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Maintenance and service logistics support are required to ensure high availability and reliability for capital goods and typically represent a significant part of operating costs in capital-intensive industries. In this paper, we present a classification of the maintenance and service logistics literature considering the key characteristics of a particular sector as a guideline, i.e., the maritime sector. We discuss the applicability and the shortcomings of existing works and highlight the lessons learned from a maritime sector perspective. Finally, we identify the potential future research directions and suggest a research agenda. Most of the maritime sector characteristics presented in this paper are also valid for other capital-intensive industries. Therefore, a big part of this survey is relevant and functional for industries such as aircraft/aerospace, defense, and automotive.

Keywords: maintenance; service logistics; capital goods; spare parts; maritime

1   Introduction

The maritime sector is of crucial importance in today's competitive and globalized world. The strategic economic importance of maritime transport cannot be overemphasized since 80% of global merchandise trade by volume is carried by sea. The world fleet has more than doubled since 2001 and new building deliveries reached historical highs in the last decade [1]. Besides maritime transport, maritime assets are used in various operations such as oil and gas terminal services, dredging, fishing, geophysical surveys, and military missions. The availability and reliability of these assets are crucial since their operations are often critical and high-value. Maintenance and service logistics support (i.e. after-sales logistics activities needed to enable capital goods to be maintained and function properly) are essential to ensure high availability and reliability during the asset life time.

In the maritime sector, maintenance and service logistics support are known to be a significant part of the overall operating costs. Maintenance activities can contribute in the range of 25-35% to the operating costs according to Turan et al. [2]. Alhouli et al. [3] show that maintenance and repair costs for a bulk carrier represent the largest proportion of operating costs with about 40%. The annual worldwide maintenance and repair costs for the Panamax type bulk carriers is estimated to be over $2.2 billion [4, 5]. Moreover, repair and maintenance expenditures are expected to rise by at least 2.5 to 3% per annum over the next couple of years [6]. On the other hand, unexpected downtimes of maritime assets lead to a significant loss of revenues. For instance, daily shipping operations of tankers yield a revenue of as much as $20,500 depending on the vessel size [1]. Breakdown of maritime assets can also affect health, safety, and environment [7]. The data analysis in [8] shows that more than 50% of accidents on fishing vessels involved machinery failure that is thought to occur due to the lack of maintenance. Therefore, the issues related to maintenance and service logistics must be given careful consideration to reduce the related costs and risks for maritime assets.

Our paper presents the literature on maintenance and service logistics management from an applicability perspective to the maritime sector. This was also motivated by a joint university – industry research project called "Integrated Maintenance and Service Logistics Concepts for Maritime Assets" (MaSeLMa). The MaSeLMa project focuses on developing innovative and smart concepts to increase the predictability of maintenance, optimize maintenance and service logistics planning and improve supply chain coordination and cooperation in the maritime sector [9]. Our paper summarizes the characteristics of the maritime sector derived from the MaSeLMa project. First, we have identified the key characteristics of the maritime sector through discussions with practitioners. The characteristics identified are significant to be considered while making decisions regarding maintenance and service logistics management. Second, we have reviewed the existing literature by particularly focusing on Operations Research/Management Science and Reliability Engineering techniques in decision making. In this respect, we have clustered the existing works into several subdomains addressing decisions about system design, maintenance service contract design, maintenance strategy selection, maintenance planning, failure/prognosis/part-demand forecasting, and spare parts inventory planning and logistics.

In our paper, we present the state-of-the-art in the subdomains reviewed considering the key characteristics in the maritime sector as a guideline. This covers various works addressing the associated characteristics directly (with an application to the maritime sector) or indirectly (with an application to another capital-intensive industry). We discuss the applicability and the shortcomings of these works and summarize them as lessons learned. In particular, we discuss to what extent the existing techniques can cope with the maritime sector characteristics and describe the extensions required to make them applicable. Finally, we identify the potential future research directions and suggest a research agenda.

To the best of our knowledge, there is no literature review on maintenance and service logistics management with a capital goods focus. Dekker [10] gives an overview of the applications of maintenance optimization models published until 1996 and discusses the gap between theory and applications. Other reviews in applications of maintenance optimization models also date from the late 90's (see, [11,12]). More recent reviews focus on specific maintenance (see, e.g., [13,14,15]) and spare parts models (see, e.g., [16,17,18]). Indeed, maintenance and service logistics management is an extremely wide area of research containing various problems and sub-problems. Therefore, it is not feasible to conduct a comprehensive literature review of this field while keeping the size of the paper within reasonable limits. In this paper, our scope is limited to the most relevant works from a maritime sector perspective. Even with this perspective many important works have not been cited to keep the size of the paper manageable. Nevertheless, our paper adopts a broader perspective than previous reviews by focusing on various types of decisions in maintenance and service logistics management. In addition, it classifies the literature according to specific sector characteristics and presents the state-of-the-art, lessons learned, and future research directions regarding each characteristic. As such, it provides an innovative literature review methodology that renders the literature accessible and comprehensible to both researchers and practitioners. We note that most of the maritime sector characteristics presented is also valid for other capital-intensive industries. In this sense, a big part of our survey is relevant and functional for other industries such as aircraft/aerospace, defense, and automotive.

The rest of this paper is organized as follows. Section 2 presents the classification scheme proposed for the maintenance and service logistics management literature. Sections 3-11 are each dedicated to a certain characteristic of the maritime sector. In each section, first, we review existing works that directly or indirectly address the associated characteristic. Second, we discuss the lessons learned adopting a maritime sector perspective. Third, we summarize

the potential research directions associated with the characteristic presented. Finally, Section 12 provides a priority setting for potential future research directions identified, highlights the current trends, and draws some conclusions.

2   Classification

In the maritime sector, some key characteristics are prominent in maintenance and service logistics management. In this paper, we provide a classification of the literature according to the following characteristics:

- *Multi-actor setting:* Maintenance networks involve several actors such as asset owners, system integrators, original equipment manufacturers (OEMs), maintenance service providers, and logistics service providers.

- *Small amount of failure-related data:* Failure data is usually limited due to a small number of similar systems and redundant execution of preventive maintenance. Moreover, it may be difficult to use failure data from one asset on another since maritime assets operate in different and continuously changing environments.

- *Mandatory surveys:* According to the conventions provided by the International Maritime Organization 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.

- *System specific spare parts:* Spare parts in the maritime sector have some specific characteristics to be considered such as obsolescence, condemnation, and criticality.

- *Multi-echelon structures:* There are multi-echelon characteristics since maintenance/ repair activities can be executed and spare part stocks can be held on the ships itself or on shore by asset owners, system integrators, service providers, or OEMs.

- *Multi-indenture systems:* Maritime assets can be considered as a collection of technical systems having multi-indenture structures.

- *Moving assets:* Maritime assets operate at remote locations and are moving. They operate under randomly varying environments in isolation from repair and spare parts storage facilities.

- *Economic dependency:* There exist significant scale effects in maintenance set-up.

- *Long life-cycles:* Maritime assets have a useful economic life of about 25 years when they are first acquired.

Considering the challenges faced in the maritime sector and the scope of Operations Research/Management Science and Reliability Engineering fields, several subdomains have been identified. According to our discussions with practitioners, the maritime sector characteristics listed above affect the decisions related to the following subdomains:

- *System design:* This subdomain studies the impact of different design options (e.g., build-in redundancy, component reliability, modularity, and commonality) to the total life-cycle-cost (LCC), i.e., the total cost to be incurred over the life of an asset. Related works focus on minimizing the total LCC considering the relation between the system design and future maintenance and resource requirements.

- *Maintenance service contract design:* Decisions related to this subdomain include selecting a particular type of maintenance service contract, determining well-founded

contract terms, and setting appropriate service level agreements between a supplier and a customer. These require investigating maintenance, resource, and service logistics requirements of customers and defining all circumstances and criteria that influence service levels and the total LCC. Other related works investigate costing, pricing, and management issues for maintenance service contracts.

- *Maintenance strategy selection:* This subdomain focuses on selecting the best maintenance strategy for a certain system, part, or component to find the optimum balance between benefits of maintenance and related costs. Different maintenance strategies are roughly classified as corrective (failure-based), preventive (scheduled-based), and predictive (condition-based) maintenance.

- *Maintenance planning:* This subdomain investigates several decisions related to the planning of maintenance activities and maintenance related tasks such as inspections, replacements, repairs, and overhauls. It also includes works that take capacity and resource restrictions into account. These include: (1) finding the optimal intervals to execute maintenance related tasks, (2) scheduling of maintenance related tasks, (3) determining components to be repaired or to be discarded upon failure, (4) for systems repaired by replacement of a component (called line replaceable unit, LRU), determining the appropriate LRU level from a maintenance logistics perspective, (5) determining the right location to execute maintenance and repair tasks in the maintenance network, (6) optimal allocation and dimensioning of maintenance resources such as service engineers, service tools (i.e., tools used by service engineers for maintenance and repair tasks) and, space (e.g., dry-docks).

- *Failure/prognosis/part-demand forecasting:* This subdomain covers condition assessment, degradation, and prognosis modeling approaches. It also includes works that use remaining useful life (RUL) information (i.e., the useful life left on a component at a particular time of operation) to predict the future maintenance and spare parts demand requirements.

- *Spare parts inventory planning and logistics:* This subdomain includes decisions such as determining appropriate spare parts provision policies, dimensioning and allocation of spare parts inventories, and designing service supply chain networks considering, e.g., emergency shipments, lateral transshipments, and spare parts pooling.

Table 1 presents the classification of the literature according to the characteristics in the maritime sector and the subdomains considered. A reference listed in this table either gives a direct application in the maritime sector or it represents a related work which can cope with the associated characteristic indirectly. An empty cell in Table 1 represents a characteristic-subdomain combination that is either irrelevant to study or corresponds to a potential future research direction. Moreover, we note that a high number of references in a certain characteristic-subdomain combination does not necessarily imply that the relevant research area is saturated. Section 12 provides a link between Table 1 and the open research topics.

Characteristics /Subdomains	System design	Maintenance service contract design	Maintenance strategy selection	Maintenance planning	Failure/prognosis/ part-demand forecasting	Spare parts inventory planning and logistics
Multi-actor setting	[2,19,20,21,22,23,24]	[25,26,27,28,29,30, 31,32]	[33,34]	[35,34,36]		[37,38,39,40,41]
Small amount of failure-related data			[42,43,44,45,46,47,48, 49,50,51,52,53]	[15,54,55,56,57,58, 59,60]	[61,62,63,64,65,66,67, 68,69,70,71,72,73,74, 75,76,77,78,79,80]	[81,82,83,84,85,86,87,88]
Mandatory surveys			[46]	[7,89,90,91,92,93,94, 95,96,97,98,99, 100,101,102]		
System specific spare parts	[21,24]			[103,104,105,106]	[107,108,109]	[110,111,112,113,114,115,116, 117,118,119,120,121,122,123, 124,125,126,127,128,129, 130,131]
Multi-echelon structures				[132,133,134]		[16,17,18,135,136,137,138,139, 140,141,142,143,144,145,146, 147,148,149,150,151,152,153, 154,155,156,157]
Multi-indenture structures				[89,90,91,158,159, 160,161]		[140,162,163,164, 165,166]
Moving assets				[55,77,159,167,168, 169,170,171,172,173, 174,175,176]	[177,178,179,180,181]	
Economic dependency				[89,91,92,182,183, 184,185]		
Long life-cycles	[186]	[187,188]		[189,190,191]	[109]	[122,124,125,126,128]

Table 1. Classification of the literature (characteristics/subdomains matrix)

3   Multi-actor setting

Maintenance networks in the maritime sector involve several actors such as asset owners, system integrators, OEMs, maintenance service providers, and logistics service providers. Traditionally, the responsibilities of these actors are defined as follows. OEMs design and manufacture maritime systems, subsystems, parts, and/or components. In accordance with the requests of asset owners, system integrators design and construct the assets by assembling the different units provided by OEMs. OEMs or system integrators usually offer warranty/support services during a certain period of time (warranty period) and provide asset owners with deliverables such as maintenance plans, spare parts, training, and test equipment that guide them to maintaining their asset. The warranty is the most basic and common type of contracting between the suppliers (i.e., OEMs, system integrators) and the asset owners. The warranty support mostly concerns the repair of failures by suppliers upon the request of asset owners during the warranty period. After the warranty period, asset owners have the full responsibility on their system, but maintenance, repair, or provision actions can be performed by OEMs, system integrators, or service providers upon their request. The current situation in the maritime sector mostly represents an "on-demand" operational model where the demand of asset owners is highly uncertain causing difficulties in planning the future maintenance, repair, overhaul, or provision activities to be carried out. This results in long lead times and/or high costs for meeting the requests. Clearly, this operational model is not beneficial for none of the actors involved. The current intention of these actors is to establish long-term maintenance service contracts with service level agreements.

3.1   State-of-the-art

The multi-actor characteristic in maintenance and service logistics management raises questions related to maintenance strategy selection, maintenance planning, maintenance service contract design, spare parts inventory planning, and system design. This section presents the state-of-the-art that includes the multi-actor characteristic in these subdomains.

The warranty servicing costs directly affect the profit of suppliers. One way to reduce these costs is to make appropriate decisions in selecting maintenance strategies. For instance, carrying out preventive maintenance (PM) before a failure occurs could reduce the degradation and the likelihood of failures during the warranty period. From the asset owner's perspective, PM actions over the warranty period can have a significant impact on the maintenance costs after the expiration of warranty. The literature dealing with warranty and PM issues simultaneously is significant (see, e.g., [33,34,35,36]). We refer to [34] for a comprehensive literature review on maintenance and warranty.

In general terms, the literature indicates a growing interest by academia, business, and government in the servitization concept where the word "services" usually refer to an offering such as maintenance, repair, or insurance [192]. At traditional manufacturers, servitization is desired because of financial drivers (e.g., stability of income and higher profit margin), strategic drivers (e.g., competitive opportunities and advantage), and by marketing drivers (e.g., customer relationships and product differentiation) [192]. For the customer, the main reasons to contract out maintenance

tasks rather than perform them in-house are focusing on core business, accessing highly specialized services at competitive costs, and sharing risks [41]. Van Horenbeek et al. [25] give a thorough overview of the existing literature on maintenance service contracts and existing business models. Performance-based contracts focusing on predefined equipment availability targets are shown to be the most successful type of contracts in capital-intensive industries such aircraft, defense, automotive, and construction. For instance, engine manufacturers such as General Electric, Pratt & Whitney, and Rolls-Royce have implemented performance-based contracts with commercial airlines in which their compensation is tied to equipment availability in terms of hours flown [38,193].

The long-term maintenance service contracting brings with it significant challenges. First, the decision of establishing a certain type of contract should be made based on well-founded computations. In this regard, Ashgarizadeh and Murthy [26] present a stochastic model to investigate the impact of different factors (such as contract terms, equipment reliability, the number of customers being serviced) on the supplier's expected profit using a game theoretical approach. Wang [27] presents a model for maintenance service contract design, negotiation and optimization for one customer and one supplier considering different contract options.

Second, suppliers need to assess the cost and the price of their service offerings properly to guarantee their profit and to stay competitive. Datta and Roy [28] review existing knowledge in cost estimation models for costing performance-based service contracts. Among most commonly adopted practices, they cite the use of expert opinion and analogy-based cost estimation. The literature also provides some examples of simulation models (see, e.g., [29,30,31]).

Third, suppliers should determine how to fulfill the pre-defined performance requirements by taking sound decisions in spare parts inventory planning. In this regard, there exist a few works that can provide guidance to the suppliers. For instance, Nowicki et al. [37] develop a multi-echelon, multi-item model that produces the optimal mix of spare parts maximizing the profit of a supplier under a performance-based contract. Kim et al. [38] combine the classical problem of managing the inventory of repairable parts with a multitask principal-agent model and analyze incentives provided by different contracting arrangements. Mirzahosseinian and Piplani [39] provide a repairable parts inventory model for a system operating under a performance-based service contract and analyze the interaction between inventory management, component reliability and repair facility efficiency. Van der Heijden et al. [40] study the trade-off between repairable parts inventory level and repair and transportation time reductions. Godoy et al. [41] provide a decision-making framework to profitably integrate the contractual conditions with critical spare parts management.

Finally, suppliers should start considering the future maintenance and logistics requirements early in the design phase of the systems [12]. The literature shows that different design options strongly affect the future maintenance and logistics requirements of customers. Turan et al. [2] discuss the effect of different design variables of ship structures on the total LCC. They develop a life cycle costing model for structural optimization during conceptual design phase of ships. Wang et al. [19] present a multi-objective model for safety-based design and maintenance optimization of large marine engineering systems. In other capital-intensive industries, several works consider the implementation of build-in redundancy for critical components (i.e., having a number of identical parts in parallel) and investigate the trade-off between the increase

in the initial system cost and the decrease in maintenance and downtime costs during the life cycle (see, e.g., [20,21,22]). Some other works consider the impact of different component reliability levels on the total system LCC (see, e.g., [23,39]). Modularity and commonality options are shown as other potential cost-effective alternatives due to the benefits resulting from spare parts pooling (see, e.g., [24]). From the supplier's perspective, it could be beneficial to invest in these design options to fulfill the performance requirements of long-term performance-based contracts at the lowest total LCC.

3.2 Lessons learned

The outcomes in other capital-intensive industries such as aircraft, defense, automotive and construction illustrate the good potential of performance-based service contracting in terms of higher profits, system availability and reliability (see, e.g., [193,194]). The lessons learned from the existing literature can be summarized as follow:

- In general, the choice of implementing a particular maintenance service contract between a supplier and a customer should be based on well-founded computations and decisions [25,27]. The maritime sector is not an exception. Asset owners should decide on what should be outsourced, what kind of relationship with the supplier should be adopted and how should the risks of outsourcing be managed [195]. Suppliers should consider the possibility of realizing higher system availabilities by collecting more statistics on failure behavior and by sharing spare parts and other maintenance resources with multiple asset owners [18].

- For successful implementations of long-term maintenance service contracts, the companies should adopt the necessary organizational structures and processes [192]. In the Dutch maritime sector, Keers et al. [196] observe that both asset owners and OEMs experience considerable internal structure fit problems in establishing service alliances. An organizational transformation is required to align internal business processes within the companies.

- In performance-based maintenance contracting, determining the right performance indicator is crucial [37,197]. In addition, an extensive performance measurement system should be in place to effectively asses the current equipment performance. In the maritime sector, it would be helpful to use condition monitoring technologies to monitor the key performance indicators. In addition, data gathered through condition monitoring can be used by the supplier to schedule maintenance tasks according to the actual condition of the equipment (i.e., to execute condition-based maintenance). This may reduce the risks and increase the benefits in terms of cost, availability, and reliability [30,32]. Besides, monitoring information can provide valuable operational feedback to the supplier, which is currently missing in the maritime sector.

- Performance-based service contracts are either standard or the outcome of negotiations [25]. Determining the right performance level for a chosen performance indicator requires defining all circumstances and criteria that influence the performance. From the suppliers' perspective, several issues are to be dealt with. First, the supplier should determine how to fulfill the performance requirements by finding new and improved ways to manage the resources required. In the long run, the supplier may find it in its best interest to invest in more efficient repair and

logistics capabilities [38]. Second, the suppliers should consider how to manage their relationships with their own suppliers. In the maritime sector, this can be a big issue especially for system integrators working with various OEMs.

- Some other challenges are related to the costing of performance-based service contracts by the suppliers. These include reliability of data supplied by the asset owners, consideration of uncertainties at different stages of service life-cycle, uncertainties of the asset owners' contribution to availability performance, and prediction of future maintenance activities. It is necessary to increase the cooperation and information sharing between the suppliers and the asset owners to remedy these issues.

- The consideration of maintenance and logistics requirements should start early in the design phase of systems [12]. In a performance-based contracting context, Mirzahosseinian and Piplani [39] argue that in order to improve the system availability, suppliers should primarily work to improve the components reliability by revising system design. Moreover, OEMs that provide similar systems to other industries beside the maritime sector (e.g., engine manufacturers) should take a closer look into the marine circumstances and usage characteristics to adapt the system design accordingly.

3.3   *Future research directions*

Regarding the multi-actor characteristic in the maritime sector, some unsolved issues remain for future consideration:

- There is little work to date that can help maritime companies in service design, organizational design and organizational transformation to solve internal structure fit problems experienced while adopting a service-oriented strategy [192,196] .

- One should analyze the impact of shifting from on-demand service contracts to performance-based service contracts in terms of asset availability, reliability, and the total LCC through studying the associated maintenance and resource requirements.

- It is worthwhile to study how to determine appropriate service level agreements in maintenance service contracts by taking all maintenance resource requirements into account and different cost-effective options such as resource sharing, pooling, and maintenance tasks coordination for several customers.

- How a system integrator can align service levels guaranteed to asset owners with the service levels quoted by its own suppliers (i.e. OEMs) remains an open research question.

- Additional research is needed to study the relation between the system design, operating environment, usage characteristics, and the future maintenance and resource requirements considering the total LCC.

4   Small amount of failure-related data

In the maritime sector, reliability information is usually not available to the degree needed for the prediction of failure times. Little historical data is available to perform forecasts from failures. The so-called "one-off systems" are very common in the

maritime sector, particularly in the naval defense industry. Moreover, maritime assets operate in different and inherently variable conditions that influence the failure behavior. This makes the use of failure data from one system on another difficult even for identical systems. Asset owners usually follow the recommendations of OEMs and system integrators which often results in too much preventive maintenance and high costs. Non-compliance with the recommendations during the guarantee period could remove the supplier from any obligations in case of a claim. Besides, asset owners would not permit occurrences of failures so as to get the failure data [42]. This leads to the contradiction stated by Moubray [44]: "successful preventive maintenance entails preventing the collection of the historical data which we think we need in order to decide what preventive maintenance we ought to be doing".

4.1 State-of-the-art

The lack of failure data in the maritime sector requires the application of some specific techniques to deal with data related issues. In this section, we summarize existing works that can cope with data related issues in maintenance strategy selection, maintenance planning, failure/prognosis/part-demand forecasting, and spare parts inventory management.

In the maritime sector, collecting failure data that is required to make optimal preventive maintenance decisions is challenging due to the above-mentioned issues. Hence, a shift from preventive (scheduled-based) maintenance towards predictive maintenance seems worthwhile. This is also consistent with the deliverables of reliability-centered maintenance (RCM) that was born in the late 1960s in the aircraft industry [45,54]. RCM is a structured approach that is used to determine a cost-effective maintenance strategy by focusing on the items that affect the system reliability. Basically, it consists of prioritizing function need, considering all applicable forms of maintenance and employing the most appropriate and cost-effective maintenance tasks in preserving system function. In RCM, all forms of maintenance and even the need for maintenance are considered [42]. Since 1980s, RCM has found several applications in the maritime sector. First, Jambulingam and Jardine [46] demonstrate the integration of RCM and LCC concepts on a part of an air conditioning system of the Canadian naval ships. They show that a considerable amount of savings can be obtained with the implementation of this approach. Mokashi et al. [42] discuss the specific problems likely to be encountered in implementing RCM on maritime assets. In the absence of sufficient failure data imposed by the traditional RCM approach, they propose a subjective qualitative approach. They show that the guideline principles of RCM can help to plan a maintenance strategy. The requirements to improve reliability of maritime systems based on RCM is listed by the American Bureau of Shipping [198]. Conachey [47] discusses the technical background of this study and provides additional information related to maintenance and risk analysis of maritime systems. Lazakis et al. [48] propose a criticality and reliability assessment methodology by using operational data and expert judgments. Their methodology was demonstrated on a diesel generator system of a cruise ship. A similar methodology is also considered by Turan et al. [49] and illustrated on the main systems of a diving support vessel. Recently, Zaal and Kuijt [50] have presented a methodology that streamlines the RCM approach by assessing only the functional critical failure modes. A propulsion gearbox has been used as a test case to demonstrate the proposed RCM approach.

Given a choice RCM often prefers condition-based maintenance (CBM) to

scheduled-based maintenance [42,43]. CBM is a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring [51]. It becomes a feasible option when a measurable condition indicator has been identified and it is possible to set warning limits using this indicator. Scarf [52] presents a framework for determining an appropriate CBM policy for a given system and provides practitioners with guidelines for CBM. Three steps can be distinguished for a CBM program: data acquisition (information collecting), data processing (information handling) and maintenance decision making [51].

There exist two main types of data collected in a CBM program: event data and condition monitoring data. Event data include the information on previous breakdowns, overhauls, and maintenance practices. Condition monitoring data contain measurements related to the health condition of the asset under consideration. So far, various sensor technologies have been designed to collect different types of condition monitoring data. These technologies have already found applications in the maritime sector for ship hulls (see, e.g., [199,200]) and marine engines (see, e.g., [63,65]).

The condition of the equipment under consideration can be monitored either continuously or at specified periods. If the equipment condition is not monitored continuously, the interval between inspections has to be determined so that actions can be taken in time, either to prevent failures or to minimize the consequences of those [54]. Delay-time-based modelling is one of the techniques for optimizing inspection planning. It has attracted significant attention and widely applied by researchers in the maintenance field. Some successful applications are also presented for maritime assets (see, e.g., [55,56,57]). A recent comprehensive review on the applications and developments regarding delay-time concept is provided by Wang [15]. Risk-based inspection (RBI) is another concept used for inspection planning. RBI planning aims at optimizing inspection by focusing on equipment with high risk which are more likely to fail, causing damage to people and environment and resulting in high costs in case of failure. We refer to Hamada et al. [58] and Rizzo et al. [59] for more information about the applications of this concept in the maritime sector.

Data processing is an essential step in a CBM program. Different methods and models are available in the literature for better understanding and interpretation of data. These are used to accomplish fault diagnostics and/or prognostics and constitute the basis of maintenance decision support. Diagnostics refer to fault detection, isolation and identification when it occurs. Prognostics deal with fault prediction before it occurs and focus on RUL estimations. A comprehensive literature review on machinery diagnostics and prognostics implementing CBM can be found in Jardine et al. [51]. Recent literature reviews on machinery prognostics and RUL estimation techniques are provided by Peng et al. [61] and Si et al. [62], respectively.

The literature on machinery diagnostics is huge and diverse [51]. There exists a large and growing variety of condition monitoring techniques for fault diagnosis. A particularly popular one for rotating and reciprocal machinery is vibration analysis (see e.g., [60,201]). This technique is also found effective for marine machinery (see, e.g., [63,64]). Prognostics is still a relatively new but very active research area in aircraft, automotive, nuclear, process controls, and defense industries [61]. Analyses of maritime machinery such as marine engines (see, e.g., [66,65]), compressors (see, e.g., [67]), and ship hulls (see, e.g., [68,69]) are also available in the literature.

Prognostic methods that are based on historical failure data are called experience-based methods. These methods rely on the collection of a sufficiently large set of failure

data and require a numerical relation describing the data [76]. An alternative approach is to use model-based methods, in which physical models are used to describe the degradation process of the component and its failure mechanism. Although model-based methods have big potential in maintenance modeling and prognostics, applications in this field are limited [77]. Tinga [76] proposes a framework for model-based maintenance, in which physical models are applied to predict failures of different components. He demonstrates that when the failure mechanisms are known and the usage or loading of the components is monitored, the uncertainty in the prediction of failures can be significantly reduced. Some other studies in which physical models are used to describe the degradation process of systems such as bearings, gear tooth, and electronic systems include [78,79,80].

Maritime assets are composed of technical systems that may comprise electronic units for which diagnostics and prognostics require additional challenges. The no failure found (NFF) phenomenon is a major problem when dealing with fault diagnosis of electronic units. A NFF event occurs when an electronic unit has been removed from a technical system due to a fault but the external test does not discover any fault on it. Within the aircraft industry, about 50% of electronic units removed during the utilization and support stages are classified as NFF [70]. NFF events may be manifested in decreased safety and availability and increased life cycle costs for maritime assets. It is the aircraft industry that has done most of the work in this area [71]. The methods presented in the literature (see, e.g., [72,73]) can also be considered to reduce or eliminate NFF events in the maritime sector.

Spare parts inventories exist for serving the needs of maintenance. Their unavailability results in higher downtimes. In general, demand for spare parts is difficult to forecast using historical data only [74]. In the maritime sector, little data is available to perform forecasts based on time series forecasting. Wang and Syntetos [75] present a generic method that can be used to make accurate predictions of spare parts demand. They provide a spare parts demand forecasting method by looking at the maintenance processes that generate the relevant demand patterns. Under certain conditions, this maintenance-based forecasting method is associated with a better performance in comparison with a well-known time series method.

By using the information on the physical condition of the equipment, it is also possible to update replacement and inventory decisions dynamically. For instance, Elwany and Gebraeel [81] integrate prognostics (by referring to RUL estimations) into replacement and spare parts decision models. Similarly, Louit et al. [82] present a model directed to the determination of the ordering decision for a spare part when the component in operation is subject to a condition monitoring program. Other related works incorporating condition monitoring information into spare parts inventory decisions can be found in [83,84,85,86].

4.2 Lessons learned

In the maritime sector, there is a trend to shift from scheduled-based maintenance towards CBM. Indeed, the rapid development of advanced sensor technologies is making the implementation of CBM more affordable and feasible for the maritime sector. However, the following points should be considered while adopting a CBM strategy:

- The importance of event data should not be underestimated since event data and

condition monitoring data are equally important in CBM [51]. For an already existing and old vessel, obtaining event data can be difficult. Ideally, event data shall be recorded starting from the early stages of the vessel life and data collection and reporting should be automated through a maintenance information system.

- Information on the operational environment should also be taken into account for an effective maintenance decision making. Since environmental influences can largely affect the failure behavior of maritime assets [202], models and methods that enable the consideration of environmental variables are more appropriate for the maritime sector (see, e.g., [69,74]).

- Peng et al. [61] summarize some general weaknesses of prognostics. These include the difficulties and high cost of collecting abundant data and the lack of a judgment criterion for the accuracy of existing prognostic techniques. These weaknesses lead to a long learning and implementation time of maintenance techniques based on prognostics.

- In model-based prognostics, much less failure data is needed compared with experience-based models since the physical mechanisms characterize the failure behavior. Moreover, changes in usage of the system can easily be incorporated into model-based methods by using the quantitative relation between usage and degradation. However, this requires a detailed understanding of the system and considerable effort is generally needed to develop physical models [77].

- Jardine et al. [51] argue that prognostics is much more efficient than diagnostics to achieve zero-downtime performance. However, asset availability also depends on the availability of maintenance resources such as spare parts, maintenance engineers, service tools, and maintenance facilities ([87,88]). Alabdulkarim et al. [53] provide numerical evidence about the fact that a higher asset monitoring level does not always guarantee a higher asset availability. If maintenance resources are not managed efficiently, investing in high cost technologies may be useless as a higher performance of the assets is not guaranteed.

4.3   Future research directions

- While implementing prognostics and CBM, the error between predicted RUL and real RUL can be significant. It is worthwhile to study how to incorporate the uncertainties in RUL estimations into maintenance and resource planning.

- A comprehensive analysis to quantify the impact of using different monitoring levels by taking resource constraints and logistics capabilities of the companies into account is lacking. This would enable the determination of conditions under which higher monitoring levels result in higher system availability.

- More research is required to effectively integrate prognostics with maintenance and resource planning.

5   Mandatory surveys

The vast majority of ships are built to and periodically surveyed for compliance with the rules defined by Classification Societies. A Classification Society is an organization that provides classification and statutory services and assistance to the maritime sector together with the requirements set down by the International Maritime Organization.

After the assignment of a class (usually reflecting the ship's tonnage and intended use), each ship is subject to a specified program of periodic surveys. These are typically based on a five-year cycle and consist of annual surveys, an intermediate survey, and a class renewal/special survey held every 5 years [203]. These surveys may include out-water examinations that require the ship to be dry-docked to verify whether the ship continues to meet the relevant requirements. The length of mandatory dry-docking intervals depends on the ship's class and age. For instance, general commercial ships are dry-docked on average every 2.5 years [204]. Major overhaul, repair, and maintenance of ships often take place during dry-docking.

5.1 State-of-the-art

In the period between mandatory surveys, it is usually the asset owner's responsibility to properly maintain their ships [203]. For each system, selecting an appropriate maintenance strategy between major overhauls (accompanied by mandatory surveys) is crucial to meet the pre-specified technical and safety requirements at a fair cost. Jambulingam and Jardine [46] analyze this problem for a maritime system. The objective of their work is to determine whether the system requires preventive maintenance (PM) between two major overhauls, if so to find the optimal PM interval.

Mandatory dry-dockings and overhauls pose both a restriction for availability and an opportunity for clustering maintenance tasks. In a holistic way, it can be less expensive and more convenient to perform preventive maintenance for a certain component during dry-docking of the ship rather than at the optimum preventive maintenance time for that component. This has a strong relation with the problem of establishing group maintenance and opportunistic maintenance policies considering economic and structural dependence of different components. This research area has received considerable attention in the literature (see, e.g., [89,90,91,92]).

The literature on aircraft maintenance planning and scheduling would be helpful to cope with some problems related to maritime assets maintenance. During the major overhaul of an aircraft (termed heavy maintenance), the aircraft is temporarily taken out of service and inspections of various system components, structural modifications, and/or alternations are performed. This is similar to what happens during the major overhaul of maritime assets. The majority of research in this area focuses on the resource-constrained maintenance scheduling of a fleet of aircraft (see, e.g., [93,94]). We refer to [95] and the references therein for further information on this research area. Similar applications in the maritime sector can be found in [7] and [96].

Maintenance tasks that have not been planned and identified before the dry-docking starts, result in significant additional costs to asset owners [97]. Similarly, about 50% of the total work involved in heavy maintenance of aircrafts are unplanned maintenance activities arising out of inspections carried out during an aircraft lay-up [95]. A framework that facilitates a proactive response that mitigates the impact of such unpredictable maintenance activities in aircraft maintenance can be found in [95].

From the viewpoint of dockyards, efficient management of capacity and time limits is a critical issue. De Waard [98] develops a process-oriented organization model applied to the Royal Netherlands Navy Dockyard through pilot tests, to cope with high degree of uncertainties associated with customer demand and maintenance execution time, and tight requirements regarding due dates, cost, quality, and flexibility. His model includes elements regarding the design of production, control, and information

structures. De Boer et al. [99] provide a decision making support in process planning, aggregate capacity planning, and scheduling also for the Royal Netherlands Navy Dockyard. A necessary condition in order to complete maintenance, overhaul, and modification projects in time is the availability of materials and spare parts. This issue is studied by Joo [100] in the aircraft industry. He focuses on the problem of scheduling overhauls for a small fleet of aircrafts when available spare parts are limited and overhauls may not be delayed beyond a due time. The dynamic programming approach proposed in this study is also applicable to maritime assets.

For asset owners, selecting the dockyard where periodic dry-dockings are to be performed is crucial since the relevant processes are critical. Several criteria such as quality of service, capacity limitations, geographical advantages, relevant costs, and time limits should be taken into account. A multi-criteria approach for selection among dockyards is developed in [101]. A real case application is presented where the capacity of the dockyard is shown to be the most important criteria for asset owners.

5.2 Lessons learned

- The majority of the literature on heavy maintenance in the aircraft industry can address the problems encountered in planning and scheduling of major overhauls/mandatory surveys in the maritime sector.

- In practice, asset owners generally work with dockyards situated in the geographical area where their assets are operating. It is shown that dry-dock availability can be an issue, leading to the use of other yards on an ad hoc basis [204]. Major overhauls should be planned in advance to make appropriate dry-docking appointments. However, accurately estimating activities and resources to be required before dry-docking is a big challenge for maritime assets [97].

5.3 Future research directions

- The integration of different maintenance strategies such as failure-based, age/usage-based, and condition-based with the fixed maintenance interval concept stemming from the periodic surveys has received little attention in the literature, the only exception that we are aware of is Zhu et al. [102].

- The research on maintenance scheduling for a fleet of ships under limited resource capacity including spare parts, maintenance engineers and dockyard space has been scarce.

- Limited number of works takes into account imperfect predictions made before dry-docking regarding maintenance activities to be performed and resources to be required. De Waard [98] describes a qualitative approach to cope with such uncertainties by re-designing the organizational structure. Future research is required to develop quantitative approaches in this respect.

6 System specific spare parts

Insufficient spare part stocks may affect the overall performance of maritime companies, as lack of spare parts results in longer downtimes, lower availability and/or increased operational risks [118]. Several aspects such as criticality, condemnation,

obsolescence, and cannibalization should be considered while making spare parts inventory and maintenance planning decisions in the maritime sector.

6.1 State-of-the-art

The spare parts classification is a crucial step in spare parts management since it enables a better management of different items by taking into account their characteristics (see, e.g., [110,111,112]). Distinctive characteristics include parts' criticality (economic, environmental, and safety consequences of a part failure), usage (demand volume, demand variability, and redundancy), inventory (price, space required, and obsolescence rate) and supply characteristics (replenishment lead time, supplier availability, risk of non-supply, and part specificity) [112]. For spare parts that possess distinctive characteristics, using several criteria as a basis for classification is particularly useful. This has led researchers to suggest different types of multi-criteria approaches for spare part inventory classification [165]. A well-known method used as a tool for classifying spare parts is the analytical hierarchy process (AHP) (see, e.g., [113,114,115]). We refer to Roda et al. [112] for advantages and disadvantages of various multi-criteria spare parts classification approaches proposed in the literature.

In spare parts management, adopting an integrated view in spare parts classification, demand forecasting and inventory management improves the overall effectiveness. To the best of our knowledge, Braglia et al. [114] provide the first paper in this direction by relating the classification of spare parts and inventory management policies. Mohammaditabar et al. [116] propose an integrated model to classify the parts and find the best inventory policy simultaneously. Bacchetti et al. [107] propose differentiated forecasting and inventory policies for different categories of spare parts. For a case study organization, their simulation results show that a total logistics cost reduction of about 20% can be achieved. A literature review on theoretical contributions of spare parts classification and demand forecasting can be found in Bacchetti and Saccani [108].

In capital-intensive industries spare parts stock is often composed of repairable and non-repairable parts. Repairable parts are the ones which are repaired and returned to use rather than discarded. These are usually expensive and/or specific parts with a long life. Typical problems are concerned with their optimal stocking levels, the location of these stocks, and the effective use of limited resource capacity for repair tasks. Dhakar et al. [117] present an approach to find optimal stock levels for repairable parts which are critical to operations and having low demand. Louit et al. [118] concentrate on relatively expensive and critical parts for which they present various approaches for the determination of the optimal stock levels, when the stock is composed of repairable and non-repairable parts. Sleptchenko et al. [119] study the trade-off between inventory and repair capacity by presenting a simultaneous optimization for both decisions. Sleptchenko et al. [120] show that assigning repair priorities to repairable parts can reduce stock investment. A complicating factor regarding repairable parts is the condemnation aspect which refers to the fact that not all failed repairable parts can be repaired; some may be condemned and have to be replaced by new procurements. We refer to [18,121,122] for discussions on the incorporation of condemnation from a modelling point of view. A review of repairable spare parts models and applications can be found in [123].

Obsolescence is a crucial problem in many sectors including the maritime sector.

From the suppliers' perspective, parts become obsolete when there is no demand for them. It is often possible to know in advance or to estimate reasonably accurately when the equipment in use will be retired (see also [109] for a linkage between demand forecasting and obsolescence). In such a setting, Pinçe and Dekker [124] propose an approximate solution to the problem of when to change the inventory control policy to reduce obsolete inventories while balancing availability. From the users' perspective, it will be difficult to procure the parts if the supplier discontinues the production. Several studies focus on finding the optimal final order quantity to be placed at the supplier, so that it covers the demand for parts until the equipment retirement (see, e.g., [122,125,126,127] and the references therein).

The procurement of spare parts after their end-of-life can be done by requesting occasional extra-production from the suppliers. For this option, the production cost can exceed regular production cost by 100% or more and often considerable lead times apply [128]. Inderfurth and Kleber [128] present a model formulation to coordinate different procurement options for end-of-life spare parts acquisition, namely final order, extra-production and remanufacturing. They show that a restriction to a final order strategy may be more costly than using the additional options of extra-production and remanufacturing. In practice, the demand of spare parts can also be met through cannibalism of a functioning part in another system when other procurement options are very costly. Fisher and Brennan [129] examine various cannibalization policies using a simulation approach to answer the question whether cannibalization should be done and when. Fisher [130] presents a continuous Markov process model for evaluating the performance of a maintenance system with spares, repair, cannibalization, and manpower constraints and identify desirable cannibalization policies under various parameters. Sherbrooke [17] evaluates the increase in availability that could be achieved under cannibalization. Numerical examples of Salman et al. [131] demonstrate that investments in spare parts inventories can reduce the need for and the value of cannibalization. These studies represent initial efforts in modelling the effect of cannibalization on the overall performance.

Maintenance models often rely on the assumption that spare parts are always available in stock [103]. As such, one can optimize maintenance and spare parts inventory decisions independently. However, this approach may lead to poor solutions since it ignores the interdependencies between maintenance and inventory decisions. The literature shows that the joint optimization provides remarkable improvement in terms of cost and service levels compared to separate optimization (see, e.g., [104,105,106]). In the last decades, several joint maintenance and inventory optimization models have been developed. We refer to [103] for a literature review on these models.

6.2 Lessons learned

- The literature disclosed the need for a multi-criteria perspective for classifying spare parts. The most common criteria used in the literature is the stock-out cost and replenishment lead time [112]. According to our company interviews, those are also amongst the most popular criteria currently in use by the asset owners involved in the MaSeLMa project. Other important criteria revealed are criticality in terms of environmental and safety consequence of a part failure, redundancy level, and part specificity emanating from one-off systems. The literature emphasizes the need of differentiating the policies between different classes of spare parts [205]. However,

this requires more data collection and induces further computational complexity compared to existing approaches.

- Repairable inventory systems are common in the maritime sector. The literature shows that these systems are considerably more complicated than traditional non-repairable ones since there are a number of complicating factors to consider. These include: imbalance between demand and returns of repairable parts and the risk of condemnation [123]. As pointed out by Rustenburg et al. [121], the condemnation rates can be as high as 30% in the naval defense industry. This important aspect should be incorporated into repairable inventory models explicitly.

- Maintenance and spare parts management are strongly interconnected since maintenance relies on the availability of spare parts. Assuming that spare parts are always available in stock is unrealistic in a maritime environment where the lead times can be very long and the spare parts can be too expensive to invest in. Therefore, such an assumption may result in poor decisions in terms of cost and service levels. In this setting, maintenance and spare parts inventory optimization should be considered simultaneously to take the trade-off between the two decisions into account [103].

6.3   Future research directions

- There is a small amount of research in integrated decision making of spare parts classification and inventory control (see [108,112]). For repairable parts, optimal planning and scheduling of repair tasks is another dimension to be considered in the integrated decision-making such as finding the best prioritization rules of part repairs and optimal inventory levels simultaneously.

- The cannibalization of functioning parts is one of the countermeasures used in practice to deal with spare parts unavailability and extra-long replenishment lead times. Although this practice is present in many capital-intensive industries including the maritime sector, its incorporation into the mathematical models is rare in the scientific literature. In particular, the questions of whether cannibalization of parts should be done and what factors affect cannibalization have received little attention.

- There are several open aspects related to joint maintenance and inventory decision making. Under performance-based service contracts, maintenance and inventory control responsibilities shift to the suppliers (cf. Section 3). In future research, one can consider the arising structure and environment [103]. Moreover, the literature shows that obsolescence has substantial impacts on optimal policies. It is also worthwhile to incorporate this aspect into the related models. Other extensions can focus on investigating the value of condition monitoring information in joint maintenance and inventory decision making.

7   Multi-echelon structures

In the maritime sector, the service logistics network has a multi-echelon structure since maintenance and repair activities can be executed and spare part stocks can be held on board of the ships or on shore by asset owners, system integrators, or OEMs. For example, the related network can be characterized as a three-echelon repair and inventory system including the ships, on shore bases of the asset owners, and on shore

depots of system integrators/OEMs (see, e.g., [133] and [158]). The questions arising from this characteristic relate to maintenance planning, spare parts inventory planning, and logistics subdomains. In particular, questions such as how to allocate spare parts and maintenance resources, where to execute maintenance and repair activities and how to configure multi-echelon maintenance network are of interest.

7.1 State-of-the-art

The question of how to allocate repairable spare parts in a multi-echelon network has been addressed by numerous researchers. The work of Sherbrooke [135] is certainly the seminal paper in this field. He develops the Multi-Echelon Technique for Recoverable Item Control (METRIC) model for a two-echelon distribution system. He proposes an approximate evaluation of number of backorders and a heuristic approach to optimize the base sock levels. A well-known variant of METRIC is VARI-METRIC studied by Graves [136] to provide a simple and accurate approximation for the variance of the number of parts in repair. For two extensive overviews of the variants of METRIC models, we refer to the books of Sherbrooke [17], Muckstadt [137], and van Houtum and Kranenburg [138].

The variants of the METRIC model use the system approach in which all components are considered jointly. Under this approach, target service levels are set, for example, considering system availability and the expected number of backorders over all spare parts. This is the key difference from the traditional item-approach, in which item-oriented service measures, such as the fill rate are used. The literature shows that great savings can be achieved with the system approach. For instance, at the Royal Netherlands Navy, a particular system approach based on VARI-METRIC model enables to achieve high availability under tight budget constraints [121]. A recent overview of the large body of literature on the system approach is given by Basten and van Houtum [18].

Determining whether a component should be discarded or repaired upon failure and at which location in the multi-echelon network to execute these repairs is called the level of repair analysis (LORA) [133]. Since these decisions significantly impact the spare parts investment cost, solving multi-echelon spare parts inventory problem in conjunction with LORA is worthwhile. Alfredsson [134] is the first who considers the two problems simultaneously but under certain simplifying assumptions for tractability. Based on this method, Basten et al. [132] present an algorithm that finds efficient solutions. They show that significant cost savings can be achieved compared to the sequential approach that first solves LORA and then the spare parts inventory problem.

Some researchers consider the trade-offs among service levels and cost components related to the network design such as installation, transportation, procurement, and inventory costs. In particular, the design factors considered in the literature include logistic network design, capacity investment, part supplier selection, and transportation modes selection (see, e.g., [142,143,144,145,146]). The literature shows that a comprehensive inclusion of such design factors with the spare parts inventory optimization problem requires significant computational efforts.

In order to reduce holding and downtime costs, certain flexibility options such as lateral transshipment, inventory pooling, or emergency shipments can be considered in the design of spare parts inventory systems. The traditional inventory networks are hierarchical, with transportation flows from upstream to downstream echelons. In

practice, vessels operating within the same region can resupply each other to cover spare parts demand. This is equivalent to allowing lateral transshipments within an echelon. Optimal control of lateral transshipments has been researched in many different settings (see, e.g., [148,149,150,151,152]). Moreover, pooling common spare parts between multiple companies operating in the same region is also an alternative to reduce spare parts holding and downtime related costs. Kilpi and Vepsäläinen [153] demonstrate the savings potential of inventory pooling arrangements among various companies in the airline industry. Karsten et al. [155] and Karsten and Basten [154] study the cost allocation problem in spare parts pools with multiple companies. In general, the literature on lateral transshipment and inventory pooling research can be found in Paterson et al. [156]. The case of emergency shipments is shown to be equivalent to the lost sales setting for which literature reviews can be found in [18] and [157].

7.2   Lessons learned

- Variants of the METRIC model are in use at various organizations. Military organizations such as the US military forces have been the first to adopt such models (see [17,18]). Multiple authors have shown that for real-life problems, these models result in savings up to 50% (see, e.g., [17,121]). However, as discussed by Rustenburg et al. [121], a direct application of VARI-METRIC model has several shortcoming since it cannot cope with specific issues faced in the maritime sector regarding parts criticality and specificity.

- Allocating spare parts stock should be determined by taking both spare parts and multi-actor characteristics into account. For spare parts with high specificity, the basic alternatives for the user are either to accept the stock-out situation or to rely on their own safety stock [205]. This is also a common practice in the maritime sector since OEMs and system integrators are not willing to hold any stock for one-off systems. However, for parts with low specificity and low criticality, it is possible to push the spare parts to the upstream echelons, i.e., to the OEMs or system integrators.

- In the maritime sector, resources such as spare parts and labor tend to be expensive. For such systems, repairs are typically performed at the upstream of the repair network [133]. However, depending on the operating regions of vessels, a central repair strategy may result in significant transportation and downtime costs. The associated trade-off should be carefully taken into account while making decisions on where to deploy the maintenance resources and perform repair activities.

7.3   Future research directions

- Parts criticality and specificity can largely affect the multi-echelon inventory decisions. More research is required to incorporate these characteristics into the existing models.

- In the maritime sector, the allocation of maintenance tasks and spare parts inventories should be made considering the conflict of interest of different actors. Future research can consider the issues related to systems with both multi-actor and multi-echelon characteristics.

- To the best of our knowledge, Chen et al. [147] are the only authors that consider a

multi-echelon spare part network in a joint maintenance and inventory decision problem. This topic can be further investigated in future research.

8 Multi-indenture systems

Maritime assets can be considered as a collection of technical systems. Due to high availability requirements, it is a common practice to repair a defective system by the replacement of a component with a functioning spare part. The components that are replaced are called line replaceable units (LRUs). The repair of LRUs is typically done by replacement of subcomponents, called shop replaceable units (SRUs). Such a SRU may itself consist of subcomponents. This means that spare parts need to be stocked to enable quick repairs of the technical systems, LRUs and SRUs [133]. This corresponds to a multi-indenture structure for which the number of spare parts to stock at each indenture level should be decided. Furthermore, what, when and where to replace are challenging questions under such structures. The associated decisions relate to the maintenance planning and spare parts inventory planning subdomains.

8.1 State-of-the-art

Several researchers considered multi-indenture systems in spare parts inventory optimization problem. Muckstadt [162] extends the METRIC model of Sherbrooke [135] to a two-echelon, two-indenture system and develops the model referred to as MOD-METRIC. Sherbrooke [163] extends the original VARI-METRIC method to a version for two-indenture, two-echelon systems with a fairly accurate approximation. Rustenburg et al. [140] generalize the VARI-METRIC model of Sherbrooke [163] by considering a general pure distribution system and a general multi-indenture system with commonality, in which the same parts are assumed to be installed in different systems. Rustenburg et al. [140] present both an exact and an approximate method for the evaluation of base stock policies under this setting.

The above-mentioned models assume ample repair capacities. Sleptchenko et al. [164] modify the VARI-METRIC model to allocate repairable spare part stocks in a multi-echelon, multi-indenture system under finite repair capacity. Sleptchenko et al. [119] present a procedure for simultaneous optimization of inventory levels and repair capacity in a multi-echelon, multi-indenture system. Van der Heijden et al. [40] provide a method for the joint optimization of spare parts inventories and throughput times of repair and transportation for multi-echelon, multi-indenture spare part networks. Additional related papers with finite repair capacity considerations can be found in Sleptchenko et al. [120], Zijm and Avşar [165] and Tiemessen and Van Houtum [166].

Multi-indenture system structures have also been considered in LORA which focuses on repair or discard decisions and determines where in the repair network to carry out these activities (see Section 7.1). The model of Basten et al. [133] is able to cope with multi-indenture systems. Recently, Basten et al. [158] have extended the LORA model to consider spare parts socking decisions for multi-indenture systems.

For multi-indenture systems, a structural dependence between items may exist as a result of interactions within the indenture structure. For example, some operating components may have to be replaced, or at least dismantled, before failed components can be replaced or repaired. In the literature, only a few papers are published on structural dependence. In general, opportunistic policies are promising candidates to

investigate such systems [91]. The core idea of opportunistic maintenance is to take advantage of maintenance opportunities arising from an event at which the component can be replaced preventively without requiring an additional set-up or preparatory task. For example, component failures can be regarded as opportunities for preventive replacement of non-failed components. Most of the related papers focus on defining the best decision on when to replace a particular item and very few papers focus on optimally determining LRUs. The key decision for the LRU definition problem is at what level within the indenture structure of a physical asset to define the LRU, i.e., the decision on what to replace [160]. Jensen [161] gives an explicit definition of which item is replaced directly from the asset, and which items are used to repair the failed LRU. In a recent paper, Parada Puig and Basten [160] develop a model for the optimal selection of replacement level within the indenture structure of a technical system.

8.2 Lessons learned

- In maritime assets, technical systems may consist of more than six indenture levels with high component commonality (e.g., the radar system in naval vessels [206]). The existence of component commonality may give rise to certain complications when there are three or more indenture levels [121]. When the commonality aspect is taken into account by making the necessary modelling adjustments, significant saving can be obtained in terms of spare parts investment. The literature shows that commonality of components is of significant value, especially when common components are expensive [140]. Hence, this aspect should be taken into account during system design by adopting a total LCC perspective.

- In practice, LRU definitions are often made based only on engineering/technical criteria and not by analyzing economic trade-offs from a total LCC perspective [160]. Since improving LRU definitions would require the redesign of the system and the involvement of different actors this decision should be considered as a strategic decision.

8.3 Future research directions

- The field of opportunistic maintenance planning under structural dependence has so far received little attention (see also [91]).

- The LRU definition research has still many open directions. These include the incorporation of limited labor capacity and the combination of LRU definition with LORA and spare part stocking decisions.

9 Moving assets

The failure of a critical item at sea can cause a costly event with potentially high environmental, safety, and/or health related effect. Some important aspects need to be considered for maritime assets which are operating at remote locations and moving during their operations:

(i) Maritime assets operate in isolation from repair and spare parts storage facilities. Some preventive maintenance tasks are very costly and not permitted during operations,

(ii)   Environmental conditions which influence the failure behavior might depend on the location and change during operations,

(iii)   Service offerings of the suppliers, related costs, and supply lead times might depend on the location where the assets operate.

Decisions on maintenance and service logistics management should be made by giving special attention to these aspects.

9.1   State-of-the-art

Aircrafts and heavy vehicles are also moving assets for which certain maintenance tasks can only be executed at designated maintenance bases and not permitted and/or feasible during operations. This is similar to what we have stated in aspect (i) for maritime assets. The so-called aircraft maintenance routing problem is widely studied in the literature, with the aim of routing aircrafts while satisfying short-term routine maintenance requirements. These studies focus on finding maintenance feasible routes for each aircraft in a fleet (see, e.g., [167,168,169,170]). To the best of our knowledge, only two studies consider the restrictions regarding preventive maintenance tasks during the operations of maritime assets. Perakis and Inozu [159] propose a reliability-based replacement model for marine diesel engines for which preventive replacements are not permitted while the system is in operation on-shore. They evaluate whether to replace or not each system component before the operating season starts based on an expected cost analysis. Christer and Lee [55] investigate how the delay-time concept (cf. Section 4) can be used to explore the consequences of inspection maintenance practice on operation periods of ships. They give the expressions for the expected number of preventive and failure returns over an operation, and illustrate an example of cost based balance to select an optimal inspection period.

As for aspect (ii), in the literature, modelling of the degradation process of systems operating in randomly varying environments has received large interest (see, e.g., [177,178,179,180,181]). These models assume that the deterioration status of systems under consideration evolves as a Markov chain and aim at deriving and computing reliability or availability of systems. As also stated by Ulukus et al. [171], despite extensive literature on this topic, relatively few studies consider the problem of determining optimal maintenance and replacement policies for systems under randomly varying environments. Xiang et al. [172] consider a single-component system subject to a Markovian operating environment such that the system's instantaneous deterioration rate depends on the state of the environment. Using a simulation model, they assess the cost benefit resulting from condition-based maintenance policy, and also the impact of the random prognostic error in estimating system condition on the cost benefit. We refer to Ulukus et al. [171] and the references therein for the studies that analyze optimal replacement policy structures for single-component systems subject to stochastic deterioration in a random environment. Zhang et al. [173] study multi-component systems and optimize the maintenance decision under a state-dependent opportunistic maintenance policy.

Aspect (iii) brings additional complexity in modelling and analysis of maintenance and service logistics problems. To the best of our knowledge, the incorporation of this aspect is barely addressed in the literature. Özekici [174] studies the maintenance problem of a system operating in a random environment by considering environmental state dependent cost structures. Çekyay and Özekici [175] provide an extension of [174]

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by considering the multi-component case with non-identical components. Çekyay and Özekici [176] study the maintenance problem of a mission-based system that is designed to perform missions consisting of a random sequence of phases with random durations. The cost structure considered in Çekyay and Özekici [176] includes phase dependent maintenance costs.

9.2 Lessons learned

- Maritime assets that are used for specific operations such as oil and gas terminal services, dredging, geophysical surveys, and military missions are typically not subject to a repetitive operation plan like for aircrafts. In addition, the duration of such operations is much longer than those of aircrafts. For example, military missions can last from three to seven months during which certain maintenance actions cannot be performed. Despite the existence of the moving asset characteristic in the airline industry, the associated literature cannot directly address the specific features in the maritime sector. To take these specific features into account, uncertainties regarding mission times, durations, and requirements associated with missions should be incorporated into the existing models.

- The condition-based information provided by sensors can be especially useful for critical systems operating in environments that vary randomly over time. Indeed, changes in environmental conditions can be related to the rate at which degradation accumulates [171]. This would be useful to compute accurate reliability and availability measures for such systems. As such, appropriate maintenance strategies can be developed.

- Lateral transshipments within an echelon are shown to be suitable when transshipment costs are relatively low compared to inventory holding and stock-out costs (cf. Section 7.1). Since maritime assets can be dispersed around the world and change location during operations the benefit of lateral transshipments should be analyzed considering some specific factors. These include distance, accessibility and possibility of information sharing during operations.

9.3 Future research directions

- In the maintenance planning literature, the consideration of moving assets under uncertainties regarding mission time, type, and duration is not elaborately addressed. For example, one can focus on models enabling dynamic pre-mission decisions such as whether to execute preventive maintenance tasks before the mission starts or to put spare parts on board of the ship to be prepared for corrective actions during missions. In this topic, the only exception that we are aware of is the work of Tinga and Janssen [77], in which the focus is the optimization of maintenance intervals considering the variation in the deployment of a maritime asset.

- The research on maintenance planning for systems facing randomly varying environments is limited. In addition, the cost, the quality, and the lead time associated with inspection, supply, maintenance and repair actions might depend on the environment and the location where the assets operate. These aspects are worthy of consideration for future research.

- A specific fact to be considered in a maritime sector environment is the last minute changes in maintenance schedules due to weather conditions. Indeed, during bad

weather times where the assets cannot operate, an opportunity to perform preventive maintenance arises. This requires the incorporation of environmental uncertainties regarding maintenance opportunities into maintenance planning and scheduling models.

- There are several open aspects related to the design of how emergency lateral transshipment should be used and how different bases should be grouped considering the possibility of spare parts pooling for moving assets.

10 Economic dependency

In technical systems on-board of the maritime assets, components are usually economically dependent, i.e., costs can be saved when several components are jointly maintained. This is the case for systems in which the maintenance of each component requires preparatory or set-up work that can be shared when several components are maintained simultaneously. In the maritime sector, the set-up cost may consist of the preparation cost associated with dismantling and opening the system (including man-hours) and the downtime cost since certain systems cannot be maintained during operations, i.e., the ship should return to the harbor and the system should be shut down for maintenance.

10.1 State-of-the-art

The literature on multi-component maintenance models under economic dependence has received great attention to date. The review article of Cho and Parlar (1991) [89] gives an overview of multi-component maintenance literature. Dekker et al. (1997) [182] review multi-component maintenance models with economic dependence. They distinguish between stationary models, where a long-term stable situation is assumed, and dynamic models, which can take the information that becomes available on the short term into account. Within the stationary models, they classify the models based on the options of grouping maintenance activities: grouping corrective maintenance, grouping preventive maintenance, and combining preventive and corrective maintenance (also referred to as opportunistic maintenance). Nicolai and Dekker (2008) [91] summarize the multi-component maintenance literature by providing a classification based on the dependence/interaction between components in the system considered: economic, structural and stochastic dependence.

Within the multi-component maintenance literature with economic dependence, a growing interest to the opportunistic maintenance is observed. A recent review and discussion on this approach is provided by Ab-Samat and Kamaruddin [92]. After reviewing various descriptions and definitions, they describe the opportunistic maintenance as: "the planning and scheduling of maintenance activities to repair a component, whilst at the same time opportunistically repair/replace other components in the system, with the aim to avoid future failures and reduce the amount of machine downtime". Some recent papers combine the opportunistic maintenance with the CBM concept. Zhu et al. [183] develop a mathematical model to optimize the CBM policy for systems with a large number of components subject to a high joint setup cost. To reduce the total setup cost, their model opportunistically coordinates the maintenance tasks by introducing a static joint maintenance interval. Their approach provides a large cost-saving potential, comparing with the corrective maintenance policy. Koochaki et al. [184] examine the impact of opportunistic maintenance on the effectiveness of CBM.

Koochaki et al. [185] analyze this problem by taking the planning of maintenance engineers into account. Both papers conclude that under certain settings, age-based replacement results in smoother maintenance plan while CBM remains cost effective.

10.2 Lessons learned

- Existing opportunistic maintenance models are theoretical rather than practical. Despite an abundance of papers conducting theoretical research on opportunistic maintenance, a few real-world applications have been done [92]. Many maintenance policies are not analytically tractable for real-world problems [91].

- By conducting corrective and preventive maintenance simultaneously, more failures can be avoided and the number of times equipment needs to be shut down for maintenance can be reduced. Sound decisions should be made while forming the groups of components to be replaced simultaneously. The main concern with certain static policies (like the block replacement policy) is replacing newly replaced components again to respect the predefined rules. This would increase maintenance costs by wasting the components lifetime [92]. Therefore, it is worthwhile to take the short term information into account while making maintenance/replacement decisions for such systems.

- The main advantage of preventive maintenance is that it is plannable. Although opportunistic maintenance provides cost effective solutions it takes this advantage away, when it combines preventive maintenance with random failure occasions. This may raise issues related to spare parts and resource planning due to the uncertainties involved.

10.3 Future research directions

- Regarding mathematical models developed for opportunistic maintenance, some adjustment with the assumptions and limitations should be made for their successful implementation in industry. Further research is needed to render opportunistic maintenance models more practical and easy to implement.

- There exist many open aspects regarding the combination of CBM and opportunistic maintenance concepts.

11   Long life-cycles

The useful life of maritime assets is more than two decades. This raises several issues including the risk of obsolete technologies, unplanned usage requirements, and unavailability of maintenance skills and spare parts. The characteristic of long life-cycles should be considered while making decisions on system design, maintenance service contract design, maintenance planning, part demand forecasting, and spare parts planning.

11.1 State-of-the-art

For assets with long life-cycle, the future system requirements and usage can largely be unknown during the design phase. For maritime assets, the degradation of difficult-to-upgrade hull structures is shown to be one of the key drivers of vessel retirement and

life cycle maintenance costing. Collette [186] reviews existing structural design approaches and recent developments in this field and give an example of the type of approach that could be taken in a more system-oriented view.

There are several challenges related to selecting a satisfactory maintenance organization to support technologically advanced assets with long life-cycle. These include on the one hand failure, cost, and usage related uncertainties and on the other hand the conflict of interest between the different actors involved. Considering a multi-dimensional decision criteria, Emblemsvåg and Tonning [187] apply the AHP to select an appropriate maintenance organization for the radar systems of the Norwegian Army. Jackson and Pascual [188] develop a non-cooperative game formulation to negotiate pricing in maintenance service contracts. They consider aging equipment with a long life-cycle and focus on a case with increased failure intensity over time.

Managers may decide to replace one asset with another at several stages of the asset life considering newly obtained information and the mitigation of uncertainties regarding future resources and costs. Zambujal-Oliveira and Duque [189] analyze the problem of asset replacement by investigating the optimal moment of replacement. They apply an operation and maintenance cost minimization model, based on the equivalent annual cost analysis. Asset replacement often occurs in the form of a new technology that renders existing spare parts inventories obsolete. Nguyen et al. [190] study the impact of spare parts inventory on equipment maintenance and replacement decisions under technological change. Kumar and Saranga [191] present mathematical models that can be used to calculate the impact of various obsolescence mitigation options on the total LCC of a system. In particular, they focus on three options: final order, redesign, and their combination. We refer the reader to Section 6.1 for other related works focusing on spare parts obsolescence.

11.2 Lessons learned

- For many complex systems (especially, defense systems such as battleship, fighter aircraft, tanks etc.), obsolescence management is the key issue. This is because such systems are subject to continuous technological changes during their long life-time. Especially, obsolescence of electronic parts is shown to be a major reason for the high LCC of such systems [207].

- For systems with long life-cycles, system knowledge may deteriorate in time rendering repairs more difficult and costly. For instance, with the retirement of expert maintenance engineers, the maintenance knowledge in old equipment may be lost. This aspect may have a significant impact in practice. Therefore, maintenance and event information should be well recorded and documented during the asset life-time. Information systems should be efficiently used to prevent the knowledge deterioration.

11.3 Future research directions

- There is scope for future research to develop mathematical models for choosing optimal obsolescence mitigation strategies [191]. This includes determining the best decision among life-time extension, cannibalization, redesign, spare parts final order, and asset replacement.

- Future research can focus on how to mitigate maintenance knowledge deterioration

for aging systems.

12 Concluding remarks and open research topics

In this paper, we have reviewed the literature on maintenance and service logistics management. The literature is classified and the lessons learned are highlighted from a maritime sector perspective. The maritime sector characteristics used for classification are derived from our observations from the maritime sector. These characteristics are also relevant for various capital-intensive industries such as aircraft/aerospace, defense, and automotive. Therefore, this review is relevant for a much broader range of capital goods than maritime assets.

We listed a number of open research directions in the previous sections. Nevertheless, based on our discussions with practitioners from the maritime sector and our overall literature review, we conclude that the following open research topics deserve a higher priority than the rest presented in our paper, when their relevance and potential impacts are considered:

(a) In practice, collecting information related to system condition, usage, and operating environment might be very costly. One should investigate appropriate maintenance and resource planning decisions under different information levels in order to assess the value of information and to identify the settings under which higher monitoring levels result in higher system availability and/or lower system costs.

(b) For systems with economically and/or structurally dependent components, investigating an efficient combination of CBM and opportunistic maintenance concepts is worthwhile for the development of dynamic maintenance and resource planning models.

(c) Future research should focus on how to optimize service levels in maintenance service contracts by considering all of the maintenance resources required (including spare parts, maintenance engineers, service tools, and infrastructure) in the multi-echelon maintenance network.

(d) More research is needed to take the requirements arising from the mandatory surveys into account while making maintenance strategy selection and maintenance planning decisions.

(e) How to incorporate the specific features resulting from the moving asset characteristic, e.g., uncertainties in operation plans (affecting the preventive maintenance opportunities), randomly varying environments (affecting the failure behaviors), and changes in operating locations (affecting service offerings of the suppliers, related costs, and lead times) into maintenance and resource planning decisions should be further investigated.

Table 2 positions these open research topics in a sub-matrix of the classification provided in Section 2. This positioning reflects a significant need of joint maintenance and resource planning models incorporating specific aspects related to scarcity of failure-related data, multi-actor setting and economic dependency.

Our selection of suggested future research topics stems from the current needs and prominent trends in the maritime sector. First of all, we observe significant issues related to data availability. Failure-related historical data is limited due to excessive

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preventive maintenance practices and the existence of one-off systems. Moreover, event data is not routinely recorded starting from the early stages of the vessel life and data collection/reporting are not always automated through a maintenance information system.

Second, there is a trend to shift from time-scheduled preventive maintenance towards CBM. The development of online sensor technologies motivates this trend. However, the current conservative maintenance strategies are partly due to the strict rules imposed by Classification Societies. In order to fully benefit from CBM concept in the maritime sector, Classification Societies may also consider changing some of their rules regarding the periodic survey intervals and the associated requirements.

Finally, the level of collaboration and information sharing is currently very low among different actors in the maritime sector. Nevertheless, there is a growing interest in improving collaboration between asset owners and system suppliers who intent to extend their role in the maintenance network. A way of facilitating this is to establish performance-based service contracts. The benefit of increased collaboration through means such as performance-based service contracts needs to be investigated before taking concrete actions.

Characteristics /Subdomains	Maintenance service contract design	Maintenance strategy selection	Maintenance planning	Failure/ prognosis/ part-demand forecasting	Spare parts inventory planning and logistics
Multi-actor setting	(c, e)	(c)	(c, e)		(c, e)
Small amount of failure-related data			(a)	(a)	(a)
Mandatory surveys		(d)	(d)		
Multi-echelon structures	(c)		(c)		(c)
Multi-indenture structures			(b)		(b)
Moving assets	(e)		(e)	(e)	(e)
Economic dependency			(b)		(b)

Table 2. Positioning of open research topics

Acknowledgements

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466	2014	An Exact Algorithm for the Vehicle Routing Problem with Time Windows and Shifts	Said Dabia, Stefan Ropke, Tom Van Woensel

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372	2012	Spare parts inventory pooling: how to share the benefits?	Frank Karsten, Rob Basten
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347	2011	An approximate approach for the joint problem of level of repair analysis and spare parts stocking	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
346	2011	Joint optimization of level of repair analysis and spare parts stocks	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
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339	2010	Analysis of a two-echelon inventory system with two supply modes	Joachim Arts, Gudrun Kiesmüller
338	2010	Analysis of the dial-a-ride problem of Hunsaker and Savelsbergh	Murat Firat, Gerhard J. Woeginger
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330	2010	Using pipeline information in a multi-echelon spare parts inventory system	Christian Howard, Ingrid Reijnen, Johan Marklund, Tarkan Tan
329	2010	Reducing costs of repairable spare parts supply systems via dynamic scheduling	H.G.H. Tiemessen, G.J. van Houtum
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