

Mouschoutzi, Maria; Ponis, Stavros T.

Article

A comprehensive literature review on spare parts logistics management in the maritime industry

Asian Journal of Shipping and Logistics (AJSL)

Provided in Cooperation with:

Korean Association of Shipping and Logistics, Seoul

Suggested Citation: Mouschoutzi, Maria; Ponis, Stavros T. (2022) : A comprehensive literature review on spare parts logistics management in the maritime industry, Asian Journal of Shipping and Logistics (AJSL), ISSN 2352-4871, Elsevier, Amsterdam, Vol. 38, Iss. 2, pp. 71-83, <https://doi.org/10.1016/j.ajsl.2021.12.003>

This Version is available at:

<https://hdl.handle.net/10419/329691>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



Original article

A comprehensive literature review on spare parts logistics management in the maritime industry

Maria Mouschoutzi*, Stavros T. Ponis

School of Mechanical Engineering, National Technical University of Athens, Athens, Greece

ARTICLE INFO

Article history:

Received 18 April 2021

Received in revised form 22 October 2021

Accepted 27 December 2021

Keywords:

Spare parts
Maintenance
Maritime
Shipping
Logistics
Supply chain

ABSTRACT

Supply chain and logistics management for spare parts is of key importance in the maritime industry, in order to ensure high availability and reliability of assets, while keeping operating costs in acceptable levels. Supply chain and logistics operations for spare parts incorporate high complexity, uncertainty and costs, due to special characteristics of the maritime sector, as for instance moving assets, globally scattered points of supply and demand, strict time windows and multi-actor setting. Typically, the asset owner purchases spare parts for their vessel from a foreign supplier, and consolidates them in a regional warehouse. Subsequently, these spare parts are shipped to a port using various means of transport such as air freight, sea freight or road freight. Finally, once the vessel calls at subject port, the spare parts are delivered and used on board for maintenance activities. For repairable items, the reverse logistics process also does exist; a spare part is offloaded from a vessel, repaired and then re-delivered on board. Efficiently handling such a logistics network constitutes a great challenge, nevertheless, this topic has received little attention in the literature and a systematic review is currently missing. In this paper, the authors attempt to address this research gap by performing a systematic literature review on spare parts supply chain and logistics management in the maritime sector. To achieve this objective, after applying the defined inclusion and exclusion criteria on the initial search results, a set of (30) eligible papers, participating in the review, has been identified. These selected papers are illustrated and discussed in detail, with the purpose of addressing the research questions initially set by the authors. Fundamentally, this study aims to describe the current state of the art in the subject area, identify existing challenges and trends, and finally provide suggestions on future research. We aspire that the results of this review can be used as the foundation for future research on spare parts supply chain management in the maritime sector.

© 2022 The Authors. Production and hosting by Elsevier B.V. on behalf of The Korean Association of Shipping and Logistics, Inc. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).
CC_BY_4.0

1. Introduction

Capital intensive industries, such as the maritime industry, are characterized by high-value assets with long lifetimes, demanding a continuous and copious support of spare parts necessary for maintenance activities, in order to ensure the availability and reliability of the assets throughout their useful lifetime. Planning requirements for the logistics of spare parts and maintaining service level requirements is a critical process, since the effects of stock-outs can be harmful, both financially and operationally. In the maritime industry, assets are used in various operations such as passenger and cargo

transport, oil and gas terminal services, dredging, fishing, geophysical surveys and military operations. With over eighty percent of global trade by volume and more than seventy percent of its value being carried on board ships and handled by seaports worldwide, the importance of maritime transport for trade and development, cannot be overemphasized (United Nations Conference on Trade & Development, 2017). From a technology perspective, a vessel is a technically sophisticated, high-value asset. For example, a newly built and large hi-tech vessel may cost up to 200 million USD (International Chamber of Shipping, 2018) and the commercial operation of a crude oil tanker, can yield a remarkable 11,655 USD of average daily earnings (Clarksons Research, 2018).

Additionally, the maritime industry is highly regulated and thus, maritime assets must adhere to an abundance of technical and operational specifications and guidelines imposed by several different

* Corresponding author.

E-mail address: mmouschoutzi@mail.ntua.gr (M. Mouschoutzi).

regulating bodies. According to the conventions provided by the International Maritime Organization (IMO) and the rules defined by Classification Societies, mandatory dry-dock surveys are imposed on ships. Major overhauls and repairs of ships practically take place during these dry-docking periods (Eruguz, Tan, & van Houtum, 2017). Additionally, the responsibility for maintenance, between the periodic surveys, lies with the owner of the vessel (Kian, Bekta, & Ouelhadj, 2018). Breakdown of maritime assets can, obviously, have a strong impact on the health and safety of the crew, as well as on the environment. Furthermore, the technical condition of a vessel is directly linked to its performance and financial yield, as well as, its commercial resale value. As a result, maintenance activities are strictly required to ensure that the vessel meets current industry standards for safe and efficient operation, meeting performance objectives and maintaining its resale value to acceptable levels. For achieving the aforementioned objectives, maintenance activities are costly and according to literature, they can contribute in the range of 25–35% to the operating costs of a maritime asset (Turan, 2009), while unexpected downtimes occurring from the failure of equipment can lead to a significant loss of revenue.

A notable element of maintenance is spare parts. The term 'spare part' is generally understood to mean an interchangeable part that is kept in inventory and used as a material resource of maintenance activities. Additionally, Spare Part Logistics are defined as the planning, design, realization, and control of the spare parts supply and distribution, along with associated information flows within a firm and between the firm and its network partners (Wagner, Jönke, & Eisingerich, 2021). Hence, spare parts logistics aim at the provision of the required spare parts for the maintenance of the asset, so as to ensure an optimal level of availability, while keeping the respective logistics cost in acceptable levels, by utilizing efficient practices.

Maritime assets can be considered as a collection of technical systems having multi-indenture structures (Eruguz et al., 2017). In order to reduce the downtime of the asset due to maintenance activities, as much as practically possible, it is a common practice to repair individual components rather than the entire asset or technical system. This leads to a large number of independent components that may fail and need to be replaced with new Ready for Use (RFU) identical components. The strategy described above is called 'repair-by-replacement' (van Houtum & Kranenburg, 2015). Nevertheless, this practice is not always feasible. For example, for major overhauls of the vessel such as maintenance of hull, inevitably dry-docking is required, resulting in downtime of the asset. The implementation of the 'repair-by-replacement' strategy clearly underpins the importance of spare parts as a material resource, as in that context, the availability of spare parts is equivalent to the availability of the vessel. Within that framework, efficiently handling the supply chain and logistics of spare parts, from the sourcing of the requested items to their delivery on board the vessel, is a major component of a successful maintenance strategy.

Apparently, under the repair-by-replacement strategy, the spare parts must be on board the vessel to allow replacement of the faulty component by a new, operation-ready, item. The latter, requires the physical transport of the various spare parts, from the manufacturer's location, where they are initially purchased, to on board the vessel. Intuitively, one would argue that spare parts can be stocked on board. This is true to some extent, however, unnecessary spare parts stock on board may result in limited space availability (Eruguz, Tan, & van Houtum, 2018) and excessive use of capital (Zhao & Yang, 2017). In addition, the latest trends explore the applicability of additive manufacturing techniques in the supply chain of maritime spare parts (Kostidi & Nikitakos, 2017). In that future scenario, spare parts are constructed in some intermediate point of the supply chain or even on board. As a result, inventory and transportation problems are limited or completely eliminated. Naturally, this scenario has inherent limitations related to the size and complexity of

the spare parts to be printed on board or at an intermediate 'print farm', the speed and cost of the printing process and the materials that can effectively be printed.

Spare parts used in maintenance operations can be broadly categorized into two groups, i.e. repairable and consumable. Repairable spare parts can be repaired at workshops and change status from under repair to RFU. Nevertheless, repairable spare parts are also subject to the risk of condemnation due to repetitive use. The workshop responsible to repair a repairable item may consider that an item is beyond repair and needs to be scrapped. In that case, a new identical spare part needs to be purchased. Repairable items are generally expensive, have long lifetimes and apparently demand from supply chain management the establishment of an effective reverse logistics process. Logistics networks that include repairable items are considerably more complicated than traditional ones (Guide & Srivastava, 1997). On the other hand, consumable spare parts are relatively cheap items that are discarded after replacement and are purchased new from a vendor. It should be noted that maritime spare parts can only be purchased from or be repaired at a limited number of specialized manufacturers, who are geographically scattered around the world. China, the Republic of Korea and Japan are the leading countries in the shipbuilding industry, accounting for 90.5% of global deliveries in 2017 (United Nations Conference on Trade & Development, 2017). As a result, a large portion of spare parts required on board originates from these countries, a fact that significantly affects the design of the spare parts logistics networks.

For a significant portion of maritime assets, such as container-ships, dredging or fishing vessels, routings are fixed and known in advance. This allows for efficient scheduling of spare part deliveries, without unexpected and excessive costs. However, this is not always the case. For naval ships and ships engaged in the tramp trade, routings may be fixed at the very last moment. Due to the fact that an ocean-going vessel trades worldwide, spare parts may be requested to be supplied at any of about 3,000 different ports (Clarkson Research Studies, 2004), each of which has a different economic, political, social and regulatory environment. It should be noted that the delivery of spare parts must take place within the time window of the port of call, which may last from several days to just a few hours. Port of call time windows, in the majority of the cases, have strict deadlines often with severe cost impacts for any overruns. In that way, the point of demand is not stationary and the problem parameter values depend on the position of the point of demand at a given point in time (Kian et al., 2018). These particularities and limitations add significant complexity to the spare parts logistics network and in most of the cases result in an overall increase of maintenance-related costs.

Various locations of supply and demand, as described above, result in a logistics network with numerous actors collaborating in a multi-echelon network setting, where spare parts inventory can be located in any of the participating intermediate parties. Specifically, maritime maintenance networks involve several different parties such as asset owners, asset managers, system integrators, original equipment manufacturers (OEMs), maintenance service providers, and logistics service providers (Eruguz et al., 2017) as shown in Fig. 1. The above-mentioned aspects of the maritime maintenance supply chain create a logistics network, which incorporates high complexity, uncertainty and costs. The establishment, operation and optimization – when possible – of such a logistics network in order for it to be responsive to the needs of the fleet in a cost-effective way, is a challenge for any ship management company.

However, based on current literature and the assessment of identified managerial practices, the benefits resulting from a structured strategic methodological approach to the problem of spare parts logistics management, are not systematically researched or even, fully understood. The most relevant work to what this paper

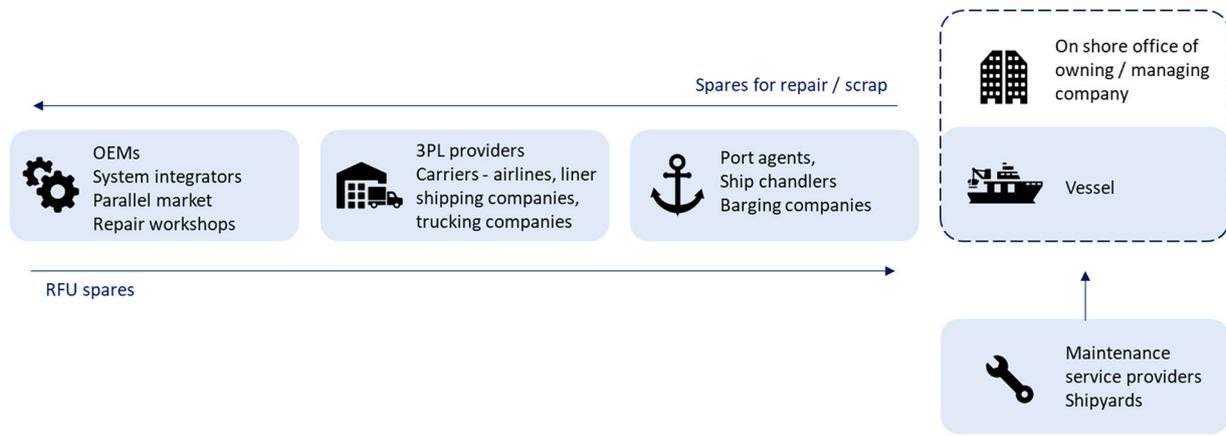


Fig. 1. The maritime maintenance ecosystem.

aims to achieve, is the survey paper of Eruguz et al. (2017). In their paper, the authors classify the literature on maintenance and service logistics management according to specific maritime sector characteristics and present the state-of-the-art, lessons learned, and future research directions regarding each characteristic. Subsequently, maintenance and service logistics management is further divided into subdomains namely system design, failure prediction, maintenance service contract design, maintenance strategy selection, maintenance planning and spare parts inventory management. Maritime spare parts inventory management papers are presented, but without being the focal point of their study. Besides, their study does not constitute a systematic literature review. Undeniably, for any research topic, a systematic literature review is particularly important in order to identify and describe the current state of the art, and establish a structured foundation of knowledge on the area, enabling further future research on the topic. In light of this and as no systematic literature review on the topic exists to the best of the authors' knowledge, this study aims to address this research gap by providing a systematic literature review on spare parts logistics management in the maritime industry. The authors strongly believe that this is an important area that needs to receive more attention and this is the research gap that this study aims to address. In this paper the authors focus on spare parts logistics for the maritime industry and evaluate works related to spare parts management at the planning (supply chain) level with severe repercussions at the operational (logistics) level of contemporary maritime maintenance networks. In that context, this paper aims to thoroughly study the existing literature on maritime spare parts logistics management, in order to evaluate the current state of the art in the respective scientific field and pinpoint areas with significant potential for new research with tangible, for the industry, implications. Additionally, this paper aims to also provide a review on existing additive manufacturing (AM) applications and pilot projects for spare parts in the maritime industry, as such applications have the potential to disrupt the traditional spare parts supply chain of this sector. Within that context the paper intends to also present the state of the art for AM applications in the maritime sector, as well as, evaluate the feasibility of such scenarios in real-life applications. By presenting both

the traditional and disruptive approach to this challenge, the paper ultimately aims to provide a comprehensive literature review on spare parts management in the maritime sector.

The rest of the paper is organized as follows. Section 2, describes the methodological approach that guided the literature review process and Section 3, provides the descriptive statistics of its results. Next, in Section 4, a discussion takes place based on review findings, categorized according to the identified themes within the studied literature. More specifically, relative studies dealing with demand forecasting, inventory classification, inventory control, logistics network design, as well as, integrated approaches for maritime spare parts are presented and their findings are evaluated and discussed in detail. Moreover, the potential of AM applications to disrupt the traditional management of spare parts supply chain is discussed here. Finally, Section 5 concludes the review by summarizing its findings, identifying shortcomings and proposing future research directions with a potential impact for both academia and the maritime industry.

2. Review methodology

This paper attempts to provide a Systematic Literature Review (SLR) on the area of maritime spare parts supply chain and logistics management. According to Siddaway, Wood, and Hedges (2019) an SLR should address most, or all, of a set of research requirements, i.e. establish to what extent existing research has progressed towards clarifying a particular problem, identify relations, contradictions, gaps, and inconsistencies, provide implications for practice and policy and describe directions for future research. The fundamental characteristics of an SLR are objectiveness, transparency, replicability and systematicness.

To that end, this paper follows a five-step methodological approach, depicted in Fig. 2.

In the first step, typically one or more research questions are defined. The research questions set for this study intend to examine the current state of the art in the field, identify most prominent research directions and propose research gaps that can be further



Fig. 2. The SLR Methodology.

investigated in the future. More specifically, the research questions of this study are the following:

RQ1: What are the current methodologies and applications in supply chain and logistics management for spare parts in the maritime industry? Which are the most prominent methodologies and what can be concluded from their application so far?

RQ2: What are the major challenges that the maritime industry is facing in the context of supply chain and logistics management for spare parts?

In the second step, the research questions were broken down into individual search terms. With these search terms, a thorough search has been performed in a set of selected literature sources, in order to identify relative literature. For the needs of this study, it was decided that the SCOPUS academic database can provide a sufficient and representative sample of relevant publications. The main reason that SCOPUS database has been chosen over other similar databases such as ISI WOS, EBSCO or ProQuest, is the significantly larger number of titles that are indexed. Apparently, SCOPUS has more loose and inclusive criteria for indexed articles, resulting in a larger number of titles. While this might lower the ‘quality’ of available studies, given the fact that this research area has received little attention in literature, the availability of as many published studies as possible was considered a priority. Additionally, Google Scholar has also been used, in order to access relative information from companies or other organizations such as government authorities, standardization bodies etc., which might not be available in a scientific database like SCOPUS. It should be mentioned that results were restricted in the English language and the ‘Trade Publication’ document type has been excluded. The search terms that have been selected represent each of the areas that compose the research questions, i.e. supply chain and logistics management, spare parts management and maritime assets. Interchangeable terms for spare parts, maritime assets, and supply chain and logistics subdomains have been used. The subject area field has been limited to the Engineering, Computer Science, Business, Management & Accounting, Mathematics and Decision Sciences, in order to exclude results from completely unrelated areas, such as Medicine or Energy. The actual search in SCOPUS has been performed by applying the following search string: TITLE-ABS-KEY ((spares OR ((spare OR service OR replacement OR repair OR replenishment) PRE/0 parts) OR (service PRE/0 logistics)) AND (vessel OR maritime OR ship OR marine OR naval OR navy) AND (logistics OR (supply PRE/0 chain) OR forwarding OR scheduling OR transport OR transportation OR demand OR inventory OR carrying OR storage)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "MATH")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p") OR LIMIT-TO (SRCTYPE, "k") OR LIMIT-TO (SRCTYPE, "b")) AND (LIMIT-TO (LANGUAGE, "English")). This resulted in 184 documents, as executed on September of 2020.

In the third step and after the initial sample of publications has been defined, a screening of the abstracts, methodologies, main results and conclusions of the documents took place. Search results were examined in order to verify the validity of used search terms. Subsequently, exclusion criteria were applied in order to narrow down the initial sample to publications potentially appropriate for addressing the research questions. The screening procedure has been implemented based on the following exclusion criteria: (a) excluding duplicate documents, (b) excluding documents that were included in the sample due to containing keywords of the search string, but were actually irrelevant to the study. The result of the screening procedure was a set of thirty (30) publications, eligible for further study and evaluation.

In the fourth step, the full text version of the potentially eligible publications that resulted from the screening procedure was read and studied in depth, in order to make sure that these are indeed

relevant and appropriate for inclusion. In that phase, the key research topic of each publication was also identified. Five main research topics were distinguished in relation to maritime spare parts management: (a) supply chain management, focusing on generation, classification and forecast of demand, (b) logistics management, focusing on inventory classification and control, (c) logistics network design, (d) studies presenting an integrated approach including both supply chain and logistics aspects, and (d) emerging disruptive technologies.

Finally, in the last step of the methodological approach, the results for each identified research category are presented. Initially, the topic of each category is discussed in relation to the maritime sector’s inherent characteristics, and within that context, a descriptive analysis is presented for the publications of each category. Additionally, for each category, possible research gaps and respective future research proposals are formulated.

3. Descriptive statistics

In this section a descriptive analysis of the initial search results is presented, aiming to provide an overview of the sample of publications, as well as, uncover potential underlying patterns. It is deemed appropriate to provide statistics on the initial search results, in order to gain a better insight and understanding on the composition of the set of documents that participated in the screening procedure. Within this context, the sample is analyzed in relation to the following attributes of each paper, i.e. year of publication, document type, subject area contribution, keywords, source, author, geographic dispersion of contributors and affiliation. The first characteristic that has been considered is the year of publication, as depicted in Fig. 3. A rise on the number of publications is clearly observed from year 2006 and on, until today.

Next, the document types included in the sample were evaluated. Results indicate that approximately half the sample is composed of ‘Conference Papers’ or ‘Conference Reviews’, and the other half is composed of ‘Articles’ or ‘Reviews’, as seen in Fig. 4. This composition also underpins the immaturity of the research area.

With regard to the subject area of contribution, as expected the top five subject areas are the ones initially imposed as search criteria. It should be mentioned that ‘Engineering’ contributions account for 48% of total, constituting the dominant subject area. Results are depicted in Fig. 5. It should be noted that each document could belong into more than one area of contribution.

Next, the keywords used in the sample of publications were analyzed. In line with subject area contributions, the most frequent keywords appearing in the sample are very similar with the keywords used for the search. The two most dominant keywords are the terms ‘Ships’ and ‘Spare Parts’, followed by terms ‘Maintenance’, ‘Costs’ and ‘Repair’. Other words that appeared as keywords are

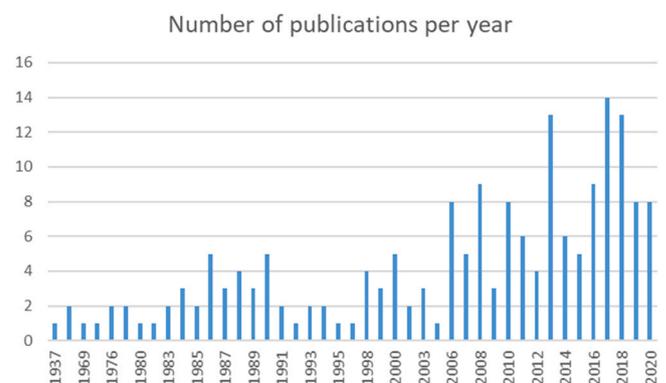


Fig. 3. Number of publications per year.

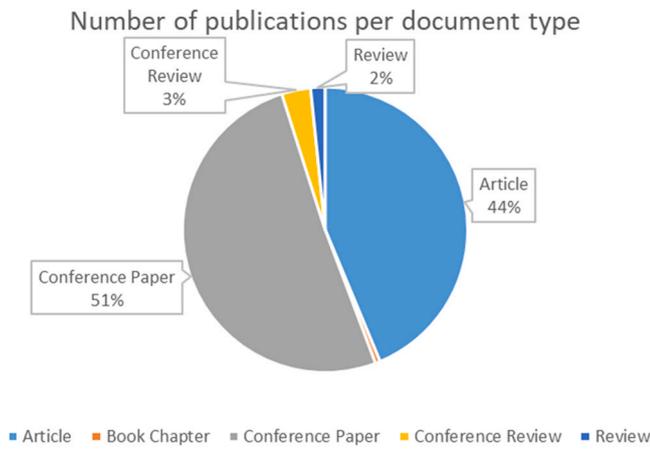


Fig. 4. Number of publications per document type.

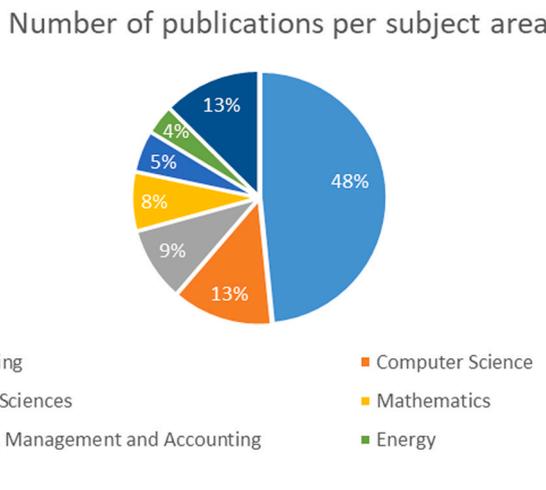


Fig. 5. Number of publications per subject area contribution.

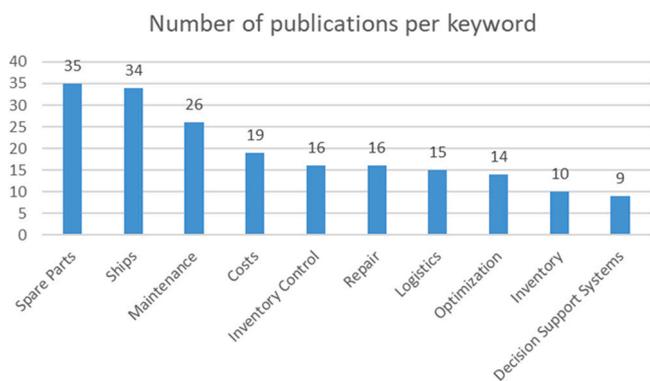


Fig. 6. Number of publications per keyword.

'Decision Support Systems', 'Inventory Control', 'Optimization' and others. It should be noted that the sample of 184 publications corresponds in 160 different keywords, however, only the 10 most used keywords are depicted in Fig. 6.

In addition, the geographic dispersion of contributing authors was examined. The results show United States having the most documents in the sample, with 31 publications in the sample, followed by Netherlands with 16 publications and China with 12 publications. The top ten (10) countries in number of publications are presented in Fig. 7.

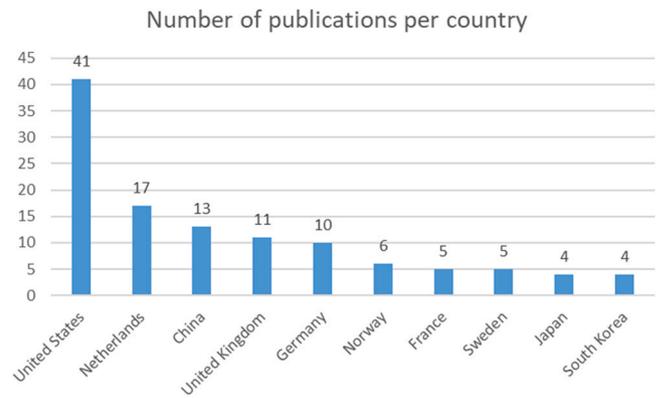


Fig. 7. Number of publications per country.

A further examination took place, with regard to the most common scientific journals and events, in which publications of the sample appear. Results show that there are only six (6) journal and events respectively, in which more than two relative studies have been published. The results are summarized in Tables 1 and 2.

Finally, an analysis of the affiliations of the retrieved documents has been performed, in order to identify the major affiliations that study the subject and contribute in the specific research area. The respective results are presented in Table 3.

4. Discussion

Following on the screening of the 184 articles that resulted from the initial search, 30 articles were selected for full text review. Subsequently, these articles have been categorized based on their main topic, in five categories, i.e. demand forecasting, inventory classification and control, logistics network design, integrated models and additive manufacturing as shown in Table 4. Demand forecasting methodologies concern the estimation for spare parts in the future and constitute the primary step for handling spare parts logistics effectively. Given the needs for spare parts, inventory control processes define which spare parts to stock, at which warehouses and in what quantities. On top of that, logistics network design is concerned with defining the number and locations of those warehouses, as well as, flexibility options such as lateral transshipments, inventory pooling, or emergency shipments. Additionally, the integrated models section includes articles combining elements from all previously mentioned three categories and proposing a holistic approach to the problem. Finally, articles illustrating additive manufacturing applications for maritime spare parts are presented, and their potential impact on the traditional logistics management approach is described in detail. In the next sections, the papers in each category are discussed separately in an attempt to highlight the current research status, existing challenges and proposals for future research in the subject area.

4.1. Demand forecasting

Unlike demand for consumer goods that arises from the behavior of an external customer, demand for spare parts arises from maintenance operations performed in capital assets. In order to perform maintenance operations, typically several resources are required such as service engineers, tools and spare parts. A large portion of maintenance operations consists of reconditioning and replacing parts of equipment. Upon failure of a system, tests are performed to isolate the failure to a specific component, called Line Replaceable Unit (LRU) and subsequently this LRU is replaced by a new functioning spare part, in the context of repair by replacement. The various maintenance policies that exist define when a specific

Table 1
Number of publications and citations per journal title.

#	Journal Title	Number of Publications	Number of Citations
1	Naval Engineers Journal	15	11
2	European Journal of Operational Research	6	36
3	Naval Research Logistics	6	71
4	Manufacturing and Service Operations Management	2	59
5	Marine Technology Society Journal	2	17
6	IHI Engineering Review (English Edition)	2	0

Table 2
Number of publications and citations per conference title.

#	Conference Title	Number of Publications	Number of Citations
1	Proceedings of the ASME Turbo Expo	5	4
2	International Journal of Production Economics	5	95
3	SAE Technical Papers	4	0
4	Proceedings of the Annual Offshore Technology Conference	4	1
5	Procedia CIRP	3	21
6	ACM International Conference Proceeding Series	3	0
7	Winter Simulation Conference Proceedings	3	26
8	Communications in Computer and Information Science	2	0
9	Applied Mechanics and Materials	2	0
10	Proceedings of the Annual Reliability and Maintainability Symposium	2	0
11	Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE	2	13
12	Safety of Sea Transportation - Proceedings of the International Conference on Marine Navigation and Safety of Sea Transportation, TRANNAV 2017	2	2
13	Annual Forum Proceedings - AHS International	2	0

Table 3
Number of publications and citations per affiliation.

#	Affiliation	Number of Publications	Number of Citations
1	Technische Universiteit Eindhoven	7	143
2	University of Twente	5	43
3	Naval Postgraduate School	4	22
4	Instituto Superior Técnico	3	26
5	Ministry of Defense, United Kingdom	3	0

component needs to be reconditioned or replaced. Inarguably the maintenance policy selection for each piece of equipment has a strong impact on the occurring demand for spare parts.

Maintenance policies can be divided into two vast categories, namely corrective maintenance (CM) and preventive maintenance (PM). CM refers to maintenance activities that take place after a component's failure. PM refers to maintenance activities that take place without the occurrence of failure and attempt to retain an item in a specified condition (Wang, 2002). PM can be further broken down to usage-based and condition-based maintenance. Usage-based maintenance is a traditional maintenance technique according to which equipment is replaced or repaired based on its usage. It should be noted that the most common technique for

measuring usage is time, and therefore usage-based maintenance is also referred to as time-based or periodic or planned maintenance. On the other hand, condition-based maintenance (CBM), can be implemented either by periodic inspections of equipment or condition monitoring. The latter is also known as predictive maintenance. More specifically, CBM with condition monitoring is a maintenance program that recommends maintenance actions based on the information collected through sensors in the system of interest (Ahmad & Kamaruddin, 2012). According to the traditional inspection, approach equipment is monitored periodically, while condition monitoring allows for continuous monitoring of the equipment. Generally, the appropriate methodology for the evaluation of the condition of equipment depends on the equipment's nature. For instance, traditionally the condition of a metal part can be evaluated by visually inspecting the number and length of cracks (Pook, 2007). Another more recent example appears in Elwany and Gebraeel (2008) who develop a sensor-driven decision model for component replacement by measuring the condition of ball-bearings via the amplitude of vibrations. Finally, CM depicts a rather outdated maintenance approach, however, in practice no matter how well structured a preventive maintenance strategy is, unpredicted component failures might still occur. A blend of methodologies, including both CM and PM elements, can enable the optimization of maintenance scheduling and improve availability of the asset by reducing downtime and maintenance costs (Tomlinson, 2015). It

Table 4
Categorization of selected articles.

Topic	Publications
Demand Forecasting	(Businger & Read, 1998); (Sampath & Singh, 2003); (Moon, Hicks, & Simpson, 2012); (Moon, Hicks, & Simpson, 2013); (Michala, Lazakis, Theotokatos, & Varelakos, 2016);
Inventory Classification & Control	(Sughayer, Attia, & Ellassal, 2017); (Willingham & Forster, 1990); (Zhou, Fan, & Li, 2010); (Goshorn, Edward, & Layton, 2010); (Jiang, Kong, & Liu, 2011); (Al Hanbali & van der Heijden, 2013); (Kiyak, Yildirim, & Tuncer, 2013); (Nenni & Schiraldi, 2013); (Wen, Fan, Jiang, & He, 2014); (Liang, Qing-min, & Ren-yang, 2016)
Logistics Network Design	(Karsten et al., 2012); (Yang, Dekker, Gabor, & Axsäter, 2013); (Brown, DeGrange, Price, & Rowe, 2017); (Sirisena & Samarasekera, 2018)
Integrated models	(Veenstra, Zuidwijk, & Geerling, 2006); (Zhao & Yang, 2017); (Eruguz et al., 2018); (Kian et al., 2018)
Additive Manufacturing	(Dalgarno, Pearson, & Woods, 2001); (Busachi, 2016); (Jha, 2016); (Proost, 2016); (Kostidi & Nikitakos, 2017); (Jovanovic, 2017); (Moreno-Sanchez, 2020)

should be noted that different items (in terms of value, criticality, reparability etc.) are usually connected to different maintenance strategies.

According to these two maintenance policies –planned and unplanned maintenance–, two streams of demand for spare parts can be distinguished. For items that are demanded in planned maintenance, timing and quantity of demand can be known in advance, and therefore demand can be considered deterministic. It is worth mentioning that demand can also be partially planned, in the case of CBM. More specifically, in the case of periodic inspection, parts that are needed in about $x\%$ of inspections for opportunistic or preventive maintenance, are termed $x\%$ -parts (Driessen, 2014). On the other hand, for items that are demanded in corrective maintenance operations, demand timing and quantities are not known in advance and therefore demand is stochastic. Apparently, using advance demand information (e.g. schedule of planned inspections) can increase the overall demand forecasting accuracy. However, it also increases the operational costs and the complexity of the project, therefore in several cases all demand might be considered as one stream of stochastic unplanned demand.

With regard to the unplanned demand problem, various techniques can be used to make forecasts. Different spare parts are associated with different underlying demand patterns, which in turn require different forecasting methods (Heinecke, Syntetos, & Wang, 2013). In order to choose the appropriate forecasting technique, firstly a demand classification should be performed. Typically, the two factors that are used for demand classification are the Average Demand Interval (ADI) and the square of the Coefficient of Variation (CV^2). Generally, demand for spare parts may be intermittent (high variation in the interval between two demand occurrences), erratic (high variation in quantity of the demand), and slow moving (low average demand quantity). Wang and Syntetos (2011) explain why demand for spare parts is intermittent. A generic review for demand classification and forecasting for spare parts can be found in (Hu, Boylan, Chen, & Labib, 2017). The variety of methods that exist for demand forecasting of spare parts may be conventionally categorized into two vast groups, namely, time-series methods and reliability-based methods.

The main advantage of time-series forecasting is that only historical data of consumption are required to predict future demand of spare parts. Generally, parametric methods occupy most of the literature for time series for spare parts demand forecasting. Additional approaches that use bootstrapping and neural networks also exist. With regards to the maritime sector, Businger and Read (1998) explore the demand forecasting techniques used by the US Navy and mention that traditionally the exponential smoothing algorithm is applied, using a quarterly time interval and a limited number of periods. Their study further explores the applicability and advantages that may occur if ARIMA modeling is used instead of the existing approach. Additionally, Moon et al. (2012) use data of the South Korean Navy to compare the performance of Simple Exponential Smoothing (SES) with several Hierarchical Forecasting (HF) methods, both Top-Down Forecasting (TDF) and Combinatorial Forecasting (CF), for predicting the demand for consumable spare parts on item level. The results of their study indicate that CF is superior to TDF and SES. Later on, Moon et al. (2013), went on developing a logistic regression classification model for predicting the performance of the alternative methods that can be used for demand forecasting for naval spare parts. However, it should be noted that both studies refer to consumable spare parts, with no zero demand occurrences, thus not intermittent.

The main disadvantage of time-series methods is that they are not based on the repair operations that cause the intermittency of the spare parts demand. Factors that may vary from one system to another, like the installed base or varying operating conditions, cannot be included directly to the forecast. It is reasonable to state

that, since demand for spare parts for corrective maintenance arises due to some kind of failure of equipment, forecasting demand is equivalent to forecasting failures. A recognition of this fact results to reliability-based forecasting (Arts, 2013). Reliability-based techniques use reliability and maintenance characteristics to provide forecasts for the demand of spare parts. Characteristics that may be used in reliability-based methods are the failure rate of the component, the size and age of the installed base (Dekker, Pinçe, Zuidwijk, & Jalil, 2013) and the operating conditions (Barabadi, 2012). It should be noted that the failure rate of a component, can be either given by the spare parts manufacturer, or be calculated by recording the part failures. However, in the maritime sector there is a shortage of historical failure related data, making the implementation of solely reliability-based methods challenging. Xu, Qian, Hu, and Dandan (2014) collect data on past failures of a component of a ship and perform demand forecasts by using Weibull's model of reliability analysis. Their study concludes that Weibull's model allows to determine the expected number of failures for a component in a period $[0,t]$, which is essentially equivalent to the expected required number of spare parts. Additional information on Weibull's model for spare parts demand forecasting that is used in their study can be found on (Kontrec & Panic, 2017). Nevertheless, reliability-based methods for demand forecasting may lead in excessive demand forecasts and stock keeping, if the individual failure rates of the components are considered (instead of the failure rate of a complete system), without considering the system redundancies.

Apart from time series and reliability-based demand forecasting, it should be noted that especially for components with intermittent nature with a large proportion of zero values in the demand pattern, condition monitoring techniques can provide substantial input on when the next non-zero demand will occur. It is widely acknowledged, that the use of CBM has the potential to decrease both inventory and downtime costs, meaning that maintenance and inventory replenishment decisions can be updated dynamically. Being able to predict next non-zero demand for a critical component is of key importance for maritime assets, as these generally operate in remote locations with limited storage space on board. Sampath and Singh (2003) present the development of a predictive maintenance model for gas turbine propelled naval ships and mention that prediction of failure assists in procuring the required spare parts in time. Michala et al. (2016) present a methodology for wireless condition monitoring of machinery and equipment on board a vessel. Off-line and real time measurements are combined allowing for the calculation of failure rates (λ), Mean Time Between Failures (MTBF) and Probability of Failure (PoF). By predicting time to failure, which is equivalent to the next demand occurrence for a component, this approach allows for better maintenance planning and spare part scheduling.

Finally, as already mentioned, maritime spare parts include a large portion of repairable items. Repairable items upon replacement from an LRU, are offloaded and returned to repair workshops where they are repaired. Therefore, it is essential to also perform forecasts for the rate of returns of repairable items. Apparently, these forecasts can be performed with time series techniques and use of historical data of returned repairable items. With regard to the reliability-based techniques, it should be noted that a part has several failure modes and a failure rate is associated with each failure mode (Ebeling, 1997). Not all failure modes of a repairable spare part correspond to a parts return; the part may also have a non-repairable failure, that requires it to be scrapped. It should be noted that the authors were not able to locate any studies relative to this particular challenge.

4.2. Inventory classification & control

Any inventory management system aims in achieving a desired service level with minimum inventory investment and administrative

cost (Huiskonen, 2001). In general, inventory classification aims in achieving administrative efficiency for the handled items of any inventory management system. Conventional inventory classification methods that are traditionally used for finished products, such as ABC analysis, in most of the cases only consider unit price and demand quantity. Nevertheless, spare parts incorporate several distinctive characteristics other than price and demand quantity, and require a rather multi-criteria classification technique in order to discriminate all the control requirements of different types of items. Roda, Macchi, Fumagalli, and Viveros (2014) state that distinctive characteristics that should be considered for item classification, include part's criticality (economic, environmental, and safety consequences of a part's failure), usage (demand quantity, demand variability, and redundancy), inventory (price, space required, and obsolescence rate) and supply characteristics (replenishment lead time, supplier availability, risk of no supply, and part specificity).

With regard to the maritime industry, Hmida, Regan, and Lee (2013) propose a multi-criteria inventory policy using an inventory classification method integrated with a preventive maintenance program, to solve the inventory management problem for spare parts at an offshore vessel company. To achieve this, they classify the various existing spare parts according to the vendor lead times and the cost of downtime in case of failure. This results in identifying each item's criticality and, subsequently developing a preventive maintenance program for the most critical parts and reducing inventory levels for non-critical parts. Sughayer, Attia & El-Assal (2017) present a management approach for spare parts of fire and rescue vessels, which relies on spare parts criticality classification according to a set of predefined criteria. Additionally, the application of the proposed approach is presented in a case study carried out in fire and rescue vessels in the Kuwait Fire Service Directorate.

It is evident that existing works relative to inventory classification for maritime spare parts, focus on criticality as a classification characteristic. Employing the lead time of the component as a classification criterion is reasonable, since delivery lead times are volatile. Nevertheless, there are several other characteristics that may be used as criteria for inventory classification. For instance, maritime spare parts incorporate a large variability in terms of value, weight and dimensions. Since for each component there is a limited number of specialized suppliers, another characteristic that may be worth further exploring is the location of the supplier.

Various organizations in capital intensive industries, both on the commercial and military side, have investigated the use of more sophisticated methods of inventory management, namely system approaches as opposed to the conventional item approaches (Rustenburger, Houtum, & Zijm, 2000). While standard inventory systems aim in high availability of individual items, sophisticated inventory systems for spare parts aim on high system availability. The handicap of item-oriented systems is that although high individual service levels may be obtained for individual items, the overall availability of the system that is composed of these items may still remain relatively low. This means that an item-oriented approach may lead to excessive stock, without a respective improvement in the system's availability. Following a system approach allows to obtain a clear view on the relationship between inventory investment and achieved system availability. A review of models and literature on system-oriented inventory management for spare parts can be found on (Basten & Houtum, 2014).

A distinction should be made between keeping stock of spare parts on board a vessel, and keeping stock of spare parts on shore, in warehousing facilities. Ideally all needed stock should be kept on board the vessel, in order to avoid additional delivery costs, stock outs and time delays. Nevertheless, this is not feasible. On the one

hand the space on board a vessel is limited, and on the other hand spare parts kept on board in varying and unpredictable environments may wear out. Defining the type and quantities of spare parts that should be carried on board constitutes a very challenging exercise. This results in all supply chain networks for maritime spare parts having at least a two-echelon structure, with one central echelon being the inventory on shore and a second echelon of moving "local warehouses" on board the vessels.

An early study on the problem of defining the type and quantities of carrying spare parts is presented by Willingham and Forster (1990). They present a case study in the environment of US Navy, concerning a complex naval radar. In their study a system approach is followed, aiming in achieving a certain system availability for the entire radar system, with the minimum quantity of spare parts on board in terms of cost. They propose that savings up to 50% can be obtained in comparison to following an item approach, taking into account MTBF of individual components. A more recent study on the carrying spare parts problem is presented by Zhou et al. (2010), who explore what is the optimal inventory on board a vessel under different maintenance policies, namely corrective, preventive and predictive maintenance, while following an item approach. Goshorn, Edward, Deegan Jr, Layton and Bradley (2010) discuss the problem of carrying spare parts for a naval vessel that is on a patrol with duration in range from 2 weeks to 6 months, while also following an item approach. In their study they define the optimal quantities of carrying spare parts based on MTBF and patrol length, aiming in a certain service level for individual components. In addition, Jiang et al. (2011) propose a multi-weighted optimization model, based on the theory of multi-objective programming and law of diminishing marginal returns, to find the optimum size of inventory of spare parts on board for a long voyage vessel. More specifically, in their study the storage of each spare part on board is considered as a decision variable with the respective service level being the objective function and various restrictions exist relative to spare part's volume, weight and cost. Proposed solution optimizes the storage to obtain the predetermined service level for each variable within certain constraint conditions. Kiyak et al. (2013) consider the problem of defining the optimum quantities of carrying spare parts for a warship and provide a solution by applying a genetic algorithm. Their study also follows an item approach and factors considered to provide the optimal solution are unit price, criticality, demand quantity, maximum replacement unit of parts and total available quantity on board. An additional approach on the carrying spare parts problem is provided by Liang et al. (2016). They provide a model specifically for equipment with long storage time and short service time and focus on the optimization of storage availability on board. Another study that follows a system approach on the carrying spare parts problem is provided by Nenni and Schiraldi (2013). They propose a methodology for the optimization of the initial level of spare parts inventory for a ship, considering a system structure with three indentation levels and the fact that a spare part may be used in several different subsystems (e.g. bearings). In their study, the optimal solution is obtained through a heuristic procedure and a case study carried out on a tanker is presented.

Some additional studies on the inventory control problem consider a simple logistics network consisting of two echelons, with one echelon being the carrying spare parts and one echelon being a warehouse onshore. Al Hanbali and van der Heijden (2013) consider the problem from the perspective of a supplier who operates under a service contract with its customer, inspired by a business case of a naval sensors and naval command and control systems manufacturer. In their study, they analyze the interval availability of two-echelon, multi-item repairable spare parts inventory systems. In addition, Wen et al. (2014) consider a Joint Inventory Management

(JIM) environment for a number of dredging vessels and a supplier. In their study, a two-echelon model is provided, with one echelon being the stock on board and one echelon being the supplier of a specific spare part. In that context, the optimal inventory for each echelon is calculated using a random demand - random lead time model.

Generally, literature on spare parts inventory management suggests that system-oriented approaches yield better results than item-oriented ones. Nevertheless, system-oriented approaches are significantly more difficult to deploy, due to the complexity that is incorporated in technical systems of maritime assets. The inventory control topic, and more specifically the problem of defining carrying spare parts types and quantities, is definitely the topic on which literature examined in this review focuses the most.

Another important characteristic of spare parts that should be considered for the inventory control problem, is that a large portion of spare parts handled in the maritime industry are repairable. The major methods that exist for inventory control of repairable items are the METRIC method and its variations. METRIC is a method of determining base and depot stock levels for a group of repairable items, that participate in a multi-indenture structure and it has originally been developed by [Sherbrooke \(1968\)](#). Various modifications of the METRIC method exist ([Sherbrooke, 1986](#)). With regard to models referring specifically to the maritime sector, [Rustenburg, van Houtum and Zijm \(2000\)](#) discuss the problem of setting spare parts levels during the initial supply phase for a frigate in the environment of the Royal Netherlands Navy, under limited budget constraints and discuss in depth the VARI-METRIC approach. In addition, they identify the shortcomings of the model, since it cannot cope with specific issues faced in the maritime sector. These issues include the concept of criticality, condemnation of repairable spare parts and existence of consumable spare parts, as well as, the non-continuous resupply phenomenon. Additionally, they suggest a number of extensions to make it suitable for use through exploitation period of the vessel as well. In their study, an infinite repair capacity is assumed. Later on, [Sleptchenko, van der Heijden, and van Harten \(2003\)](#) include the repair capacity of the repair shops as a constraint. They present a procedure for simultaneous optimization of inventory levels of repairable items and repair capacity of workshops in a naval logistic environment, based on a modification of the VARI-METRIC method. Subsequently, [Sleptchenko, van der Heijden, and van Harten \(2005\)](#) went on to examine the impact of the assignment of repair priorities in spare part networks, whereas in former studies a First Come First Served (FCFS) rule is used.

4.3. Logistics network design

In the maritime sector, and especially for ocean going vessels that trade worldwide, the structure of the logistics network is crucial. Selected suppliers and warehousing facilities have to be located in agreement with the vessel's trading pattern, so delivery of spare parts on board is feasible without excessive costs. Within that context, [Sirisena and Samarasekera \(2018\)](#) develop a model to identify the optimum location for a vessel spare parts distribution hub. To achieve this, they use a mixed research approach, where both qualitative and quantitative data are collected. Interviews with industry professionals and survey questionnaires are used as the main data sources, while the Analytical Hierarchy Process (AHP) and Factor Rating Method are used as data analysis tools to derive the best location. [Brown, DeGrange, Price and Rowe \(Brown et al., 2017\)](#) present a different approach on the problem, as implemented in the environment of US Navy. They present the case of US Navy which has a worldwide fleet of special replenishment ships dedicated to supply its warships with all types of needed resources, including spare

parts. In their article, they solve the occurring scheduling problem for the replenishment ships with integer linear optimization and a purpose-built heuristic.

In order to further reduce holding and downtime costs, certain flexibility options such as lateral transshipment, inventory pooling, or emergency shipments ([Eruguz et al., 2017](#)) can be incorporated in the design of the logistics network. With regard to the lateral transshipment practice, [Yang et al. \(2013\)](#) argue that in equipment-intensive industries, such as in the dredging industry, spare parts are often slow-moving items for which the transshipment time is not negligible. In their study, a customer-oriented service measure which considers pipeline stock and lateral transshipment flexibility, is presented. [Karsten, Slikker and Houtum \(2012\)](#) consider the generic situation of several independent decision makers who stock expensive, low-demand, repairable spare parts for their high-tech machines, who can collaborate by full pooling of their inventories via free transshipments. The characteristics of maritime spare parts completely match this description. They examine the stability of such pooling arrangements, and address the issue of fairly distributing the collective holding and downtime costs over the participants, by applying concepts from cooperative game theory. Based on the above, one can argue that in the maritime sector, and especially in the tramp market of ocean-going vessels, pooling of spare parts based on the trading region, can become of strategic significance. Trading routes for merchant vessels are fixed under certain time periods, following the pattern of the commodities they carry, resulting in high traffic in certain ports. With this in mind, it is reasonable to state that shipping companies could derive great benefits in terms of expenditure, by implementing such a scheme.

Research efforts discussed in this section mainly focus on flexibility options incorporated in the logistics network. More effort should be put on the direction of addressing facility location problems, such as ([Sirisena & Samarasekera, 2018](#)), given the worldwide operating locations of maritime assets and suppliers of spare parts. Additionally, transportation scheduling of spare parts and selection of the mode of transport is closely related to the network structure and resulting costs. Since the routing of a maritime asset may be variable, different modes of transport may need to be used, in order to achieve inventory replenishment within a certain time-window. Surprisingly, no published work has been found, regarding models for transportation for maritime spare parts. Nevertheless, similar studies do exist for other capital-intensive industries, indicatively for automotive ([Kargari & Sepehri, 2012](#)) or railway ([Lin, 2017](#)).

4.4. Integrated models

Studies presented in previous sections discuss specific aspects of maritime spare parts supply chain management, like demand forecasting, inventory classification, inventory control and network design, but neglect the interconnections between those aspects. On the contrary, integrated approaches, such as joint optimization of maintenance and spare parts inventory, generally yield significantly better results than approaches focusing on the optimization of a single aspect of the problem ([Horenbeek, 2013](#)).

With regard to the maritime industry, [Veenstra et al. \(2006\)](#) consider the maintenance management of a dredging vessel and explore the logistic consequences of the implementation of different maintenance policies. To achieve this, they deploy a simulation model for a clearly identifiable component in a dredging vessel and the related spare parts supply chain. Various maintenance policies are analysed for their impact on the spare part supply chain in terms of stock keeping, order fulfillment and productivity of the asset.

With the ever-expanding spread of CBM with condition monitoring in the maritime sector, relevant studies that present

integrated supply chain decision models under a CBM strategy have been carried out. Given that such a maintenance strategy in most of the cases is implemented in critical and high value equipment, these studies deal with emergency deliveries of spares. Zhao and Yang (2017) consider a vessel operating on a standard route, given as a sequence of port visits, under a CBM environment. For the case that a failure warning occurs, they propose a bi-objective optimization model aiming to simultaneously minimize maintenance costs and maximize vessel's reliability. Maintenance cost is defined as the sum of costs for fuel consumption, renting extra vessels, shipping delay penalties and spare parts inventory. Vessel's reliability is depicted as the reliability of the vessel's main engine and is calculated according to a wear model. The bi-objective model is solved with a non-dominated sorting genetic algorithm. The solution of the problem results in deciding in which port, spare parts delivery and maintenance activities should be carried out. Later on, Kian et al. (2018) consider the same problem and formulate it as a mathematical programming model. A shortest path dynamic programming formulation is presented, for a single component, which solves the problem in polynomial time complexity. In subject study, it is assumed that if failure occurs at sea, the vessel can still operate but with decreased performance, which will result in delay penalty costs. Delivery costs and lead times fluctuate between different ports, which efficiently depicts the geographically dispersed locations of ports and suppliers. However, a liner shipping environment is assumed, where the schedule of the vessel is fixed and known in advance. Assuming a naval or tramp trade environment, would further increase the complexity of the problem.

Eruguz et al. (2018) consider the integrated problem of inventory and maintenance optimization. They also consider a critical component for which the degradation level is observable, and can be modeled as a function of the operating mode. The operating mode is defined as a random variable that represents the location of a moving asset, the usage of the component and the environmental conditions. It should be noted that considering the operating mode a random variable, meaning randomness in sequence and duration of operating modes, allows a much more realistic depiction for maritime assets without fixed routings. They propose a Markov decision process formulation for the integrated maintenance and spare parts optimization problem. Within that context, the degradation level of a component, the operating mode of the moving asset and the number of replacement parts on board are modeled as Continuous-Time Markov Chains. Finally, the structure of the optimal inventory policy (keeping stock of a component on board or order just-in-time) is derived, which is an operating mode dependent bi-threshold policy.

Studies discussed in this section follow an integrated approach on the maritime spare parts logistics problems and are considerably more sophisticated. Undeniably, the ever-increasing use of CBM with condition monitoring is an important facilitator for more efficient supply chain decisions. It is reasonable to state that future research should focus in the direction of considering the moving asset characteristic, in combination with supply chain decisions. A large portion of maritime assets operates in unpredictable and globally scattered locations. Future integrated models on this area should incorporate this characteristic, as this is the main differentiator of the maritime from other capital-intensive industries.

4.5. Potentially disruptive technologies: additive manufacturing

A considerable portion of the sample resulting from the initial search examines the concept of AM applications for maritime spare

parts and the impact of such applications on the traditional supply chain management for maritime spare parts. Such applications, if widely implemented, are going to greatly disrupt the traditional supply chain management for maritime spare parts, and for this reason it is considered appropriate to further discuss relative articles in this study. AM techniques have been implemented in the supply chains of several sectors in the recent years, including the maintenance supply chains of capital-intensive industries such as automotive, aviation and defense. AM is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" as per standard ASTM F2792. A general review on status, challenges and future of AM can be found at Gao (2015).

With regard to the maritime sector, an early case study in the UK Navy as presented in (Dalgarno et al., 2001), underlines the importance of rapid manufacturing for spare parts supply chain management. Later on, various works discuss the potential of 3D printing for spare parts in the maritime sector. The study of Jha (2016) mentions that the use of 3D printing for spare parts, will drastically simplify their complex supply chain management and as a result reduce the large inventory costs. Additional articles that explore the potential of 3D printing for maritime spare parts are (Kostidi & Nikitakos, 2017) and (Proost, 2016). Busachi (2016) provide a military perspective on the same topic. Despite the fact that the application of 3D printing for maritime spare parts is still on trial phase, mentioned works indicate a clear trend. In that direction, several initiatives and pilot projects exist that consider the use of AM for the manufacturing of maritime spare parts, both from the commercial and the military side.

With regard to military initiatives, the 'Print the Fleet' program initiated by US Navy in 2013, aims in selecting, building and delivering spare parts for the war fighter by AM techniques, as well as, training non-engineers in the use of 3D printers (Naval Sea Systems Command, 2013). For that purpose, a multidisciplinary team of engineering and education faculty has developed a series of workshops to train on-duty sailors in designing, testing, reverse engineering, and printing parts needed for their daily operations (Jovanovic, 2017). Scheck (2016) state that AM implementations can beneficially impact total ownership cost, operational availability and war fighter readiness.

With regard to commercial initiatives, in 2016, the Port of Rotterdam and Innovation Quarter with the participation of 28 other businesses, initiated a pilot project named '3D Printing Marine Spares'. Within the scope of this project seven selected metal maritime spare parts were redesigned and manufactured using different AM techniques. More specifically, the selected parts included a propeller, a cooled valve seat, a spacer ring, a hinge, a T-connector, a seal jig, and a hydraulic manifold. These parts were subsequently tested in terms of surface, geometric, mechanical and material requirements (Port of Rotterdam Authority, 2016). The "3D printing in the maritime industry" project explores the opportunity space of 3D printing in the maritime industry, while at the same time raises the awareness and level of knowledge about additive manufacturing within the industry (Green Ship of the Future, 2016). Within the scope of this project real applications were tested regarding 3D printing on board for commercial vessels, as well as, repair and re-conditioning (Green Ship of the Future, 2018). It is worth mentioning that TruMarine, a company with turbocharger reclamation expertise has developed proprietary processes in 3D printing and offers nozzle ring repairs by layer-wise building which enables reconstructing worn out areas directly onto the original component (TruMarine, 2015). A recent conference paper presents a study carried out using

platforms that simulate vibrations produced in a naval vessel environment and explore the feasibility of the project (Moreno-Sanchez, 2020).

The application of AM is not as wide-spread in the maritime sector as it is in other similar industries (e.g. aviation) and research is still immature. A major challenge for the application of AM for the production and repair of maritime spare parts is the reluctance of regulating organizations to recognize and approve them. Additionally, AM technology is still costly and its purchase should only be considered when the demand for printed parts can be aggregated. For the scenario of 3D print on board, the human element might be the most crucial factor and the ship owner will have to invest in ensuring the needed competences for the crew on board. More research is required in this direction for these scenarios to become commercially viable in the future.

Be that as it may, it should be noted, that the use of 3D printing for the manufacturing of maritime spare parts, if commercially implemented in the future, would be a game changer and disrupt the traditional spare parts maritime supply chain. AM allows for local and on demand production of spare parts in any point of the traditional supply chain and closer to point of use, such as local vendors, intermediate hubs, ports or even on board. It should be noted that such a scenario is going to also have a great impact on the sea port industry, as port facilities may also serve as 'print farms' for maritime spare parts. Localization of the production is going to be accompanied by significant benefits such as shorter delivery times for requested parts, as well as, lower transport and customs costs. Additionally, on demand production allows for decreased inventory, as well as production of spare parts that are obsolete or highly customized, which will result in possibility of solving the obsolescence and cannibalism issues. Apart from the obvious supply chain benefits that derive from the use of AM, some additional benefits occur due to the changes in product design. AM techniques allow for the creation of complex geometries with integrated functionality (e.g. cooling channels). This characteristic can result in reduced need for assemblies of multiple parts, less processing stages, weight reduction through topology optimization, as well as, less waste in comparison to conventional subtractive processes. These characteristics can indirectly further simplify and enhance spare parts supply chain operations. Undeniably there is a strong trend for further research in this direction, as the resulting advantages can greatly enhance the competitive edge of maritime firms.

5. Conclusions

Efficient supply chain and logistics management for maritime spare parts is undeniably a complex discipline that poses a significant challenge for any company operating in the industry. The review provided in this paper summarized existing relative literature by presenting the current methodologies and applications in supply chain and logistics management for spare parts in the maritime industry. More specifically, the examined articles were relative to traditional supply chain and logistics topics, namely, demand forecasting, inventory classification, inventory control, logistics network design, integrated models, as well as, emerging technologies, more specifically, additive manufacturing. Within that context the major challenges that the maritime industry faces were identified. Thus, the review provided in this paper fulfilled the initially stated research questions. A major challenge identified by this review, is the scarcity of failure related data for maritime equipment. As discussed, this fact has a strong impact in the research efforts in the area of demand forecasting, and in combination with the fact that maritime assets operate in varying and unpredictable

environments, renders demand forecasting challenging. Nevertheless, the ever-increasing use of condition monitoring in the maintenance of maritime equipment has the potential to significantly impact models developed to address this issue. More efforts have been made on the inventory classification and control areas. A second significant challenge that has been acknowledged in this review is the design of the logistics network. Global locations of supply along with the moving asset characteristic result in logistics networks incorporating high uncertainty and costs. Defining number and locations of echelons is of paramount importance, as it strongly affects the responsiveness of the logistics network and forms the resulting transportation costs. Given the high volatility of the maritime business, embodying flexibility characteristics in the logistics network, such as inventory pooling, lateral transshipments and emergency shipments is deemed to be critical. The authors strongly believe that more research is needed towards this direction, and especially regarding the transportation scheduling problem, a sub-domain for which -surprisingly- no studies have been identified. Works presenting integrated approaches on the problem are expected to develop, along with research on the individual subdomains they include. With regard to the potential of additive manufacturing on disrupting the traditional supply chain approach, technology is still immature for application in large scale and real environments. Nevertheless, additive manufacturing remains a very promising breakthrough that is going to significantly affect the supply chain management of maritime spare parts, in the near future.

This review paper aspires to have an impact on both the academia and the industry. On the one hand, supply chain and logistics management for maritime spare parts has received little attention in the academic literature. Relative articles discussed in this review originate from a wide spectrum of different organizations and disciplines, which results in presenting very different perspectives on the challenge. Approaches from liner shipping, military operations and the dredging industry were examined, from the perspective of the supplier of the equipment, the asset owner or the system integrator, providing in that way a holistic view on the existing challenge. Hence, this review aims to provide a solid foundation for further future research efforts directed towards this area. At the same time, the authors expect this review to also have an impact on the industry. Most of the companies in the maritime business have a rather traditional and outdated approach to supply chain management for spare parts, and seem reluctant to test and adopt more sophisticated approaches to address these issues. In that context, this review also aims to provide industry managers and practitioners, with the state of the art on this area and encourage them to maybe follow more advanced methodologies. In that way, significant improvements in the spare parts supply chain management can be achieved, contributing in improving the overall efficiency of a maritime company.

This study has potential limitations. A major potential limitation of this study that should be mentioned, is the inconsistency in used terms among researchers and industry practitioners to refer on this topic, which may potentially result in a nonrepresentative sample. A conscious effort was made in forming a search string that leads to an inclusive search, resulting in search results comprising of all relative existing literature. Additional research limitations occur due to the selected search database and language. Working on this review authors concluded that research in the sector of maritime spare parts supply chain management is still immature and rather unstructured, with the little published works that exist being mostly case specific. Hence, more studies suggesting more generalized approaches and applications should be welcomed by the research community in the future. The authors plan to further explore the

area of transportation scheduling for maritime spare parts, and more specifically the case of merchant vessels operating in tramp market, aspiring to address the earlier identified research gap.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

None. No funding to declare.

References

- Ahmad, R., & Kamaruddin, S. (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering*, 63, 135–149.
- Al Hanbali, A., & van der Heijden, M. (2013). Interval availability analysis of a two-echelon, multi-item system. *European Journal of Operational Research*, 494–503.
- Arts, J. J. (2013). *Spare Parts Planning and Control for Maintenance Operations*. Eindhoven: Technische Universiteit Eindhoven.
- Barabadi, A. (2012). Reliability and spare parts provision considering operational environment: A case study. *International Journal of Performability Engineering*, 8(5), 497–506.
- Basten, R., & Houtum, V. (2014). System-oriented inventory models for spare parts. *Surveys in Operations Research and Management Science*, 19, 34–35.
- Brown, G., DeGrange, W., Price, W., & Rowe, A. (2017). Scheduling combat logistics force replenishments at sea for the US Navy. *Naval Research Logistics*, 677–693.
- Busachi, A., et al. (2016). *Defining Next-Generation Additive Manufacturing Applications for the Ministry of Defence (MoD)*, 302–307 (s.l., s.n.).
- Businger, M. P., & Read, R. R. (1998). Identification of demand patterns for selective processing: a case study. *Omega*, 189–200.
- Clarkson Research Studies, 2004, *The Tramp Shipping Market*, s.l.: Clarkson Research Studies.
- Clarksons Research, 2018, *Shipping Review and Outlook*, s.l.: Clarksons Research.
- Dalgarno, K. W., Pearson, M. A., & Woods, M. (2001). The UK Navy RAMP Project: Improving the spares provisioning process through the rapid acquisition of manufactured parts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 283–296.
- Dekker, R., Pinçe, Ç., Zuidwijk, R., & Jilil, M. (2013). On the use of installed base information for spare parts logistics: A review of ideas and industry practice. *International Journal of Production Economics*, 143, 536–545.
- Driessen, M., et al. (2014). Maintenance spare parts planning and control: A framework for control and agenda for future research. *Production Planning and Control*, 407–426.
- Ebeling, C. E., 1997, *An Introduction to Reliability and Maintainability Engineering*, s.l.: Waveland Pr Inc.
- Elwany, A., & Gebraeel, N. Z. (2008). Sensor-driven prognostic models for equipment replacement and spare parts inventory. *IIE Transactions*, 629–639.
- Eruguz, A. S., Tan, T., & van Houtum, G. (2018). Integrated maintenance and spare part optimization for moving assets. *IIE Transactions*, 230–245.
- Eruguz, A. S., Tan, T., & van Houtum, G. J. (2017). A survey of maintenance and service logistics management: Classification and research agenda from a maritime sector perspective. *Computers & Operations Research*, 184–205.
- Gao, W., et al. (2015). The status, challenges, and future of additive manufacturing in engineering. *Comput Aided Des*, 65–89.
- Goshorn, J., Edward, M. D. J., & Layton, E. B. (2010). Spare Part Storage Optimization Onboard Deployable Military Support Assets. *Naval Engineers Journal*, 137–147.
- Green Ship of the Future, 2016, *The opportunity space of 3D print in the maritime industry*, s.l.: Green Ship of the Future.
- Green Ship of the Future (2018). *3D print the maritime industry: from concept to implementation*. Copenhagen: Green Ship of the Future.
- Guide, V., & Srivastava, R. (1997). Repairable inventory theory: Models and applications. *European Journal of Operational Research*, 102, 1–20.
- Heinecke, G., Syntetos, A., & Wang, W. (2013). Forecasting-based SKU classification. *International Journal of Production Economics*, 455–462.
- Hmida, J., Regan, G., & Lee, J. (2013). Inventory management and maintenance in offshore vessel industry. *Journal of Industrial Engineering* Article 851092 (p. Article ID).
- Horenbeek, A., et al. (2013). Joint maintenance and inventory optimization systems: A review. *International Journal of Production Economics*, 143, 499–508.
- van Houtum, G., & Kranenburg, B. (2015). *Spare Parts Inventory Control under System Availability Constraints*, s.l.: Springer.
- Hu, Q., Boylan, J., Chen, H., & Labib, A. (2017). OR in spare parts management: a review. *European Journal of Operational Research*, 395–414.
- Huiskonen, J. (2001). Maintenance spare parts logistics: Special characteristics and strategic choices. *International Journal of Production Economics*, 71, 125–133.
- International Chamber of Shipping, 2018, (<http://www.ics-shipping.org>). [Online] Available at: (<http://www.ics-shipping.org>).
- Jha, S. (2016). Emerging technologies: Impact on shipbuilding. *Maritime Affairs Journal of the National Maritime Foundation of India*, 78–88.
- Jiang, C., Kong, M., & Liu, M., 2011, *Research on the storage scheme of spare parts for long voyage vessel*, s.l., s.n., pp. 1173–1178.
- Jovanovic, V. et al., 2017, Active duty training for support of navy's additive manufacturing strategy. Columbus, Ohio, s.n., pp. 1–12.
- Kargari, M., & Sepehri, M. (2012). Stores clustering using a data mining approach for distributing automotive spare-parts to reduce transportation costs. *Expert Systems with Applications*, 4740–4748.
- Karsten, F., S. M., & Houtum, G. (2012). Inventory pooling games for expensive, low-demand spare parts. *Naval Research Logistics (NRL)*, 311–324.
- Kian, R., Bekta, T., & Ouelhadj, D. (2018). Optimal spare parts management for vessel maintenance scheduling. *Advances in Theoretical and Applied Combinatorial Optimisation*, 323–353.
- Kiyak, E., Yildirim, M. & Tuncer, A., 2013, *Stock optimization of spare parts with genetic algorithm*, s.l., s.n., pp. 19–23.
- Kontrec, N. & Panic, S., 2017, Spare Parts Forecasting Based on Reliability. In: *System Reliability*, s.l.:s.n., pp. 113–127.
- Kostidi, E. & Nikitakos, N., 2017, *Exploring the potential of 3D printing of the spare parts supply chain in the maritime industry*, s.l., s.n., pp. 171–178.
- Liang, Z., Qing-min, L. & Ren-yang, L., 2016, *Optimal Inventory Control of Spare Parts Based on Storage Availability*, Yinchuan, s.n., pp. 6409–6414.
- Lin, B., et al. (2017). Inventory-Transportation integrated optimization for maintenance spare parts of high-speed trains. *PLoS ONE* Article e0176961 (p. Article number).
- Michala, A., Lazakis, I., Theotokatos, G. & Varelas, T., 2016, *Wireless condition monitoring for ship applications*. London, UK, s.n.
- Moon, S., Hicks, C., & Simpson, A. (2012). The development of a hierarchical forecasting method for predicting spare parts demand in the South Korean Navy. *International Journal of Production Economic*, 140, 794–802.
- Moon, S., Hicks, C., & Simpson, A. (2013). The development of a classification model for predicting the performance of forecasting methods for naval spare parts demand. *International Journal of Production Economics*, 449–454.
- Moreno-Sanchez, D. et al., 2020, On board additive manufacturing of spare parts for the naval sector, s.l., s.n., pp. 75–81.
- Naval Sea Systems Command, 2013, *Warfare Centers: NSWC Dahlgren*. [Online] Available at: (<https://www.navsea.navy.mil/>).
- Nenni, M., & Schiraldi, M. (2013). Optimizing spare parts inventory in shipping industry. *International Journal of Engineering and Technology*, 3152–3157.
- Pook, L. (2007). *Metal Fatigue: What It Is, Why It Matters*, s.l.: Springer Science & Business Media.
- Port of Rotterdam Authority (2016). *Pilot project: 3D Printing Marine Spares*. Rotterdam: Port of Rotterdam Authority.
- Proost, J., 2016, Printing metal spare parts: At a former shipyard in Rotterdam. *Maritime by Holland*, December, pp. 68–70.
- Roda, I., Macchi, M., Fumagalli, L., & Viveros, P. (2014). A review of multi-criteria classification of spare parts: From literature analysis to industrial evidences. *Journal of Manufacturing Technology Management*, 528–549.
- Rustenburg, W., Houtum, G., & Zijm, W. (2000). Spare parts management at the Royal Netherlands Navy: vari-metric and beyond. *IIE Transactions*, 1013–1026.
- SamPATH, S., & Singh, R. (2003). *Managing Maintenance and Operational Availability of Gas Turbine Propelled Naval Ships Through Advanced Engine Fault Diagnostics*. Atlanta, Georgia: ASME, 473–481.
- Scheck, C., et al. (2016). Naval additive manufacturing: improving rapid response to the Warfighter. *Naval Engineers Journal*, 128, 71–75.
- Sherbrooke, C. C. (1968). Metric: a multi-echelon technique for recoverable item control. *Operations Research*, 16, 122–141.
- Sherbrooke, C. C. (1986). VARI-METRIC: improved approximations for multi-indenture, multi-echelon availability models. *Operations Research*, 34, 190–330.
- Siddaway, A., Wood, A., & Hedges, L. (2019). How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. *Annual Review of Psychology*, 747–770.
- Sirisena, H. & Samarasekera, N., 2018, *Vessel Spare Parts Distribution Center Location Decision Model for Ship Maintenance Supply Chain*, s.l., s.n., pp. 185–190.
- Sleptchenko, A., van der Heijden, M., & van Harten, A. (2003). Trade-off between inventory and repair capacity in spare part networks. *Journal of the Operational Research Society*, Volume 54, 263–272.
- Sleptchenko, A., van der Heijden, M., & van Harten, A. (2005). Using repair priorities to reduce stock investment in spare part networks. *European Journal of Operational Research*, 163, 733–750.
- Sughayer, Z., Attia, E., & Ellassal, A. (2017). *Spare Parts Classification in Marine Rescue and Fire Services' Stores with Case Study*. Dubai, United Arab Emirates: Association for Computing Machinery, 100–106.
- Tomlinson, N., 2015, *What is the ideal maintenance strategy? A look at both MoD and commercial shipping best practice*, s.l.: BMT Defence Services.
- TruMarine, 2015, *Tru-Marine's World's First 3D Printed Turbocharger Nozzle Ring Offers Breakthrough Resolution of Common Erosion Problems*. [Online] Available at: (www.trumarine.com/).

- Turan, O., et al. (2009). Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage. *Ships and Offshore Structures*, 4(2), 107–125.
- United Nations Conference on Trade and Development (2017). *Review of Maritime Transport 2017*. s.l.: UNCTAD.
- Veenstra, A., Zuidwijk, R. & Geerling, B., 2006, *Maintenance logistics in the Dutch Dredging Industry*. s.l., s.n., pp. 436–441.
- Wagner, S. M., Jönke, R., & Eisingerich, A. B. (2021). A Strategic Framework for Spare Parts Logistics. *California Management Review*, 69–92.
- Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research*, 139, 469–489.
- Wang, W., & Syntetos, A. (2011). Spare parts demand: Linking forecasting to equipment maintenance. *Transportation Research Part E-Logistics and Transportation Review*, 47, 1194–1209.
- Wen, Q., Fan, S., Jiang, P., & He, S. (2014). Multistage Inventory Control Research of Engineering Ships' Spare Parts. *Advanced Materials Research*, 236–240.
- Willingham, D. G. W. & Forster, J. D., 1990, *Availability tradeoffs for today's complex systems (military radar)*. Los Angeles, s.n., pp. 242–249.
- Xu, T., Qian, Y., Hu, Z., & Dandan, C. (2014). Reliability analysis of ship equipment based on maintenance data. *Prognostics and System Health Management Conference*, 530–535.
- Yang, G., Dekker, R., Gabor, A., & Axsäter, S. (2013). Service parts inventory control with lateral transshipment and pipeline stock flexibility. *International Journal of Production Economics*, 278–289.
- Zhao, J., & Yang, L. (2017). A bi-objective model for vessel emergency maintenance under a condition-based maintenance strategy. *Simulation*, 609–624.
- Zhou, B., Fan, S. & Li, D., 2010, *Research on ship spare parts inventory based on selective maintenance*. Wuhan, s.n., pp. 1–5.