Approximate Dynamic Programming by Practical Examples	M.K.R. Mes, A.S. Pérez Rivera
494	2016	Design of a near-optimal generalized ABC classi?cation for a multi-item inventory control problem	E. Van Wingerden, T. Tan, G.J.J.A.N. Van Houtum
493	2015	The delivery dispatching problem with time windows for urban consolidation centers	W.J.A. van Heeswijk, M.R.K. Mes, J.M.J Schutten
492	2015	Anticipatory Freight Selection in Intermodal Long-haul Round-trips	A.E. Pérez Rivera, M.R.K. Mes
491	2015	Base-stock policies for lost-sales models: Aggregation and asymptotics	J.J. Arts, R. Levi, G.J.J.A.N. van Houtum, A.P. Zwart
490	2015	The Time-Dependent Pro_table Pickup and Delivery Traveling Salesman Problem with Time Windows	P. Sun, S. Dabia, L.P. Veelenturf, T. Van Woensel
489	2015	A survey of maintenance and service logistics management: Classification and research agenda from a maritime sector perspective	A.S.Eruguz, T.Tan, G.J.J.A.N. van Houtum
488	2015	Structuring AHP-based maintenance policy selection	A.J.M. Goossens, R.J.I. Basten, J.M. Hummel, L.L.M. van der Wegen
487	2015	Pooling of critical, low-utilization resources with unavailability	L.P.J. Schlicher, M. Slikker, G.J.J.A.N. van Houtum
486	2015	Business Process Management Technology for Discrete Manufacturing	I.T.P. Vanderfeesten, PW.P.J. Grefen
485	2015	Towards an Architecture for Cooperative-Intelligent Transport System (C-ITS) Applications in the Netherlands	M. van Sambeek, F. Ophelders, T. Bijlsma, B. van der Kluit, O. Turetken, H. Eshuis, K. Traganos, P.W.P.J. Grefen
484	2015	Reasoning About Property Preservation in Adaptive Case Management	H. Eshuis, R. Hull, M. Yi

Nr.	Year	Title	Author(s)
483	2015	An Adaptive Large Neighborhood Search Heuristic for the Pickup and Delivery Problem with Time Windows and Scheduled Lines	V. Ghilas, E. Demir, T. Van Woensel
482	2015	Inventory Dynamics in the Financial Crisis: An Empirical Analysis of Firm Responsiveness and its Effect on Financial Performance	K. Hoberg, M. Udenio, J.C. Fransoo
481	2015	The extended gate problem: Intermodal hub location with multiple actors	Y. Bouchery, J.C. Fransoo, M. Slikker
480	2015	Inventory Management with Two Demand Streams: A Maintenance Application	R.J.I. Basten, J.K. Ryan
479	2015	Optimal Design of Uptime-Guarantee Contracts	B. Hezarkhani
478	2015	Collaborative Replenishment in the Presence of Intermediaries	B.Hezarkhani, M. Slikker, T. Van Woensel
477	2015	Reference Architecture for Mobility-Related Services A reference architecture based on GET Service and SIMPLI-CITY Project architectures	A. Husak, M. Politis, V. Shah, R. Eshuis, P. Grefen
476	2015	A Multi-Item Approach to Repairable Stocking and Expediting in a Fluctuating Demand Environment	J.J. Arts
475	2015	An Adaptive Large Neighborhood Search Heuristic for the Share-a-Ride Problem	B. Li, D. Krushinsky, T. Van Woensel, H.A. Reijers
474	2015	An approximate dynamic programming approach to urban freight distribution with batch arrivals	W.J.A. van Heeswijk, M.R.K. Mes, J.M.J. Schutten
473	2015	Dynamic Multi-period Freight Consolidation	A.E. Pérez Rivera, M.R.K. Mes
472	2015	Maintenance policy selection for ships: finding the most important criteria and considerations	A.J.M. Goossens, R.J.I. Basten
471	2015	Using Twitter to Predict Sales: A Case Study	R.M. Dijkman, P.G. Ipeirotis, F. Aertsen, R. van Helden
470	2015	The Effect of Exceptions in Business Processes	R.M. Dijkman, G. van IJzendoorn, O. Türetken, M. de Vries
469	2015	Business Model Prototyping for Intelligent Transport Systems. A Service-Dominant Approach	K.Traganos, P.W.P.J. Grefen, A. den Hollander, O. Turetken, H. Eshuis
468	2015	How suitable is the RePro technique for rethinking care processes?	R.J.B. Vanwersch, L. Pufahl, I.T.P. Vanderfeesten, J. Mendling, H.A. Reijers
467	2014	Where to exert abatement effort for sustainable operations considering supply chain interactions?	Tarkan Tan, Astrid Koomen
466	2014	An Exact Algorithm for the Vehicle Routing Problem with Time Windows and Shifts	Said Dabia, Stefan Ropke, Tom Van Woensel
465	2014	The RePro technique: a new, systematic technique for rethinking care processes	Rob J.B. Vanwersch, Luise Pufahl, Irene Vanderfeesten, Hajo A. Reijers
464	2014	Exploring maintenance policy selection using the Analytic Hierarchy Process: an application for naval ships	A.J.M. Goossens, R.J.I. Basten
463	2014	Allocating service parts in two-echelon networks at a utility company	D. van den Berg, M.C. van der Heijden, P.C. Schuur
462	2014	Freight consolidation in networks with transshipments	W.J.A. van Heeswijk, M.R.K. Mes, J.M.J. Schutten, W.H.M. Zijm
461	2014	A Software Architecture for a Transportation Control Tower	Anne Baumgrass, Remco Dijkman, Paul Grefen, Shaya Pourmirza, Hagen Völzer, Mathias Weske
460	2014	Small traditional retailers in emerging markets	Youssef Boulaksil, Jan C. Fransoo, Edgar E. Blanco, Sallem Koubida
459	2014	Defining line replaceable units	J.E. Parada Puig, R.J.I. Basten
458	2014	Inventories and the Credit Crisis: A Chicken and Egg Situation	Maximiliano Udenio, Vishal Gaur, Jan C. Fransoo
457	2014	An Exact Approach for the Pollution-Routing Problem	Said Dabia, Emrah Demir, Tom Van Woensel
456	2014	Fleet readiness: stocking spare parts and high-tech assets	Rob J.I. Basten, Joachim J. Arts
455	2014	Competitive Solutions for Cooperating Logistics Providers	Behzad Hezarkhani, Marco Slikker, Tom Van Woensel
454	2014	Simulation Framework to Analyse Operating Room Release Mechanisms	Rimmert van der Kooij, Martijn Mes, Erwin Hans
453	2014	A Unified Race Algorithm for Offline Parameter Tuning	Tim van Dijk, Martijn Mes, Marco Schutten, Joaquim Gromicho

Nr.	Year	Title	Author(s)
452	2014	Cost, carbon emissions and modal shift in intermodal network design decisions	Yann Bouchery, Jan Fransoo
451	2014	Transportation Cost and CO2 Emissions in Location Decision Models	Josue C. Vélazquez-Martínez, Jan C. Fransoo, Edgar E. Blanco, Jaime Mora-Vargas
450	2014	Tracebook: A Dynamic Checklist Support System	Shan Nan, Pieter Van Gorp, Hendrikus H.M. Korsten, Richard Vdovjak, Uzay Kaymak
449	2014	Intermodal hinterland network design with multiple actors	Yann Bouchery, Jan Fransoo
448	2014	The Share-a-Ride Problem: People and Parcels Sharing Taxis	Baoxiang Li, Dmitry Krushinsky, Hajo A. Reijers, Tom Van Woensel
447	2014	Stochastic inventory models for a single item at a single location	K.H. van Donselaar, R.A.C.M. Broekmeulen
446	2014	Optimal and heuristic repairable stocking and expediting in a fluctuating demand environment	Joachim Arts, Rob Basten, Geert-Jan van Houtum
445	2014	Connecting inventory control and repair shop control: a differentiated control structure for repairable spare parts	M.A. Driessen, W.D. Rustenburg, G.J. van Houtum, V.C.S. Wiers
444	2014	A survey on design and usage of Software Reference Architectures	Samuil Angelov, Jos Trienekens, Rob Kusters
443	2014	Extending and Adapting the Architecture Tradeoff Analysis Method for the Evaluation of Software Reference Architectures	Samuil Angelov, Jos J.M. Trienekens, Paul Grefen
442	2014	A multimodal network flow problem with product quality preservation, transshipment, and asset management	Maryam SteadieSeifi, Nico Dellaert, Tom Van Woensel
441	2013	Integrating passenger and freight transportation: Model formulation and insights	Veaceslav Ghilas, Emrah Demir, Tom Van Woensel
440	2013	The Price of Payment Delay	K. van der Vliet, M.J. Reindorp, J.C. Fransoo
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