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A brief literature review on ship management in maritime transportation

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Abstract. This article briefly surveys the current state-of-the-art on ship management in maritime transportation. It covers three most important aspects of ship management: crew scheduling, maintenance scheduling, and spare part management.

1 Ship management

Shipping is the most important way for long-distance container transportation around the world. Nowadays 85% of the international trades are carried out by ships. There are worldwide 25 000 to 30 000 vessels and over 1.4 million seamen. Managing these ships and crew results in a potential market size of 3 to 5 billion US dollars per annum [15]. Besides, maritime transportation is also an active research field of operations research (OR). Christiansen et al. [5] have summarized various OR problems arising in the maritime transportation, including ship design, liner network design, ship routing and scheduling, speed selection, environmental routing, ship loading, and ship management. Most of the research effort in the OR community are devoted on the field of ship routing and scheduling, as can be found in a recent survey by Christiansen et al. in [6] or a survey of works mainly from the last century in [7]. In this article, we focus on the issue of ship management. The main research problems in ship management include *crew scheduling*, *maintenance scheduling*, and *spare part management*, as identified in [5]. Each of these problems will be detailed below.

2 Crew scheduling

The term "crew scheduling" is widely used for personell management in transportation such as ships, airlines, trains, buses, trucks, and also other non-transportation systems such as home care, police services (see a literature survey in e.g. [11]), while the term “crew” originally refers to the seamen working on board a ship. However, the crew scheduling problem at sea has received little attention by the OR community. Christiansen et al. [5] distinguished the maritime crew scheduling problem by two types of ships: short-sea vessels and deep-sea vessels. Short-sea vessels make frequent port calls and the crew may live on shore. In such case, the crew may change frequently, and the crew scheduling becomes a challenging problem. One such example was presented in a study by Wermus and Pope [30] on scheduling the harbour pilots that guide the big ships into a harbour. A schedule of a harbour pilot is a sequence of on-days, off-days, and standby-days, such that the labor regulations such as maximum consecutive working hours are satisfied, and the workloads are distributed fairly. A simple heuristic was applied to this end. On the other hand, the deep-sea vessels usually have a stable crew staff which will spend a long time such as months at sea, and the crew live on board. The crew scheduling is not considered a major issue by [5].

Since the recession in 2008, ship managers are facing increasing pressure in the management of the vessels so as to increase competitiveness and provide better service. According to a joint managerial survey by Germanischer Lloyd and Fraunhofer CML in 2013 [15], 88% of the ship managers considered crew management as a big challenge, and 62% considered technical management, including maintenance management, as a big challenge, due to mainly cost pressure and compliance with new regulations. With the growing global fleet size and the stricter regulations, a computer-based crew management tool is facing increasing demand to replace pinboards or Excel sheets. Such crew scheduling software should be able to plan and schedule crew to their qualified positions, in compliance with the regulations such as Maritime Labor Convention 2006 (MLC 2006) [1] which has been in force in major countries around the globe since the end of 2014. Such labor regulations ensure appropriate manning on board, guarantee regular safety and maintenance tasks to be carried out, and stipulate sufficient resting hours for each seaman. However, there exist few software that implement such new regulations. The Crew Compliance Optimizer (CCO) jointly developed by Fraunhofer CML, E. R. Schifffahrt and Bernard Schulter Shipmanagement is tailored for the compliant maritime crew scheduling, and is reported in 2014 [19]. The CCO consists of two optimization modules: the onshore module that decides crew composition and manning level under the objective of minimizing cost; the onboard module that reoptimizes working and resting hours for the crew under the objective of minimizing and balancing workload, subject to changes at short notice such as schedule delay, port facility availability, unplanned maintenance, etc. A more detailed description of how the decision support system for crew requirement construction is also given in [17].

Within the CCO framework, two different crew scheduling tasks are presented by the developer: the long-term crew scheduling with a plan horizon of months to years, and the short-term crew scheduling with a plan horizon of half-hourly based. John et al. [16] presented the long-term crew scheduling problem with a integer linear programming model for it. The goal is to help the ship manager assign up to thousands of seamen to hundreds of ships in a time span of one year. A two-step approach is used. Firstly, the contract periods are constructed taking into account the possible crew changes and position changes on a ship. In the second step, these contract periods will be assigned to qualified seamen, such that the working regulations such as minimum and maximum leave time for a seaman after serving a contract are satisfied, and the total cost is minimized. The total cost include staff salary, and also the travel cost if the seaman needs to travel (usually by air) to or from the starting or ending port of the contract. Such possibility of "deadhead" trip is also one of the main differences between maritime crew scheduling and airline crew scheduling. The airline crew scheduling [2, 14] is usually divided into two subproblems: crew pairing that chooses a sequence of flight legs that starts and ends at the same crew base and each flight destination coincides with the next flight departure; then the following crew assignment step assigns crew members to each pairing. Due to the additional deadhead possibility from one contract end port to another contract start port of maritime crew, the crew pairing and assignment can be integrated into one optimization process, which should lead to a higher optimization benefit. Besides, each flight leg takes only hours, while the contract period on a ship is usually between two and nine months, therefore, a long-term crew scheduling should also take the employee career planning into account, e.g., the seaman's experience should be distributed among different types of ships and different skills, such that they can achieve better training and obtain certain qualification and promotion. This is also termed crew planning by Chajakis [4], where it was considered important for marine transportation industry. Different professionals with specialized skills are needed on a ship, e.g., engineer, or with specific geographical acquaintance, e.g., pilot. The crew planner should decide the the right number of professionals of each specialty to hire, train, and promote, taking into account the forecasted fleet's crewing demands and the attrition in the next years. A MIP model is mentioned to be used to address a fleet's forecasted crewing needs for a time period of one to five years. The model takes as input the compensation levels, training costs, historical attrition rates and crewing demand forecasts by specialty, and suggests new hires per position versus training and promotion of existing staff.

The short-term crew scheduling problem has also started to attract attention due to the decreasing manning level onboard and the stricter labor regulations on working and resting hours as in MLC 2006. John et al. [18] presented a decision support tool for short-term crew scheduling. The goal is to schedule onboard tasks, such as watch keeping, port works, maintenance tasks, and administrative tasks, to crew members on a half-hourly basis, such that their working and resting hours are in compliance with the labor regulation MLC 2006. Such regulations on working and resting hours include, e.g., one should not work more than 14 hours in any 24 hours, one should not work more than 91 hours in any 7 days, and there should not be more than two resting period for each member per day and each resting period should be at least 6 hours. The onboard tasks can be differentiated by the time flexibility: the fixed-time tasks such as watchkeeping, port works etc. that must be performed at the planned time; and the flexible-time tasks, such as administrative tasks, maintenance tasks etc. that allows time flexibility to be done within e.g. one day. An integer linear programming model for this working and resting hours optimization is presented, and a greedy-type heuristic is proposed as solution approach, which sort the list of tasks by flexibility such that more flexible task (in terms of time and crew eligibility) will be assigned later. The greedy objective of the assignment is two-fold: the objective of the office mode is to reduce crew cost, while the objective onboard mode is to balance workload and to reoptimize in case of unplanned change in port schedule and crew availability.

3 Maintenance scheduling

Maintenance management forms the most important aspect from the technical management, which is considered the second biggest challenge by ship managers [15]. Maintenance can be classified into two basic types according to [29]: the *corrective maintenance* and the *preventive maintenance*. The corrective maintenance is performed *after* a failure onboard a ship occurs and a repair is required to restore its function. Such maintenance is also referred to as repair. The preventive maintenance is usually performed *before* an onboard failure occurs to keep the ship in good state and avoid unexpected breakdowns. The preventive maintenance can be further distinguished into two types: the first type consists of *onboard* maintenance activities that can be performed every day during the voyage without disturbing the operations, such as routine inspection; the second type consists of *harbour-based* maintenance activities which can be performed only when the ship is at harbour, including mandatory system survey, overhaul, etc. Deris et al. [9] further distinguished harbour-based maintenance activities into medium scale and major scale by whether they require a dockyard (major) or can be performed when anchored (medium). Here, we extend the harbour-based maintenance by including also corrective maintenance, since they do not have major difference from the scheduling perspective.

Most of the existing works focus on harbour-based maintenance. De Boer et al. [8] presented a decision support system for harbour-based maintenance, overhaul and repair of navy ships in Netherlands. The maintenance tasks of each ship are divided into several jobs with precedence constraints. Each job has a release date and requires certain amount of different resources, such as personnel working hours, and equipments such as dockyard. The objective is to efficiently plan and schedule all maintenance tasks within the resource capacity. Two capacity planning models are presented, an aggregate model that uses aggregate data to make rough estimation of project completion time under capacity constraints, and a detailed model based on the resource constrained project scheduling problem. Mourtzis [20] also presented a similar software system of capacity planning for managing ship repair operations. Deris et al. [9] considered also scheduling harbour-based maintenance tasks including overhaul and repair for the naval ships in Malaysia. The maintenance tasks are assumed to be given in a cyclic fashion based on maintenance requirements, with a plan horizon of 200 weeks, and a plan time interval of one week. The task is to optimize the starting time of the maintenance cycle of each ship, such that the ship availability is maximized, and the resource constraints, such as dockyard availability, are satisfied. This problem is modelled into a constrained satisfaction problem, and solved by genetic algorithm.

Only few works considered scheduling onboard maintenance activities. Go et al. [13] presented a work on scheduling of both maintenance and ship subsystem operations for a container ship in Korea. They classified the onboard maintenance activities into two types, the routine maintenance activities and the operation-dependent maintenance activities. The routine maintenance activities, such as simple inspection and repair, are usually cyclic and deterministic. On the other hand, the operation-dependent maintenance activities, such as part replacement, are usually performed on a due date when the cumulative usage time of a certain part reaches a prescribed limit. For an overview on the usage based maintenance requirement prediction in preventive maintenance, we refer to [27]. The maintenance scheduling also takes into account the crew availability and their maximum working hours. The delay of maintenance task from its due date, or tardiness, is to be minimized, as it increases systematic risks, while the early maintenance from its due date is also to be minimized, since it increase spare part cost and crew workload. The objective is to schedule ship operations and maintenance simultaneously, such that the total deviation from maintenance due dates are minimized. A mixed integer programming model is presented to define the problem, and due to the difficulty of this real-world problem, one problem specific construction method and a local search method is proposed as solution approach.

More literature survey on the topic of maintenance and service logistics in the maritime sector can be also found in [12].

4 Spare part inventory planning

In order to perform onboard maintenance, the ship must carry spare parts on board. The amount of spare parts to carry onboard depends on the frequency of the port calls, and the spare part availability at these ports [5]. Furthermore, the spare part inventory to carry onboard also depends on the inventory planning model based on the available procurement budget, the onboard spaces to store them, and the maintenance and repair by the crew. Therefore, which spare parts to be carried onboard and at which port to order the needed spare parts is an open problem.

Spare parts in general can be distinguished into two types, the *repairable* parts and the *consumable* parts. When the maintenance requirement for a repairable part is due, it is first replaced by a new part, then it is sent to a repair shop for reparation, and thereafter it joins the inventory to replace another part that is required maintenance. On the other hand, the consumable parts are discarded once its maintenance requirement is due, and is replaced by a new part. Some repairable items may fail to recover. Such phenomena are referred to as *condemnation*.

The traditional inventory models use item-oriented service measures such as to maximize the fill rate, i.e., the percentage of requested parts that can be filled immediately (see e.g. [25]). A system-oriented approach measures the availability of the whole system instead of a particular item. One of the first such ideas was implemented in the Multi-Echelon Technique for Recoverable Item Control (METRIC), proposed by Sherbrooke in his seminal work [22] on the inventory management for US Air Force. In the METRIC model, a technical system is composed of multiple items, each of which is assumed to require maintenance according to a Poisson process. Also given in the model are multiple warehouses where the spare parts are stocked. If an item fails at a warehouse without enough stock, a backorder is sent to a central depot, and a shipment time for the order needs to be waited. The optimization model is to minimize the total cost for holding the stocks, such that certain service level is attained, e.g., a maximum expected backorders is not exceeded, or alternatively the expected waiting time is not too long. Extensive survey on the system-oriented inventory planning can be found in the book by Sherbrooke [24], and a more recent survey is presented by Basten and van Houtum [3]. Rustenburg et al. [21] have studied under the maritime context an extended METRIC model, namely, VARI-METRIC [23], and applied it to the spare part inventory management for the Royal Netherlands Navy. They pointed out the limitations of the VARI-METRIC models such as the assumption of infinite capacity for repair, and the assumption that all items can be repaired, i.e., with no consumable parts and zero condemnation. The first limitation was addressed in the work by Diaz and Fu [10]. They introduced a queuing system to represent the capacitated repair shop, integrated it into the METRIC models, and observed that the traditional METRIC models may lead to underestimation of spare part requirements. The trade-offs between spare part inventory and repair capacity is further analyzed in [26], and an integrated optimization of the inventory control and repair capacity is presented. Van der Heijden et al. [28] have further observed that enabling faster maintenance activities by, e.g., hiring more manpower, leads to less spare part requirements to achieve the same service level.

The last a few works show that the spare part management has a strong interrelation with the onboard maintenance scheduling as in Section 3 and the crew scheduling in Section 2. A higher manning level onboard for the maintenance and repair tasks may reduce the amount of spare parts to be carried. Therefore, the decision of maintenance schedule in Section 3 can be made jointly with the spare part inventory planning to achieve higher optimization potential.

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