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Step-wise stowage planning of roll-on roll-off ships transporting dangerous goods

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ABSTRACT

Planning stowage with the presence of dangerous goods is critical to ensure safety at sea. In this paper, we propose a step-wise stowage planning approach to generate optimal stowage plans for roll-on roll-off ships transporting trailers (some containing dangerous cargo) between two ports. The planning approach consists of three steps, where Step 1 maximizes the number of dangerous cargo units to transport while adhering to the International Maritime Dangerous Goods regulations. Step 2, which is optional, maximizes the safety distance among the dangerous cargo units found in the first step. Finally, in Step 3, the ballast water intake needed to ensure stability of the ship is minimized, as this has a significant effect on the fuel consumption. Computational results on instances generated based on real data from a shipping company show that the proposed planning approach might both reduce the ballast water intake (and hence reduce the fuel consumption) and increase the safety distance among dangerous cargo units.

1. Introduction

From 2015 to 2019, there have been 19,418 marine casualties and incidents, including 496 fatalities, 6210 persons injured and 21,392 ships involved (European Maritime Safety Agency, 2020). Safety at sea has been improved during the past years through better ship design and stability, advanced maritime technologies and more strict international regulations developed by International Maritime Organization. As one of the most international and dangerous industries, shipping is responsible for the transportation of a great amount of dangerous cargo. When transporting dangerous goods in closed forms, they need to be properly packaged and segregated according to the International Maritime Dangerous Goods (IMDG) Code (International Maritime Organization, 2016) in order to be loaded on for example, container, roll-on roll-off (RoRo) or general cargo ships. The IMDG Code classifies dangerous goods into nine classes with various sub-classes within and provides a general segregation rules with a detailed explanation when stowing these cargo on different type of ships.

According to the IMDG code, there are mainly four segregation rules, supplemented by exceptional rules for all shipping segments, see Fig. 1. The rules in the table have the following meaning in general:

1. “away from”
2. “separated from”
3. “separated by a complete compartment or hold from”
4. “separated longitudinally by an intervening complete compartment or hold from”

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CLASS	1.1 1.2 1.5	1.3 1.6	1.4	2.1	2.2	2.3	3	4.1	4.2	4.3	5.1	5.2	6.1	6.2	7	8	9
Explosives 1.1, 1.2, 1.5	*	*	*	4	2	2	4	4	4	4	4	4	2	4	2	4	X
Explosives 1.3, 1.6	*	*	*	4	2	2	4	3	3	4	4	4	2	4	2	2	X
Explosives 1.4	*	*	*	2	1	1	2	2	2	2	2	2	X	4	2	2	X
Flammable gases 2.1	4	4	2	X	X	X	2	1	2	2	2	2	X	4	2	1	X
Non-toxic, non-flammable gases 2.2	2	2	1	X	X	X	1	X	1	X	X	1	X	2	1	X	X
Toxic gases 2.3	2	2	1	X	X	X	2	X	2	X	X	2	X	2	1	X	X
Flammable liquids 3	4	4	2	2	1	2	X	X	2	2	2	2	X	3	2	X	X
Flammable solids (including self-reactive substances and solid desensitized explosives) 4.1	4	3	2	1	X	X	X	X	1	X	1	2	X	3	2	1	X
Substances liable to spontaneous combustion 4.2	4	3	2	2	1	2	2	1	X	1	2	2	1	3	2	1	X
Substances which, in contact with water, emit flammable gases 4.3	4	4	2	2	X	X	2	X	1	X	2	2	X	2	2	1	X
Oxidizing substances (agents) 5.1	4	4	2	2	X	X	2	1	2	2	X	2	1	3	1	2	X
Organic peroxides 5.2	4	4	2	2	1	2	2	2	2	2	2	X	1	3	2	2	X
Toxic substances 6.1	2	2	X	X	X	X	X	X	1	X	1	1	X	1	X	X	X
Infectious substances 6.2	4	4	4	4	2	2	3	3	3	2	3	3	1	X	3	3	X
Radioactive material 7	2	2	2	2	1	1	2	2	2	2	1	2	X	3	X	2	X
Corrosive substances 8	4	2	2	1	X	X	X	1	1	1	2	2	X	3	2	X	X
Miscellaneous dangerous substances and articles 9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Fig. 1. General Segregation Table (International Maritime Organization, 2016).

In this paper we consider the stowage planning problem for RoRo ships operating in short sea shipping, which are facing great challenges transporting dangerous goods. RoRo shipping is a major transport mode in the world, especially for countries with long coastlines, due to its flexible connection with road and rail transportation. These RoRo ships are carrying a number of truck trailers and several of these are classified as dangerous cargo according to the IMDG Code. Generating a stowage plan that can assign all dangerous goods with positions on various decks on board the RoRo ship while respecting their respective segregation rules and additional constraints is a challenging task, but also crucial for the safety of the ship. Furthermore, as shown by Jia et al. (2020), a good stowage plan can also reduce the need for ballast water on board the ship, which again can give significant reductions in fuel consumption, and hence environmental emissions.

Stowage planning for ships is a critical part that links different activities of the cargo operations together. This interesting yet challenging problem has attracted many researchers to tackle its variations in different sectors within maritime transportation, especially the container sector. Most of the efforts have been put on minimizing the shifting of containers in the container stowage planning, known as the master bay planning problem. A few researchers have investigated stowing container ships in the presence of dangerous goods. Parreño et al. (2016) consider stack segregation in the slot planning problem. Ambrosino and Sciomachen (2021) propose a novel procedure for stowing containers based on the principle included in the IMDG Code. We refer readers with interest to a detailed literature review (Voßet al., 2004) and an update (Stahlbock and Voß, 2007) on the topic of container terminal operation including stowage planning. Moreover, Hvattum et al. (2009) study the stowage problem in bulk shipping for chemical and product tankers, i.e. the tank allocation problem with the presence of dangerous cargo.

Stowage planning in RoRo shipping has not gained much attention from the researchers until recently. Several studies focus on deep-sea going car carriers that usually operate on routes with multiple port calls and optional cargo. Therefore the problem deals with maximizing profit by taking as many as optional cargo and minimizing shifting cost due to blocking cargo (Hansen et al., 2020; 2016; Øvstebøet al., 2011; Puisa, 2021). Other studies have also put more focus on the stability and safety side of the stowage planning. Puisa (2021) proposes three improvements to the optimization of RoRo stowage, namely finer approach to ship stability, fire safety, and cargo handling efficiency. Jia et al. (2020) propose an integrated stowage planning approach and present an optimal stowage model that minimizes ballast water intake. Some other researchers also study the stowage planning of passenger ferries (Bayliss et al., 2019; 2021). To the authors' knowledge, no research with the inclusion of the dangerous goods transportation has been conducted, which is essential to stowage planning for many RoRo ships.

This paper aims to fill the gap by extending the problem and study conducted by Jia et al. (2020), incorporating dangerous goods segregation and maximizing the safety onboard in the stowage planning process. Furthermore, in contrast to the all-in-one deterministic stowage planning model, we propose a step-wise stowage optimization method, to better accommodate the experts' opinions into the stowage planning process.

The rest of the paper is structured as follows. We start in Section 2 by introducing the problem formulation and relevant mathematical notations for the RoRo stowage planning problem with dangerous cargo, extended from the stowage problem with optimal ballast water introduced by Jia et al. (2020). Thereafter, in Section 3, we propose the step-wise optimization approach and formulate the optimization problems arising in the different steps as binary/mixed integer programming models. In Section 4, the step-wise optimization approach is tested on a number of realistic test instances, randomly generated from historical data from a RoRo shipping company, before we conclude in Section 5.

2. The RoRo ship stowage problem with dangerous goods

We consider a given RoRo ship with a set of fixed decks $\mathcal{D}$. For each deck d, there is a set of slots $\mathcal{S}_d$ where cargo units can be placed. Each slot s fits one standard sized trailer. The ship has in total N^S slots, where $N^S = \sum_{d \in D} |\mathcal{S}_d|$. RoRo ships transport primarily trailers, but also trucks, cars, and other wheeled cargo units. The scope of this paper delimitates to standard sized trailers, also called cargo units.

We consider a given departure or voyage between two ports for the ship where a set of booked trailers, hereafter referred to as cargo units C, is waiting to be planned and loaded onto the ship for its destination port. Depending on the content of the cargo units, it can be further categorized as a subset of dangerous cargo units C^D and a subset of general cargo units C^G. Usually, dangerous cargo units have an earlier cut-off time than general cargo units, meaning that they are required to be present at the terminal and ready to be loaded several hours before ship departure. An earlier cut-off time is to ensure that stowage planners can have enough time to make a good segregation plan for safety reasons. The dangerous cargo units need to be segregated on board with a certain distance according to a set of segregation rule N depending on their classes. For each cargo unit c, C_{cn} is a subset of cargo units that conflicts with cargo unit c according to segregation rule $n \in N$. $\mathcal{S}^N_{dsn}$ is a subset of slots on deck d that are prohibited to load dangerous goods according to rule n. For example, if a cargo unit c is loaded at a slot s on deck d, then no cargo units from C_{cn} can be loaded to any slot in $\mathcal{S}^N_{dsn}$ subject to segregation rule n. In addition, the commitment class of a cargo unit is categorized as either mandatory or optional. Mandatory cargo units are required to be transported on the given departure whereas optional cargo units can wait until the next departure. However, for the optimal utilization of the deck space, it is beneficial to ship as many optional cargo units as possible. We assume dangerous cargo units in general has a higher value and thus priority over general cargo units.

We introduce the following notation for various subsets of the cargo units: $C^{D,M}$ is the set of mandatory dangerous cargo units, $C^{D,O}$ is the set of optional dangerous cargo units, where $C^{D,M} \cup C^{D,O} = C^D$. $C^{G,M}$ is the set of mandatory general cargo units, $C^{G,O}$ is the set of optional general cargo units, where $C^{G,M} \cup C^{G,O} = C^G$. Each cargo unit c is contained in a standard sized trailer with a specific weight C^W_c and each deck d has a maximum allowable weight $D^{W,\max}_d$ for safety reasons. All cargo units are delivered at the terminal and available to be stowed. Loading and unloading operations are performed by tug masters driving in and out of the ship through the ramp.

The given RoRo ship has a set of ballast tanks $\mathcal{T}$, including a subset of heeling tanks $\mathcal{T}^H$ and a subset of regular ballast tanks $\mathcal{T}^B$. Ballast tanks are located and distributed alongside the bottom of the ship, carrying usually sea water with a density of ρ to balance the ship. The volume capacity of tank i is defined as $T^{\max}_i$. Heeling tanks are used to balance the ship transversely at any time, therefore, the total water volume stored in heeling tanks should satisfy a range between $H^{\max/\min}$ to provide sufficient anti-heeling capability. In addition, the regular ballast tanks come into place if stability cannot be satisfied by only adjusting the heeling tanks. According to the Admiralty Coefficient (Man Diesel & Turbo, 2011), for a given cargo load and sailing speed, the more ballast water a ship carries, the higher becomes the fuel consumption.

Stability of the ship is measured along three dimensions: vertical, transverse and longitudinal forces that are influenced by the distribution of the weight of all components on the ship. Due to the complexity of these calculation, we apply a good approximation of such measures through the composite vertical center of gravity from the keel $\overline{VCG}$, transverse center of gravity from midship $\overline{TCG}$ and longitudinal center of gravity from aft perpendicular $\overline{LCG}$, taking into account not only the weight of cargo units but also the weight of the ballast water and lightweight of the ship L^W. To achieve seaworthiness, each measurement should satisfy its maximum and minimum limiting values, that is $\overline{VCG}^{\max/\min}$, $\overline{TCG}^{\max/\min}$, and $\overline{LCG}^{\max/\min}$, respectively. For more detailed explanations of the dimensions and calculations, we refer our readers to Jia et al. (2020) and the text book by Rhodes (2003).

The aim of the RoRo ship stowage problem with dangerous goods is to minimize the fuel consumption by carrying the minimal amount of ballast water while at the same time maximizing safety by maximizing the distance among the dangerous cargo units on board the ship. We consider decisions such as the number of optional dangerous cargo units to carry, the mass of water in each ballast tank t_i, and the placement of each individual cargo unit subject to the IMDG segregation rules, weight distribution, and other stowing requirements. We introduce the binary decision variable x_{cds} for the placement of the cargo units, which is equal to 1 if cargo unit c is loaded at slot s on deck d, and 0 otherwise.

3. Step-wise stowage optimization approach

As a decision support tool, we propose a step-wise stowage optimization approach with the ability to incorporate experts inputs, thus more robustness, flexibility and usability to the generated final stowage plan. The solution approach consists of three steps, where each step includes an optimization problem with given objectives and constraints. The flow of proposed step-wise planning process is illustrated in Fig. 2. Step 1 maximizes the number of optional dangerous cargo units to be carried on board the ship as it is assumed that one always wants to transport as many dangerous cargo units as possible to reduce this number for the following departures along the same route. It selects a list of optional cargo units to be loaded and generates a preliminary stowage plan for both mandatory and optional dangerous cargo units that obeys the IMDG segregation rules. Depending on whether we want to maximize

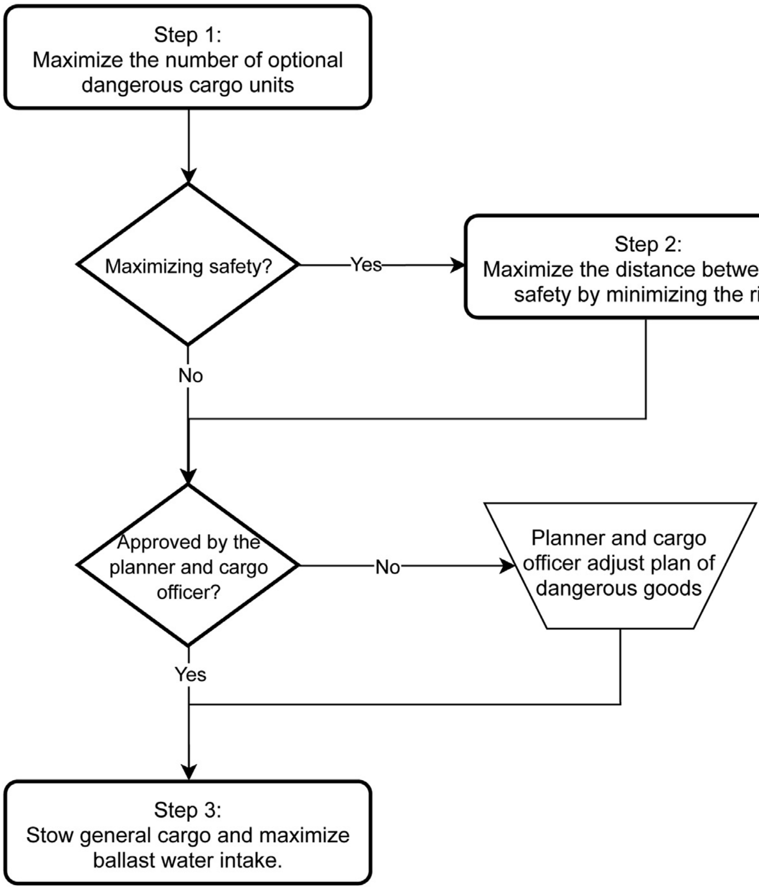


Fig. 2. Step-wise stowage optimization process with the presence of dangerous goods.

safety by maximizing the distance among the dangerous cargo units even beyond the minimum requirements given by the segregation rules, the step-wise solution approach follows either one of two directions: 1) *full optimization* and 2) *partial optimization*.

In 1) full optimization, we aim at maximizing the safety (i.e. beyond the minimum requirements defined by the segregation rules). Step 2 is then activated to maximize the distance between slots that are loaded with dangerous cargo units. It generates a preliminary plan for all dangerous cargo units selected in Step 1. Now the preliminary stowage plan for all the dangerous goods selected is available for approval. The stowage planners and/or cargo officers have the flexibility to manually adjust the optimal stowage plan for dangerous goods if there are any preferences or exceptions to be made due to certain circumstances. In the end, Step 3 fixes the approved preliminary stowage plan for dangerous goods as input from Step 2, and stows the rest of the cargo units, namely the general cargo units to minimize the ballast water intake and thus reduce fuel consumption. In 2) partial optimization, Step 2 is skipped and Step 3 takes the fixed stowage plan for the dangerous cargo units from Step 1 as input.

The rest of the section describes the optimization problem of each step. We refer readers to Appendix A for a complete list of notations used in this paper.

3.1. Step 1: IMDG planning - maximizing dangerous cargo units intake

For a given departure with a load list that has more cargo units to transport than the ship capacity allows, a stowage plan becomes simply infeasible without selecting which cargo units to transport. The difficulty arises in the presence of dangerous cargo units since it is not intuitive how many can be loaded on the ship without violating the segregation rules. In Step 1, we want to create a feasible stowage plan with the maximum number of dangerous goods the ship can carry while obeying the segregation rules. This is done through the following optimization model:

$$\max \sum_{c\in C^{D,O}} \sum_{d\in D} \sum_{s\in S_d} x_{cds} \tag{1}$$

subject to:

$$\sum_{d\in D} \sum_{s\in S_d} x_{cds} = 1, \quad c \in C^{D,M} \tag{2}$$

$$\sum_{c \in C^D} x_{cds} \leq 1, \quad d \in \mathcal{D}, s \in \mathcal{S}_d \tag{3}$$

$$\sum_{c \in C^{D,O}} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} x_{cds} \leq N^S - |C^{D,M}| - |C^{G,M}| \tag{4}$$

$$\sum_{c' \in C_{cn}} \sum_{s' \in \mathcal{S}^N_{dsn}} x_{c'ds'} \leq 1 - x_{cds} \quad c \in C^D, d \in \mathcal{D}, s \in \mathcal{S}_d, n \in \mathcal{N} \tag{5}$$

$$x_{cds} \in \{0, 1\} \quad c \in C^D, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{6}$$

Objective function (1) maximizes the number of optional dangerous cargo units that are are carried on board the ship. Constraints (2) make sure that all the mandatory dangerous cargo units are loaded, while constraints (3) ensure that each slot contains at most one (dangerous) cargo unit. Constraint (4) makes sure that the number of optional dangerous cargo units does not exceed its capacity on the ship, which is calculated by deducting the number of mandatory cargo units from the number of available slots on the ship. Segregation rules are represented in constraints (5). If dangerous cargo unit c is placed in slot s on deck d, then no cargo unit $c' \in C_{cn}$ can be loaded at any slot $s' \in \mathcal{S}^N_{dsn}$. Binary requirements for the variables are imposed through constraints (6).

As a result of solving the Step 1 model, a set of optional dangerous cargo units is selected and a preliminary stowage plan for the mandatory and selected optional dangerous cargo units is generated. An updated set of dangerous cargo units $C^{D'}$ including the selected optional dangerous cargo units and mandatory dangerous cargo units is formed and used as input in Steps 2 and 3. Accordingly, since the ship capacity remains the same and should be utilized at most, we load as many general optional cargo units as possible. The available capacity for general optional cargo units is the ship's capacity minus the number of mandatory general cargo units and selected dangerous cargo units. We denote the new subset of general optional cargo units that are selected for loading as $C^{G',O}$. Thus, by updating relevant cargo sets, we have the followings: $C^{G'} = C^{G,M} \cup C^{G',O}$ and $C' = C^{G'} \cup C^{D'}$.

3.2. Step 2: IMDG planning - maximizing safety

For a given list of dangerous cargo units to be loaded (obtained from Step 1), it is important to ensure that the stowage complies with the segregation rules. Moreover, it is beneficial to stow them as further apart from each other as possible to reduce the risk of accidents. Step 2 therefore aims to improve the safety beyond the minimum requirements given in IMDG segregation rules, i.e. maximizing the distance among slots loaded with dangerous cargo units. We propose two alternative models for this purpose: an intuitive distance maximization formulation (Section 3.2.1) and a risk minimization formulation (Section 3.2.2).

3.2.1. Distance formulation

We define $D_{dsd's'}$ as the distance between slot s on deck d and slot s' on deck d'. If slots s and s' are on the same deck, the distance is calculated as the minimum Euclidean distance between them. If the slots are on different decks, the distance is given as a number that is slightly larger than the distance required by the strictest segregation rule. We assume that if two dangerous cargo units are placed so far apart from each other then it does not matter if they are on the same deck. The objective of maximizing the distance among the dangerous cargo units can the be written as follows:

$$\max \sum_{c \in C^{D'}} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} \sum_{c' \in C^{D'}} \sum_{d' \in \mathcal{D}} \sum_{s' \in \mathcal{S}_{d'}} D_{dsd's'} x_{cds} x_{c'd's'} \tag{7}$$

The objective function (7) maximizes the sum of distance between slots loaded with dangerous cargo units. It can be noted that it becomes quadratic. Therefore, we introduce a new binary variable $y_{dsd's'}$, which takes the value 1 if dangerous cargo units are placed in both slots $s \in \mathcal{S}_d$ and $s' \in \mathcal{S}_{d'}$, and 0 otherwise. We can then obtain the following linear formulation for maximizing the distance among slots with dangerous cargo units:

$$\max \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} \sum_{d' \in \mathcal{D}} \sum_{s' \in \mathcal{S}_{d'}} D_{dsd's'} y_{dsd's'} \tag{8}$$

subject to:

(5)

$$\sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} x_{cds} = 1, \quad c \in C^{D'} \tag{9}$$

$$\sum_{c \in C^{D'}} x_{cds} \leq 1, \quad d \in \mathcal{D}, s \in \mathcal{S}_d \tag{10}$$

$$y_{dsd's'} \leq \sum_{c \in C^{D'}} x_{cds}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, d' \in \mathcal{D}, s' \in \mathcal{S}_{d'} \tag{11}$$

$$y_{dsd's'} \leq \sum_{c' \in C^{D'}} x_{c'd's'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, d' \in \mathcal{D}, s' \in \mathcal{S}_{d'} \tag{12}$$

$$y_{dsd's'} + 1 \geq \sum_{c \in C^{D'}} x_{cds} + \sum_{c' \in C^{D'}} x_{c'd's'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, d' \in \mathcal{D}, s' \in \mathcal{S}_{d'} \tag{13}$$

$$x_{cds} \in \{0,1\} \quad c \in C^{D'}, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{14}$$

$$y_{dsd's'} \in \{0,1\} \quad d \in \mathcal{D}, s \in \mathcal{S}_d, d' \in \mathcal{D}, s' \in \mathcal{S}_d \tag{15}$$

The model additionally requires the segregation constraints (5) introduced in Section 3.1. Constraints (9) require that all the dangerous cargo units selected in Step 1 are placed in a slot. Constraints (10) ensure that each slot contains at most one cargo unit. Constraints (11), (12) and (13) link the new binary variables y with the original decision variables x. Constraints (11) ensure that if slot s does not contain dangerous cargo unit c, $y_{dsd's'}$ is forced to be 0, similarly with constraints (12). Constraints (13) force $y_{dsd's'}$ value to be 1 if and only if both x_{cds} and $x_{c'd's'}$ are 1. However, since the objective function maximizes the value of y, this set of constraints becomes redundant. Finally, the binary requirements on the variables are imposed through constraints (14) and (15).

3.2.2. Risk formulation

Even though the distance formulation in Section 3.2.1 is intuitive, the enumeration of combination of slots on different decks results in a vast number of y variables and constraints. Therefore, we propose another formulation by introducing a risk parameter $R_{dss'}$ to represent the risk measurement between slots s and s' on (the same) deck d. $R_{dss'}$ is set to its maximum value if slots s' and s are neighboring slots, and its value decreases as the distance between slots increases until it takes the value 1 when slots s and s' are as far apart from each other as possible on the given deck. The risk parameter between two slots on different decks is set to zero.

Based on this, we can implicitly maximize the distance between dangerous cargo units by minimizing the total risk with the following binary programming model:

$$\min \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} \sum_{s' \in \mathcal{S}_d} R_{dss'} y_{dss'} \tag{16}$$

subject to:

(5)

(9)

(10)

$$y_{dss'} \leq \sum_{c \in C^{D'}} x_{cds}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{17}$$

$$y_{dss'} \leq \sum_{c' \in C^{D'}} x_{c'ds'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{18}$$

$$y_{dss'} + 1 \geq \sum_{c \in C^{D'}} x_{cds} + \sum_{c' \in C^{D'}} x_{c'd's'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{19}$$

$$x_{cds} \in \{0,1\} \quad c \in C^{D'}, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{20}$$

$$y_{dss'} \in \{0,1\} \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_d \tag{21}$$

The structure of the constraints in the risk formulation resembles that of the distance formulation in Section 3.2.1. Segregation is enforced through constraints (5) introduced in Section 3.1. The risk formulation shares the same constraints (9) and (10) that ensure dangerous cargo units are loaded exactly once and that each slot can not load more than one cargo unit respectively. Constraints (17), (18) and (19) link the new linear variables y with the decision variables x. Unlike the distance formulation, constraints (19), which force $y_{dss'}$ to be 1 if and only if both x_{cds} and $x_{c'ds'}$ are 1, are necessary in the risk minimization formulation due to its objective of minimizing the risk. Finally, the binary constraints on the variables are imposed through constraints (20) and (21).

Compared to the distance formulation, the advantage of the risk formulation is that it significantly reduces the number of y variables (and constraints) since we no longer need to consider the combination of slots between decks. The objective function will automatically prioritize the stowage of dangerous goods into separate decks if possible, where the risk parameter is set to zero. Therefore, we choose to adopt the risk formulation for Step 2 of the step-wise stowage optimization approach based on its better performance (based also on preliminary tests with both formulations).

The solution of the Step 2 risk formulation generates a preliminary stowage plan for all dangerous cargo units that minimizes the risk of accidents. The plan illustrates how dangerous goods can be stowed with maximal distance in between and supports both cargo stowage planners and cargo officers to make a safer stowage plan that is at least in accordance with the minimal requirements of the IMDG segregation rules.

3.3. Step 3: general cargo units planning - minimizing fuel consumption

Given a preliminary stowage plan with fixed positions for dangerous cargo units either from Step 2 (in case of full optimization) or from Step 1 (in case of partial optimization), Step 3 aims to minimize the fuel consumption by minimizing the intake of ballast water. This step deals with the stowage of the rest of cargo units, i.e. the general cargo units that do not require any segregation. By designing a plan that optimally places cargo units into the right slot by using its weight to balance the ship and satisfy stability and safety requirements, we can significantly reduce the amount of excess ballast water the ship has to carry.

In addition to the notations described in Section 2, we introduce the following notations for parameters used to calculate stability in Step 3. In order to calculate $\overline{VCG}, \overline{TCG}$, and $\overline{LCG}$, we introduce the vertical, transverse, and longitudinal center of gravity for cargo units as $C_c^{VCG}, C_c^{TCG}, C_c^{LCG}$, for slots as $S_s^{VCG}, S_s^{TCG}, S_s^{LCG}$ and for the ship as $L^{VCG}, L^{TCG}, L^{LCG}$ respectively. The vertical center of gravity of each ballast tank $i \in T$ depends on the mass of the water t_i inside the tank and its area of base T_i^{AoB}. The objective of the third step of stowage planning is to optimize the amount of water carried in regular ballast tanks. The formulation of Step 3 is adopted based on the model introduced in Jia et al. (2020) and shown as below:

$$\min \sum_{i \in \mathcal{T}^B} t_i \tag{22}$$

subject to:

$$\sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} x_{cds} = 1, \quad c \in \mathcal{C}^{G'} \tag{23}$$

$$\sum_{c \in \mathcal{C}'} x_{cds} \leq 1, \quad d \in \mathcal{D}, s \in \mathcal{S}_d \tag{24}$$

$$\sum_{c \in \mathcal{C}'} \sum_{s \in \mathcal{S}_d} C_c^W x_{cds} \leq D_d^{\max}, \quad d \in \mathcal{D} \tag{25}$$

$$\rho H^{\min} \leq \sum_{i \in \mathcal{T}^H} t_i \leq \rho H^{\max} \tag{26}$$

$$\overline{VCG}^{\min} \leq \overline{VCG} \leq \overline{VCG}^{\max} \tag{27}$$

$$\overline{TCG}^{\min} \leq \overline{TCG} \leq \overline{TCG}^{\max} \tag{28}$$

$$\overline{LCG}^{\min} \leq \overline{LCG} \leq \overline{LCG}^{\max} \tag{29}$$

$$\overline{VCG} = \frac{\sum_{c \in \mathcal{C}'} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} (S_s^{VCG} + C_c^{VCG}) C_c^W x_{cds} + L^{VCG} L^W + \sum_{i \in \mathcal{T}} \frac{t_i}{\rho T_i^{AoB}} t_i}{\sum_{c \in \mathcal{C}'} C_c^W + L^W + \sum_{i \in \mathcal{T}} t_i} \tag{30}$$

$$\overline{TCG} = \frac{\sum_{i \in \mathcal{T}} T_i^{TCG} t_i + \sum_{c \in \mathcal{C}'} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} S_s^{TCG} C_c^W x_{cds} + L^{TCG} L^W}{\sum_{c \in \mathcal{C}'} C_c^W + L^W + \sum_{i \in \mathcal{T}} t_i} \tag{31}$$

$$\overline{LCG} = \frac{\sum_{i \in \mathcal{T}} T_i^{LCG} t_i + \sum_{c \in \mathcal{C}'} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} S_s^{LCG} C_c^W x_{cds} + L^{LCG} L^W}{\sum_{c \in \mathcal{C}'} C_c^W + L^W + \sum_{i \in \mathcal{T}} t_i} \tag{32}$$

$$x_{cds} \in \{0, 1\}, c \in \mathcal{C}^{G'}, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{33}$$

$$x_{cds} \text{ value from Step 1 or Step 2}, c \in \mathcal{C}^{D'}, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{34}$$

$$0 \leq t_i \leq \rho T_i^{\max}, i \in \mathcal{T} \tag{35}$$

Given by the stowage of the dangerous cargo units (either from Step 1 or Step 2), the Step 3 objective (22) is to minimize the total amount of ballast water carried by the ship in order to reduce the fuel consumption caused by excess ballast water. For the updated cargo list subject to ship capacity, constraints (23) make sure that all the general cargo units will be assigned a slot on board, and constraints (24) make sure that each slot will only have at most one cargo unit loaded. Ship safety and stability are ensured through limits on maximum deck weight, heeling capability and three dimensional forces. Constraints (25) limit the total weight of cargo units loaded on each deck. The heeling capability is guaranteed in constraint (26) so that the tanks have sufficient forces to heel the ship. Lastly, vertical, transverse and longitudinal stability calculations are presented in Eqs. (30), (31) and (32), and are limited by constraints (27), (28) and (29), respectively. Lastly, domains for decision variables are given by constraints (33), (34) and (35).

Equation (30) shows that vertical center of gravity (VCG) of ballast tanks becomes a function of the decision variables as a result of the inclusion of ballast tanks in the decision variables. We apply the level discretization method for linearization. We refer readers for a detailed description of the method in Jia et al. (2020). Each tank i is divided into various filling levels denoted by a set of discrete points $k \in \mathcal{K}_i$. A set of binary variables z_{ik} equals to 1 if the tank i is filled with ballast water to a certain level k. Correspondingly, each level k is associated with a volume of water T_{ik}^{VOL} and a VCG value T_{ik}^{VCG}.

The linearized formulation for the amount of water in ballast tank t_i, its corresponding VCG, and its gravity moment can now be rewritten as follows:

$$t_i = \sum_{k\in\mathcal{K}_i} \rho T_{ik}^{VOL} z_{ik} \qquad i \in \mathcal{T} \tag{36}$$

$$T_i^{VCG} = \sum_{k\in\mathcal{K}_i} T_{ik}^{VCG} z_{ik} \qquad i \in \mathcal{T} \tag{37}$$

$$T^{VCG} t_i = \sum_{i\in\mathcal{K}_i} T_{ik}^{VCG} \rho T_{ik}^{VOL} z_{ik} \qquad i \in \mathcal{T} \tag{38}$$

Correspondingly, the quadratic constraint (27) is now represented in the following linear form:

$$\begin{aligned} &\overline{VCG}^{\min}\Big(\sum_{c\in C} C_c^W + L^W + \sum_{i\in\mathcal{T}} \sum_{i\in\mathcal{K}_i} \rho T_{ik}^{VOL} z_{ik}\Big) \le \\ &\sum_{c\in C}\sum_{d\in D}\sum_{s\in S_d} (S_s^{VCG} + C_c^{VCG}) C_c^W x_{cds} + L^{VCG} L^W + \sum_{i\in\mathcal{T}}\sum_{k\in\mathcal{K}_i} T_{ik}^{VCG} \rho T_{ik}^{VOL} z_{ik} \\ &\le \overline{VCG}^{\max}\Big(\sum_{c\in C} C_c^W + L^W + \sum_{i\in\mathcal{T}}\sum_{i\in\mathcal{K}_i} \rho T_{ik}^{VOL} z_{ik}\Big) \end{aligned} \tag{39}$$

By updating t_i with constraints (36) in the original formulation and replacing constraint (27) with constraint (39), we obtain a linear formulation in Step 3.

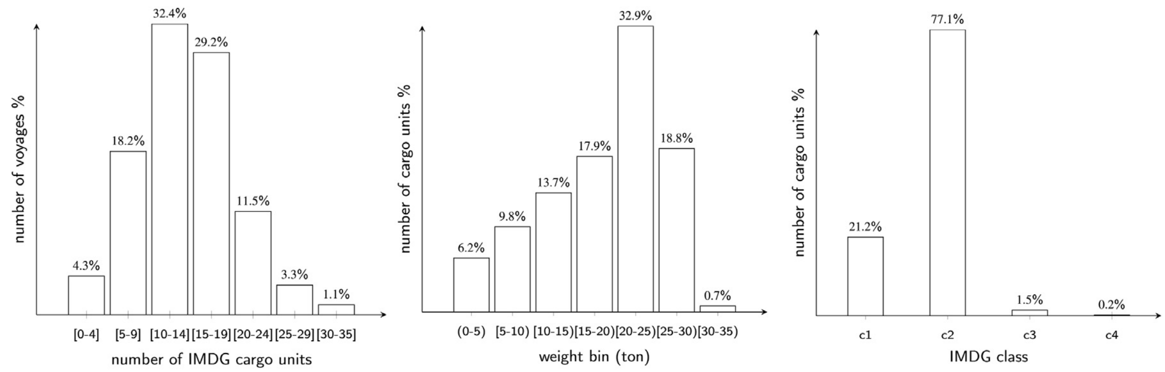
The output of Step 3, which is the last part of the step-wise stowage planning process, provides a final optimized stowage plan that maximizes the number of dangerous optional cargo units, maximizes the safety in between dangerous cargo units (if Step 2 is applied) and minimizes the excess intake of ballast water to achieve fuel reduction.

4. Computational study

We conduct the computational study based on data from two identical sister ships deployed on the short sea route between Vlaardingen in the Netherlands and Immingham in UK. All ship specification data and historical data on the voyages are provided by the shipping company this research has been done in collaboration with. The ship type has a total capacity of 262 standard trailers, distributed through four fixed decks. The ship has a number of ballast tanks and two heeling tanks along both sides of the ship. The number of discretization levels for the tanks in Step 3 is set to be 10, as it has been demonstrated with high accuracy and fast run time by Jia et al. (2020). Due to the large number of dangerous cargo units categories, we simplify the classification according to the number of segregation rules for the purpose of demonstration and simplicity. In this paper, dangerous cargo units are simplified and classified into four classes. The segregation rules applied among different classes are shown in Table 1. No segregation is needed between dangerous cargo units and general cargo units.

Table 1
IMDG segregation rules for four classes.

cargo unit	general	class 1	class 2	class 3	class 4
general	-	-	-	-	-
class 1	-	1	1	1	1
class 2	-	1	2	2	2
class 3	-	1	2	3	3
class 4	-	1	2	3	4



(a) IMDG cargo units distribution (b) weight distribution (c) IMDG class distribution

Fig. 3. Histograms of historical distributions based on 654 voyages.

Table 2
Tabular data of sampling distribution based on historical data.

Weight (ton)	(0,5) 6.17%	[5,10) 9.78%	[10,15) 13.73%	[15,20) 17.94%	[20,25) 32.89%	[25,30) 18.78%	[30,35] 0.63%
IMDG per voyage	[0,4] 4.28%	[5,9] 18.20%	[10,14] 32.43%	[15,19] 29.30%	[20,24] 11.47%	[25,29] 3.36%	[30,35] 1.07%
IMDG Class	c1 21.22%	c2 77.07%	c3 1.47%	c4 0.24%			

In this paper, for the purpose of demonstration and simplicity, we assume all decks are open and the general segregation requirements for distance apart on an open deck for RoRo ships are defined as follows for each number in Table 1:

1. 3 m
2. 6 m
3. 36 m
4. 48 m

We refer readers to Section 7.5.3.2 in the IMDG Code for a detailed description of segregation rules for the RoRo sector.

4.1. Generation of test instances

When generating the test instances, we fix the total number of cargo units to be 280 (somewhat more than the capacity of the ships considered), including 240 mandatory and 40 optional cargo units. The commitment class of a dangerous cargo unit being either mandatory or optional is randomly assigned to cargo unit and regardless of its dangerous property. In order to represent the real world instances, we collected one year of historical data for 654 voyages on the studied route. We generated 30 instances based on the historical distributions for three key parameters: the weight of cargo units, the total number of dangerous cargo units, and the composition of different classes of dangerous cargo units, as shown in Fig. 3a–c, respectively.

Note that due to the simplification of the dangerous cargo units classification, the distribution for the IMDG class is a derivation of the original IMDG class distribution from the historical data. Based on the frequency of each rule appeared in the historical data, we approximate a distribution of the four dangerous cargo units classes such that frequencies for each rule resemble the historical ones.

Overall, the distributions for the weight of cargo units, total number of IMDG cargo units and the composition of different classes per voyage are summarized in Table 2.

We describe our instance by its id, commitment distribution ("m/o") for mandatory and optional dangerous cargo units and dangerous class distribution ("c1/c2/c3/c4") for class 1 - 4 cargo unit, where each number represents the number of cargo units for that specific category. The total number of dangerous cargo units matches the sum of mandatory and optional dangerous cargo units $m + o$, as well as the sum of each dangerous class cargo units $c1 + c2 + c3 + c4$. The 30 instances are sorted by the total number of dangerous cargo units from small to large and listed in Table 3 together with the computational results in Section 4.2.

4.2. Computational results

In order for the performance to be comparable to when the model is run on a stowage planner's computer, the computational tests are conducted on a Windows laptop with Intel(R) Core(TM) i7-7820HQ CPU @ 2.90GHz and 16.0 GB RAM. The model is implemented

Table 3
Computational results. Solution times are in seconds.

Instance			Full optimization							Partial optimization		
			Step 1	Step 2				Step 3		Step 1	Step 3	
id	m/o	c1/c2/c3/c4	Time	Time	Gap	Δ d.	Δ c. d.	Time	Obj.	Time	Time	Obj.
1	3/0	3/0/0/0	0	0	0.0%	0.0%	0.0%	10	0	0	3	0
2	4/0	0/4/0/0	0	1	0.0%	4.3%	14.3%	12	0	0	3	0
3	5/0	0/5/0/0	0	1	0.0%	5.4%	20.5%	6	0	0	4	0
4	6/1	5/2/0/0	1	8	0.0%	12.0%	51.9%	11	0	0	3	0
5	8/0	1/7/0/0	0	13	0.0%	15.7%	116.2%	6	0	0	3	0
6	6/2	2/6/0/0	1	7	0.0%	15.7%	116.2%	8	0	0	4	0
7	7/1	1/7/0/0	1	8	0.0%	15.7%	116.2%	7	0	1	4	0
8	10/0	0/9/1/0	0	15	0.0%	1.1%	66.3%	8	0	0	3	0
9	9/2	3/8/0/0	2	3601	5.1%	5.5%	-9.1%	5	0	1	3	0
10	7/4	0/11/0/0	1	3601	7.3%	1.1%	4.6%	57	34	1	15	13
11	10/1	5/6/0/0	2	3600	3.5%	5.2%	68.1%	4	0	2	3	0
12	12/0	3/8/0/1	0	3600	9.9%	3.8%	91.1%	5	0	0	5	0
13	9/3	3/9/0/0	1	3601	10.0%	2.4%	159.0%	25	46	1	5	0
14	11/2	4/9/0/0	3	3601	13.0%	4.3%	38.6%	3	0	2	3	0
15	12/1	3/10/0/0	2	3601	13.3%	0.0%	20.0%	10	9	2	6	9
16	10/4	2/12/0/0	3	3600	11.0%	5.2%	22.9%	4	0	2	3	0
17	13/1	3/11/0/0	3	3600	10.1%	7.7%	31.4%	5	0	2	3	0
18	11/3	3/11/0/0	4	2634	0.0%	1.5%	13.1%	3	0	3	3	0
19	12/2	2/12/0/0	2	3600	7.2%	1.4%	1.2%	3	0	2	3	0
20	11/4	2/13/0/0	4	3601	13.5%	1.8%	10.4%	3	0	4	4	0
21	15/1	4/10/2/0	3	3601	15.4%	3.7%	29.9%	6	0	3	4	0
22	13/4	6/11/0/0	3	3601	14.8%	5.7%	32.2%	3	0	3	3	0
23	17/1	5/12/1/0	4	3601	20.3%	6.1%	15.9%	4	0	4	3	0
24	17/1	0/17/1/0	8	173	0.0%	-0.3%	3.2%	3	0	6	4	0
25	17/2	5/14/0/0	4	3601	19.1%	6.0%	11.5%	19	53	4	20	40
26	15/4	8/11/0/0	3	3601	17.0%	6.5%	7.3%	12	24	3	3	0
27	18/1	4/15/0/0	5	3600	21.2%	7.4%	4.3%	4	0	5	3	0
28	19/2	4/17/0/0	6	3601	10.7%	0.3%	6.0%	3	0	5	3	0
29	20/3	10/12/1/0	8	3601	34.7%	1.5%	22.6%	3	0	8	3	0
30	18/6	10/14/0/0	7	3601	29.7%	1.6%	-9.3%	5	9	6	21	27

in Julia with JuMP package and Gurobi optimizer. We conduct the test runs with two setups: 1) *full optimization* where we optimize the instance with all three steps and objectives sequentially and 2) *partial optimization* where we omit Step 2. The results for both setups are summarized in Table 3 for comparison. Each step of optimization has been given a time limit of 3600 s. All solution times are measured in seconds and objective values for Step 3 are presented in tons of ballast water.

Additionally, in order to quantify the significance of maximizing safety, we compare the average total distance between dangerous cargo units after Step 1 (*original distance*) with the average total distance from Step 2 (*optimized distance*). The average distance is calculated using the total distance divided by the number of dangerous goods, whereas the total distance of a solution is calculated according to the objective function (7) of the distance formulation in Section 3.2. The distance between slots on different decks is set as 48 m taken from the strictest rule 4 mentioned in the beginning of this section. In addition to the average total distance, which is what we seek to maximize, we also compare the average closest distance between a dangerous cargo unit and its closest other dangerous cargo unit after Step 1 (*original closest distance*) with the average closest distance from Step 2 (*optimized closest distance*). We calculate the average distance improvement (Δ d.) as the (optimized distance - original distance)/original distance and average closest distance improvement (Δ c. d.) as the (optimized closest distance - original closest distance)/original closest distance. Positive numbers suggest an improvement.

When we ran some preliminary tests with the full optimization, we noticed that the optimality gaps (i.e. the gaps between the integer feasible solutions and the lower bounds) in Step 2 were very large even after one hour of running time (i.e. over 20% for 60% of the instances) due to symmetry in the problem. Attempts to reduce symmetry have been conducted by removing half of the y variables due to the symmetry caused by slot s and s'. Specifically, we redefined variables $y_{dss'}$ where $d = 1, 2, \dots, |\mathcal{D}|; s = 1, 2, \dots, |\mathcal{S}_d| - 1; s' = s + 1, \dots, |\mathcal{S}_d|$. However, preliminary results indicated worse performance. Therefore, we have chosen the technique of fixing variables to reduce symmetry to some extent. The logic of fixing variables is that we fix one dangerous cargo unit on each deck at a slot that is the furthest away from the others. This reduces some of the symmetry and the average gap is reduced significantly to the numbers seen in Table 3. Small instances with a total number of dangerous cargo units less than 10 are solved to optimality in less than 15 s. Note that even though fixing variables significantly reduces symmetry, it might also lead to sub-optimal solutions, which is seen for instance 24, where the safety distance becomes larger when applying Step 2.

The results in Table 3 compares the performance of full optimization with partial optimization proposed in the step-wise stowage optimization process. For the setup of partial optimization, where we optimize the number of dangerous optional cargo units (Step

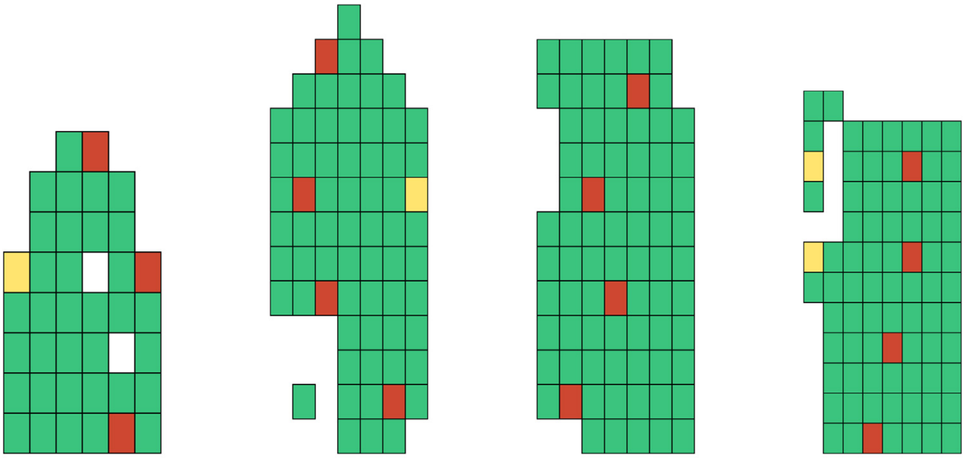


Fig. 4. Stowage plan for instance 27 using partial optimization, a view of the ship from above and aft. Color green, yellow and red indicate the class of cargo units being general, 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

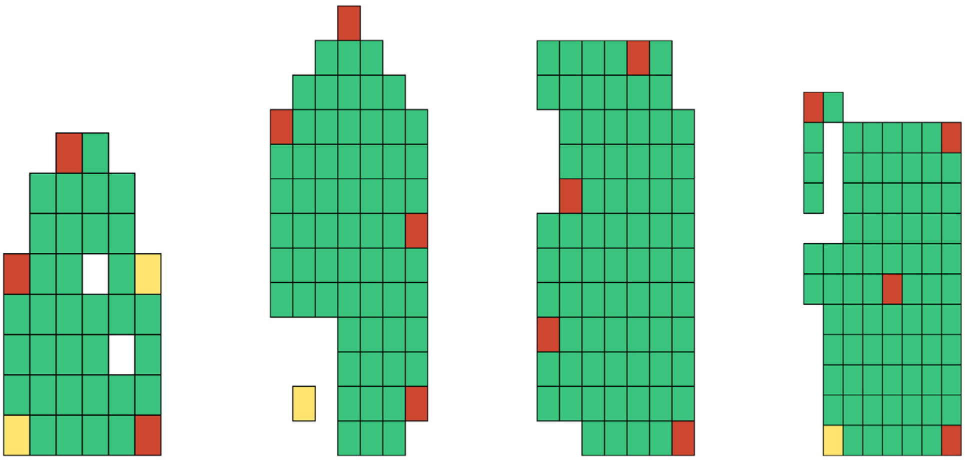


Fig. 5. Stowage plan for instance 27 using full optimization, a view of the ship from above and aft. Color green, yellow and red indicate the class of cargo units being general, 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1) and then minimize the ballast water intake (Step 3), all 30 instances are solved to optimality within less than 30 s. In Step 1, as the number of dangerous cargo units grows, the computational time also increases. However, the difference is almost negligible since the model runs so fast. In Step 3, the computational time depends on primarily two factors, the distribution of the cargo weight, and the placement of the dangerous cargo units. It is therefore no clear pattern between number of dangerous cargo units and the computational time.

In the case of full optimization, which ensures even more safety regarding the segregation of dangerous cargo units, the instances with few dangerous cargo units can be solved to optimality within reasonable time. However, it takes a significant amount of time to solve the model in Step 2 for the instances with more than 10 dangerous cargo units, even when we applied the technique of fixing some of the variables. The gain from including Step 2 is that the total distance and the closest distance among slots with dangerous cargo units are increased by 5% (Δ d.) and 36% (Δ c. d.) on average among all instances, respectively. This clearly shows that the safety level is significantly increased by segregating the dangerous cargo units even beyond the minimum requirements given by the regulations, thus minimizing the risk of accidents. We demonstrate this by the solutions obtained for instance 27, as shown in Fig. 4 for partial optimization and Fig. 5 for full optimization. As stated in Table 3, the total distance among dangerous cargo units for instance 27 is increased by 7.4%, which is also presented in the stowage plan of full optimization where all the dangerous cargo units are stowed as far away from each other as possible.

As for Step 3, it takes longer time to solve and results in worse objective on average in full optimization than in partial optimization. One explanation could be that the fixed stowage plan for dangerous goods is made sparse by maximizing their distance in between, and it takes more computational power to satisfy the stability with a more sparsely fixed stowage plan for dangerous cargo units, therefore potentially more ballast water is needed as well.

The step-wise stowage planning approach has great potential for being implemented by shipping companies to improve the safety on board. First and foremost, it ensures that the plan complies with the complex segregation rules in Step 1 within seconds of computational run time. Secondly, it enables a significantly better safety through Step 2 optimization by maximizing the distance among dangerous cargo units. Moreover, the step-wise approach provides experts the possibility and flexibility to incorporate additional preferences and constraints to the preliminary generated stowage plan for dangerous cargo units, before generating an optimal stowage plan for all cargo units in Step 3 that can potentially reduce fuel and CO_2 emission by around 6.7% (Jia et al., 2020). The approach aims to provide decision support to the planners and cargo officers to facilitate their daily operations and not to replace any decision makers.

The choice of implementing either full or partial optimization depends on many factors. Shipping companies apply different cut off time for dangerous goods. An earlier cut off time ensures the availability of dangerous cargo units, i.e. those present at the terminal by the time of planning. This gives shipping companies more time to plan for the stowage of dangerous goods, potentially using Step 2 to maximize the safety. Computing power might also be a determining factor. Since the results are tested on a standard laptop to mimic the environment that is generally at the terminal or on the ship, the computational time can be decreased significantly by using more powerful computers, e.g. on the cloud, so that full optimization becomes realistically fast. Last but not the least, the preference between being safer and complying with minimum requirements guides the adoption of full and partial optimization, respectively.

5. Conclusion

In this paper, we have addressed the important planning problem of generating optimal stowage plans for roll-on roll-off ships transporting trailers (some containing dangerous cargo) between two ports. We proposed a planning approach with the ability to include experts' opinions for generating a more robust and flexible plan. The planning approach includes three steps, each step consisting of a (mixed) integer programming model solved by a commercial solver. Step 1 maximizes the number of dangerous cargo units to transport while adhering to the IMDG Code. Step 2, which is optional, maximizes the safety distance among the dangerous cargo units found in the first step. Finally, in Step 3, the ballast water intake needed to ensure stability of the ship is minimized, as this has a significant effect on the fuel consumption. In order to test the step-wise planning approach we generated a number of test instances based on real data from a shipping company. The computational results showed great potential for industrial implementation considering improved safety through maximizing total distance (Δ d.) by 5% and maximizing closest distance (Δ c. d.) by 36%; and reduced fuel consumption and CO_2 emission by around 6.7%. As the first research study in the topic of stowing RoRo ships transporting dangerous goods, we hope to provide fundamental insights and potential approach for the problem to both academic researchers and industrial practitioners.

Future work may include improved solution methods to reduce symmetry for the model in Step 2, which is the one which experiences the highest computational times. It may be interesting to further investigate the cause of the worse performance of removing variables from the perspective of symmetry study. Alternatively, it would also be interesting to develop a heuristic for solving the integrated problem in one go. This could potentially reduce the computational time and improve the solution quality compared to the mathematical three-step optimization approach and make it an even more efficient planning tool in a practical setting.

Declaration of Competing Interest

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

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Appendix A. List of Notations

Sets	
$\mathcal{N}$	set of segregation rules indexed by n
$\mathcal{C}$	set of cargo units indexed by c, $\mathcal{C} = \mathcal{C}^D \cup \mathcal{C}^G$
$\mathcal{C}^D$	set of dangerous cargo units, $\mathcal{C}^D = \mathcal{C}^{D,M} \cup \mathcal{C}^{D,O}$
$\mathcal{C}^{D,M}$	set of dangerous, mandatory cargo units
$\mathcal{C}^{D,O}$	set of dangerous, optional cargo units
$\mathcal{C}^G$	set of general cargo units, $\mathcal{C}^G = \mathcal{C}^{G,M} \cup \mathcal{C}^{G,O}$
$\mathcal{C}^{G,M}$	set of general, mandatory cargo units
$\mathcal{C}^{G,O}$	set of general, optional cargo units
$\mathcal{C}_{cn}$	set of cargo units that are in conflict with cargo unit c based on rule n
$\mathcal{C}'$	updated set of cargo units, $\mathcal{C} = \mathcal{C}^{D'} \cup \mathcal{C}^{G'}$
$\mathcal{C}^{G'}$	updated set of general cargo units, $\mathcal{C}^{G'} = \mathcal{C}^{G,M} \cup \mathcal{C}^{G',O}$
$\mathcal{C}^{G',O}$	selected set of general optional cargo units to be loaded
$\mathcal{C}^{D'}$	updated set of dangerous cargo units, $\mathcal{C}^{D'} = \mathcal{C}^{D,M} \cup \mathcal{C}^{D',O}$
$\mathcal{C}^{D',O}$	selected set of dangerous optional cargo units to be loaded
$\mathcal{D}$	set of decks indexed by d
$\mathcal{S}_d$	set of slots on deck d indexed by s
$\mathcal{S}^N_{dsn}$	set of slots that cannot be used to load conflicting cargo $c' \in \mathcal{C}_{cn}$ if any $c \in \mathcal{C}^D$ is loaded in slot s on deck d
$\mathcal{T}$	set of ballast tanks indexed by i, $\mathcal{T} = \mathcal{T}^B \cup \mathcal{T}^H$
$\mathcal{T}^B$	set of regular ballast tanks
$\mathcal{T}^H$	set of heeling ballast tanks
$\mathcal{K}_i$	set of discretisation levels for each ballast tank $i \in \mathcal{T}$
Parameters	
N^S	total number of slots on the ship
$D_{dsd's'}$	distance between slot s on deck d and slot s' on deck d'
$R_{dss'}$	risk value between slot s and s' on deck d
C^W_c	weight of cargo unit c
C^{VCG}_c	vertical center of gravity of cargo unit c
$D^{\max}_d$	maximum weight limit of deck d
ρ	sea water density
$H^{\min/\max}$	limiting volume of heeling tanks
$\overline{VCG}^{\min/\max}$	limiting $\overline{VCG}$ value
$\overline{TCG}^{\min/\max}$	limiting $\overline{TCG}$ value
$\overline{LCG}^{\min/\max}$	limiting $\overline{LCG}$ value
S^{VCG}_s	vertical center of gravity of slot s
S^{TCG}_s	transverse center of gravity of slot s
S^{LCG}_s	longitudinal center of gravity of slot s
L^{VCG}	vertical center of gravity of the lightship
L^{TCG}	transverse center of gravity of the lightship
L^{LCG}	longitudinal center of gravity of the lightship
L^W	lightship weight
T^{AoB}_i	area of base of ballast tank i
T^{TCG}_i	transverse center of gravity of ballast tank i
T^{LCG}_i	longitudinal center of gravity of ballast tank i

(*continued on next page*)

$T_i^{\max}$	maximum volume of ballast tank i
T_{ik}^{VOL}	volume of water inside ballast tank i when filled at level k
T_{ik}^{VCG}	vertical center of gravity of ballast tank i when filled at level k
Variables	
$x_c ds$	equals 1 if cargo unit c is loaded on deck d at slot s, otherwise 0
$y_{dsd's'}$	equals 1 if both slot s on deck d and slot s' on deck d' are loaded with cargo, otherwise 0
$y_{dss'}$	equals 1 if both slot s and s' on deck d are loaded with cargo, otherwise 0
t_i	the mass of water in ballast tank i
$\overline{VCG}$	equation for the composite vertical center of gravity from keel
$\overline{TCG}$	equation for the composite transverse center of gravity from midship
$\overline{LCG}$	equation for the composite longitudinal center of gravity from aft perpendicular
z_{ik}	equals 1 if ballast tank i is filled at level k

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