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IFAC PapersOnLine 54-1 (2021) 982–987

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Advances in Spare Parts Classification and Forecasting for Inventory Control: A Literature Review

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Abstract: Ensuring availability of spare parts is essential for original equipment manufacturers (OEMs) to support after-sales maintenance and repair services for their products. Previous studies have pointed out shortcomings of literature in supporting practitioners with guidelines on development of effective spare parts management systems. This paper assesses the extent to which recent research advances address these shortcomings, through a review of recent literature on spare parts management. We find that most research gaps identified by previous studies continue to persist. Moreover, we find that majority of recent spare parts management research takes the perspective of owners of assets or equipment, and fewer case studies take the perspective of manufacturers or suppliers of the equipment and spare parts, i.e., OEMs. Majority of the recent case studies are from aviation, domestic appliance, and automotive industries.

Keywords: spare parts, service parts, classification, forecasting, inventory management, integration.

1. INTRODUCTION

It is essential for manufacturing companies in various industry sectors, e.g., consumer electronics, automotive manufacturing, industrial machinery, etc., to ensure availability of spare parts for supporting after-sales repair and maintenance of their products. After-sales services and spare parts' business create additional revenue streams for Original Equipment Manufacturers (OEMs), while enabling them to contribute in minimising downtimes and maximising availability of their products in the usable life of these products (Cohen et al., 2006, Eruguz et al., 2017). Effective demand management and inventory control for spare parts, collectively referred to as spare parts management, play a central role in this by taking measures to achieve target service levels while minimising the incurred costs (Eaves and Kingsman, 2004).

The design and operation of spare parts management systems are complex tasks as they require simultaneous consideration of a wide range of factors, e.g., demand volume, demand frequency, criticality of part, cost or value of part, procurement and/or production lead times, etc. Activities within spare parts management include classification, forecasting and inventory control (Bacchetti and Saccani, 2012), where inventory control is the primary focus, while classification and forecasting can be considered supporting activities. Bacchetti and Saccani (2012) refer to this notion as an integrated approach to spare parts management. Following Boylan and Syntetos (2010), they argue that spare parts classification and demand forecasting should be linked with inventory control policies. They propose organising spare parts management activities in a closed loop as shown in *Figure 1*. Since spare part inventories consist of stock-keeping-units (SKUs) with a wide range of service requirements, physical and economic attributes, demand patterns, etc., classification is essential for differentiating forecasting methods and inventory policies based on parts' characteristics. Finally, performance assessment is necessary to assess whether service requirements are fulfilled and if the classification, forecasting methods and inventory policies must be reassessed.

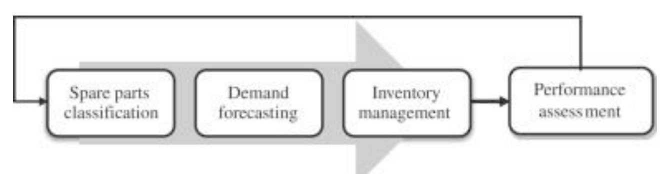


Figure 1 Elements of integrated spare parts management (Bacchetti and Saccani, 2012)

Despite substantial research efforts having been dedicated towards development of methods and models for supporting spare parts management, Bacchetti and Saccani (2012) find gaps between the needs of practitioners and results from research. In their mixed methods study, the lack of an integrated approach to spare parts management is highlighted as one of the main knowledge gaps. They point out that literature lacks normative guidelines on the selection of spare parts management approaches for specific production environments based on contextual factors. Therefore, the extent to which recent literature has addressed these knowledge gaps is worth investigating. To this end, this paper investigates advances in research vis-à-vis gaps previously highlighted in literature on spare parts management, focussing on development of integrated spare parts management systems. In doing so, the paper addresses

10.1016/j.ifacol.2021.08.118

the following research question(s): *What are the recent advancements in integrated spare parts management research and which industrial contexts has this research been conducted in?*

The paper extends the review of Bacchetti and Saccani (2012) on integrated spare parts management by reviewing recent literature (2012 – 2020) on the subject. The review allows for identification of new research that is relevant for informing practice while also revealing persisting research gaps. The methodology for identifying literature for the review is described in Section 2. Section 3 gives an overview of research areas within spare parts management and reviews the identified recent literature. Based on the review, we identify research gaps and future research areas to support the development of integrated spare parts management systems in practice, summarising these findings in section 4.

2. METHODOLOGY

This paper takes a systematic literature review approach, which emphasizes on transparency of the literature identification process to facilitate replication. The literature was identified through a keyword search on the Scopus database using the following search string: [“spare part(s)” OR “service part(s)”] AND [management] AND [forecast OR forecasting OR inventory OR stock OR classification OR performance]. We limited the period of publication to ‘>2011’, since the purpose of our literature review is to extend the review presented by Bacchetti and Saccani (2012) and identify advancements since the publication of their study. Ideally, we would replicate the literature identification protocol of Bacchetti and Saccani (2012) for this purpose. However, despite their literature review being arguably comprehensive, Bacchetti and Saccani (2012) do not explicitly describe their process for identifying literature. Therefore, the search string presented above was formulated based on the core elements of integrated spare parts management, as shown in *Figure 1*. For content analysis of literature, we follow the structure similar to that of Bacchetti and Saccani (2012), i.e., under the themes of spare parts classification, demand forecasting, stock control and its integration with classification and forecasting.

The first search yielded 607 documents. We then filtered the results by source type, limiting to journal publications, which reduced the number of results to 313. After excluding irrelevant subject areas such as ‘immunology’, ‘veterinary’, ‘biochemistry’, etc., 253 results remained. The titles and abstracts of these results were screened to identify relevant documents. At this screening stage, documents were excluded if their topic had a different focus than forecasting, classification, or inventory control for spare parts or if the topic was broader than spare parts management, e.g., joint optimisation of maintenance scheduling and spare part inventory. Through the screening process, 41 contributions were identified for detailed reading, review, and content analysis. Thereafter, 13 of these contributions were excluded during detailed reading because they lacked motivation or validation through industrial cases. Consequently, 28 contributions were included in the final review.

3. RECENT ADVANCES IN LITERATURE

The 28 articles identified for detailed content analysis are reviewed in this section. The section first gives an overview of the practical relevance of spare parts management research and the main research areas. This is followed by a review of recent literature to identify the recent advances in literature on topics within spare parts management.

3.1 Overview of spare parts management

The practical relevance of spare parts management research primarily stems from two broad areas of application. First, inventory management for maintenance, repair, and operations (MRO) supplies that are used in production but do not become part of the finished product, e.g., hand tools, spare parts, lubricants, etc. that are used by manufacturers to maintain production equipment. Second, inventory management for spare parts for providing after-sales repair and maintenance services to customers during the products’ usable lives. For industrial equipment, these application areas represent two perspectives of repair and maintenance activities – the MRO perspective represents owners of an asset or equipment, while after-sales service perspective represents the manufacturer of the equipment, the OEM. Both perspectives can be found in literature, e.g., Bacchetti and Saccani (2012) take the after-sales perspective, while Roda et al. (2014) take the MRO perspective. Literature with the after-sales perspective also refers to spare parts as service parts (see, for instance Van der Auweraer and Boute (2019)). Research with either spare parts management perspective has been focussed on primarily three areas, as described below.

The first research area within spare parts management concerns classification of spare parts, which is aimed at supporting three broad decision areas – (1) selection of relevant classification criteria such as part cost or value, stock-out cost, lead time, part criticality, supply uncertainty, etc.; (2) the definition of categories or classes of SKUs, e.g., ABC (Teunter et al., 2010), VED (vital – essential – desirable) (Stoll et al., 2015), and FSN (fast-moving – slow-moving – non-moving) (Marichelvam et al., 2017); and (3) the process of classification through methods and frameworks, e.g., Analytical Hierarchy Process (AHP) (Braglia et al., 2004, Lolli et al., 2014), statistical clustering (Ernst and Cohen, 1990), unsupervised machine learning techniques such as hierarchical clustering, k-means clustering, etc. (Balugani et al., 2018, Lolli et al., 2019).

The second research area concerns demand forecasting for spare parts, which requires specialised methods because of lumpy and intermittent demand patterns that characterise many spare parts. The focus of this research area is the development of forecasting methods that can be used for items with such demand, e.g., advanced time-series and explanatory forecasting methods (Bacchetti and Saccani, 2012). The third research area within spare parts management concerns the selection of inventory policies for spare parts, and is aimed at supporting decisions such as periodic review vs. continuous review, fixed vs. variable order quantities, specifying the order quantities and reorder points, etc.

*Table 1 Industrial context and research focus of reviewed literature - **boldfaced and italicised** references integrate two or more research areas*

Perspective	Industry	Classification	Forecasting	Inventory control
Mainten-ance, repair and operations inventories (MRO)	Energy	***[23]***		[9], ***[23]***
	Automotive	***[25]***		***[25]***
	Open-cast mining	***[22]*** , [18]		***[22]*** , [17]
	Iron-ore mining	[19]		
	Bio-diesel refinery	[7]		
	Textile	[3]		
	Aerospace			[4], [8]
	Various	[10], [16], [27]	[26], [20]	
After-sales service parts (OEMs)	White goods	***[2]***	***[2]***	***[2]***
	Automotive	***[6]***	***[6]***	
	Semiconductors		[24]	
	MRO parts and service provider	***[12]*** , [13]		***[12]***
	Consumer electronics		[14]	
	Machinery		[11], [28], [15]	
	Aerospace	***[1]***		***[1]*** , [21]
	Various		[5]	

[1] Ayu Nariswari et al. (2019), [2] Bacchetti et al. (2013), [3] Baykasoğlu et al. (2016), [4] Costantino et al. (2018), [5] Dekker et al. (2013), [6] do Rego and Mesquita (2015), [7] Ferreira et al. (2018), [8] Gehret et al. (2020), [9] Guajardo et al. (2015), [10] Heinecke et al. (2013), [11] Hellingrath and Cordes (2014), [12] Hu et al. (2017), [13] Ishizaka et al. (2018), [14] Kim et al. (2017), [15] Lelo et al. (2019), [16] Lengu et al. (2014), [17] Moharana and Sarmah (2016), [18] Moharana and Sarmah (2018), [19] Muniz et al. (2020), [20] Pennings et al. (2017), [21] Rezaei et al. (2018), [22] Sarmah and Moharana (2015), [23] Scala et al. (2013), [24] Stip and Van Houtum (2020) , [25] Stoll et al. (2015), [26] Syntetos et al. (2012), [27] Turrini and Meissner (2019), [28] Van der Auweraer and Boute (2019)

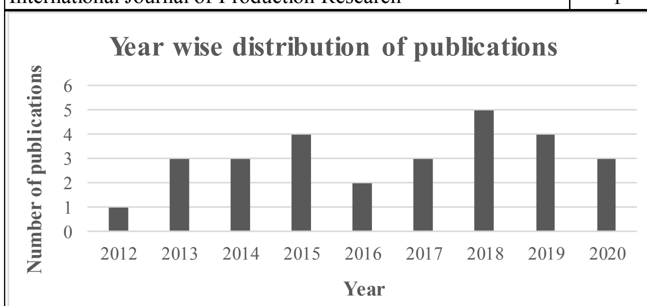
As argued by Bacchetti and Saccani (2012) and Boylan and Syntetos (2010), integrating stock control with forecasting and classification can facilitate effective spare parts management. In the following subsections, we review recent literature that addresses classification (3.2), forecasting (3.3), inventory control and its integration with classification and forecasting (3.4) for spare parts management. *Table 1* summarises the industrial context and research area of focus in the reviewed contributions. The contributions that integrate two areas of spare parts management are indicated in boldface and italics. *Table 2* shows the journals that the reviewed literature was published in, and the distribution of publications over the years.

3.2 Recent advancements - spare parts classification

Bacchetti et al. (2013) apply a hierarchical multi-criteria classification approach in a case study of a white goods manufacturer, using product lifecycle phase, lead time, minimum number of orders, demand frequency, part criticality and part value to classify after-sales spare parts. Scala et al. (2013) use AHP for classification of MRO parts in the context of a nuclear power generation facility, where they score parts based on their criticality, defining criticality based on part failure, vendor availability, costs, preventive maintenance schedule, etc. For the case of MRO parts of an automotive manufacturer, Stoll et al. (2015) use AHP to classify parts into ABC, XYZ and VED categories based on parts' value, demand predictability, and part criticality respectively. Sarmah and Moharana (2015) propose a multi-criteria fuzzy-rule-based model to classify spare parts for inventory control based on consumption value, unit price, lead-time, spare parts criticality, and commonality, that is applied for classifying MRO inventory in an open cast mining company. In the case of an automotive manufacturer, do Rego and de Mesquita (2015) classify after-sales spare parts based on average-inter-demand-interval and squared coefficient of variation, while also using target fill rates. For a case of MRO spare parts in a textile company, Baykasoğlu et al. (2016) propose the use of fuzzy set theory for classifying spare parts into multi-criteria ABC categories using durability, availability, criticality, replenishment time, and total annual cost as criteria. Ferreira et al. (2018) use AHP with fuzzy logic to classify MRO parts in a biodiesel refinery based on criticality, demand volume, unit value, lead time and number of potential suppliers.

Table 2 Journal/source of reviewed literature and year wise distribution of publications

Journal/source title	Quantity
International Journal of Production Economics	7
European Journal of Operational Research	4
IFAC-PapersOnLine	2
Journal of the Operational Research Society	2
Computers and Industrial Engineering	2
Journal of Quality in Maintenance Engineering	2
Production Planning and Control	1
Applied Soft Computing Journal	1
Omega (United Kingdom)	1
Production and Manufacturing Research	1
International Journal of Advanced Manufacturing Technology	1
International Journal of Logistics Management	1
IEEE Transactions on Engineering Management	1
Production Engineering	1
International Journal of Production Research	1



In the case of a company that produces spare parts and provides maintenance, repair and overhaul services, Hu et al. (2017) propose a three-phase multicriteria classification framework that uses a dominance-based rough set approach (DRSA), where they use criticality, annual cost usage, unit price and lead time as classification criteria. For a case of a maintenance, repair and overhaul service provider, Ishizaka et al. (2018) propose the use of data envelopment analysis (DEA) with AHP to classify spare parts into ABC categories, where the criteria used are annual usage value, frequency of issue per year and current stock value. Moharana and Sarmah (2018) propose a hierarchical clustering-based approach for identifying demand dependencies between MRO parts that are frequently consumed simultaneously in an open cast mining company. Ayu Nariswari et al. (2019) test an AHP model for spare part classification in the context of an aircraft maintenance and repair company, using several criteria under the headings of operational criticality, technical characteristics, and supply characteristics. For an iron-ore mining company, Muniz et al. (2020) propose a 'hybrid' classification method combining AHP and multi-objective integer optimisation for classifying MRO parts into VED categories using criteria under the headings of production criteria, maintenance criteria and supply criteria.

Heinecke et al. (2013) propose cut-off values of parameters for classifying spare part demand patterns to support differentiation of forecasting methods, testing the propositions on data from military sector and electronics and automotive industries. Lengu et al. (2014) investigate the goodness-of-fit of probability distributions for modelling spare part demand using datasets from domestic appliances industry and commercial airlines. In a similar contribution, Turrini and Meissner (2019) investigate distribution fitting for spare part demand in datasets from renewable energy industry and military sector.

From the above review, we observe that majority of recent literature on spare parts classification is motivated or validated by practical cases, thus enriching the diversity of case studies in literature. Secondly, 10 of 15 recent contributions focus on inventory management of MRO spare parts, with few contributions taking the after-sales service perspective of OEMs with the exceptions of Bacchetti et al. (2013), do Rego and de Mesquita (2015), Hu et al. (2017), Ishizaka et al. (2018) and Ayu Nariswari et al. (2019).

3.3 Recent advancements - spare parts forecasting

Syntetos et al. (2012) investigate the fit of probability distributions to different demand patterns found in empirical datasets from military sector and electronics industry. In the case of after-sales spare parts management at a white goods manufacturer, Bacchetti et al. (2013) propose causal forecasting for items with no demand history, no forecasting for items with less than three orders per year and for items with low demand frequency, and aggregate moving average for items with high demand frequency. In a case of automotive spare parts, do Rego and de Mesquita (2015) recommend simple moving average for intermittent demand when target fill rates (TFR) are low and bootstrapping for high TFR; Syntetos-Boylan Approximation (SBA) for erratic demand items, and for smooth demand items under high TFR; and their proposed bootstrapping forecasting method for lumpy demand, for slow demand under high TFR, and for smooth demand under low TFR. Pennings et al. (2017) propose a forecasting method for cases where demand is correlated with time elapsed since the last demand, and test the model with datasets from a spare parts supplier for lamp production, and other secondary data sets. Stip and Van Houtum (2020) develop a method to detect errors in service bill-of-materials (BOMs) that are used as input for spare part forecasting in a company that supplies lithography equipment to the semiconductor industry.

Dekker et al. (2013) discuss the concept of 'installed base forecasting', which entails the use of data from in-use products to forecast spare parts requirements, and present practices from case studies in the aviation, computing, maritime and railway sectors. Kim et al. (2017) propose an installed base forecasting method with an illustrative case study within consumer electronics. Hellingrath and Cordes (2014) propose a conceptual approach for integrating condition monitoring information into forecasting for spare parts used for providing after-sales services by a machine manufacturer. Van der Auweraer and Boute (2019) propose a forecasting method for utilising service maintenance information such as number of machines that use a part, parts' failure behaviour, maintenance strategy, etc. Lelo et al. (2019) propose a spare parts forecasting method that utilises condition monitoring data, and test this for a case of turbomachinery blades.

Majority of recent literature on spare parts forecasting has focussed on development of explanatory or hybrid forecasting methods that assume the availability of usage data from products. While these methods could support promising advancements in practice, data availability and other practical applicability issues are still under-emphasised in literature. Finally, while there are contributions that give normative guidelines on suitable forecasting methods for different item categories (Bacchetti et al., 2013, do Rego and de Mesquita, 2015), the guidelines vary across these papers, suggesting the lack of a "conclusive and practitioner-oriented indication on which is "the best" forecasting method for spare parts" as concluded in their review by Bacchetti and Saccani (2012). Nevertheless, findings of Bacchetti et al. (2013) suggest that simple and easily understandable forecasting methods are more likely to be adopted in practice as compared to mathematically complex ones.

3.4 Recent advancements - spare parts inventory control

In this subsection, we first consider literature that only addresses inventory control issues, i.e., papers that were not reviewed in subsections 3.2 and 3.3. Next, we consider papers that were reviewed in those subsections, that also address inventory policy guidelines for their cases – thus integrating inventory control with classification and/or forecasting.

Guajardo et al. (2015) address the problem of determining control parameters for a continuous review (r, S) policy for spare part inventories in an energy company. Moharana and Sarmah (2016) propose a method for determining the order-up to level in a periodic review (T, S) policy for production spare parts in a case study of an open cast mining company. Costantino et al. (2018) use a continuous review base stock (S-1, S) policy in their proposed inventory model for a case of an airline fleet. The model is based on Multi Echelon Technique for Recoverable Item Control (METRIC) method using a Zero-Inflated Poisson demand distribution. Rezaei et al. (2018) propose a continuous review (r, Q) policy based inventory model for a case study of an aircraft manufacturer. Gehret et al. (2020) propose a procedure for determining parameters for continuous review (*r*, *Q*) inventory policies for spare parts for an aircraft fleet.

Among papers that were already reviewed in subsections 3.2 and 3.3, Scala et al. (2013) propose a continuous review base stock (*S-1*, *S*) policy. Sarmah and Moharana (2015) propose a base stock (*S-1*, *S*) policy, an (*r*, *Q*) policy and EOQ for the three part classes in their case. Bacchetti et al. (2013) propose a periodic review (*T*, *r*, *S*) policy for introductory parts and parts with low demand frequency; periodic review (*T*, *S*) policy for spare parts with fewer than 3 orders per year; and continuous review (*r*, *Q*) policy with EOQ for parts with high demand frequency. Stoll et al. (2015), Hu et al. (2017) and Ayu Nariswari et al. (2019) provide qualitative inventory policy guidelines for their cases, e.g., no-stock, single-unit-stock, EOQ, just-in-time delivery, etc. As evident, a wide range of policies have been used in recent research on spare parts inventory control – continuous/periodic review; fixed order-up-to/order quantity; with/without reorder points. Consistent with the findings of Sani and Kingsman (1997) and Bacchetti and Saccani (2012), (*r*, *S*) policies are predominantly proposed for spare parts with low and intermittent demands, while (*r*, *Q*) policies are predominant for spare parts with high and frequent demand. Nevertheless, contributions that integrate classification and forecasting with inventory control are still scarce in comparison to papers that only address one of these elements.

4. CONCLUSION

In this paper, we reviewed empirical research contributions on spare parts management since the year 2012, analysing literature under the topics of classification, forecasting and inventory control. We highlighted the case environment of the research contributions and investigated the persistence of gaps vis-à-vis findings of the literature review by Bacchetti and Saccani (2012). We find that the after-sales service perspective of OEMs is under-represented in recent spare parts classification literature, as majority of the contributions focus on MRO inventories. Furthermore, majority of the case studies in literature with the after-sales perspective are from the aviation, domestic appliance, and automotive industries. There are various issues within integrated after-sales spare parts management in other industries producing big-sized equipment, e.g., maritime equipment (Eruguz et al., 2017), that require further investigation.

Within forecasting, majority of recent research has focussed on development of explanatory or hybrid forecasting methods that require accessibility and availability of usage data from products. While there is a dearth of normative practitioner-oriented guidelines on suitable forecasting methods for different spare part categories, results from industry-oriented case studies suggest that simple, well-understood forecasting methods are more likely to have utility for practitioners.

Within literature on inventory control, different policies have been used in recent research within different contexts. Consistent with previous research findings, order-up-to (*r*, *S*) policies are predominantly used for low- and intermittent-demand spare parts, while (*r*, *Q*) policies are preferred for high- and frequent-demand spare parts. Following up on the findings of Bacchetti and Saccani (2012), we find that integration of spare parts inventory control with classification and forecasting continues to be under-emphasised in literature. Furthermore, following up on recommendations of do Rego and de Mesquita (2015) and Topan et al. (2020), we find that few papers address the issue of updating forecasting and inventory control parameters, and the frequency of this activity in their cases. Finally, exploring the applications of machine learning methods for classification and clustering of spare parts also represents a growing research area (see for instance Balugani et al. (2018); Lolli et al. (2019)), however, such contributions have not been extensively discussed in this paper due to lack of case studies in such contributions.

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