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Sustainable Short Sea Roll-on Roll-off Shipping through Optimization of Cargo Stowage and Operations

Jia, Beizhen

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SUSTAINABLE SHORT SEA ROLL-ON ROLL-OFF SHIPPING THROUGH OPTIMIZATION OF CARGO STOWAGE AND OPERATIONS

BY
BEIZHEN JIA

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

Sustainable Short Sea Roll-on Roll-off Shipping through Optimization of Cargo Stowage and Operations

Ph.D. Dissertation

Beizhen Jia

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PhD supervisor: Assoc. Prof. Niels Gorm Malý Rytter
Aalborg University

Assistant PhD supervisor: Assoc. Prof. Line Blander Reinhardt
Roskilde University

PhD committee: Professor Kenn Steger Jensen (chair)
Aalborg University

Prof. Dr. Stefan Voss
University of Hamburg

Associate Professor Dario Pacino
Technical University of Denmark (DTU)

PhD Series: Faculty of Engineering and Science, Aalborg University

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Abstract

Maritime transport is the backbone of global trade. In Europe, short sea Roll-on/Roll-off (RoRo) shipping is a dominant transportation mode due to its flexibility and connectivity. Faced with many challenges to comply with international regulations and remain competitive, there calls for a need for researchers to investigate inefficiencies and propose solutions, as scarce research is found related to the RoRo shipping industry. Thus, the PhD study aims to contribute to the field of sustainable RoRo cargo operations with a focus on stowage through digitalization and optimization methods. The principle is to develop solutions that can be implemented and integrated into planning tools to support decision makings of practitioners.

Specifically, this thesis investigates the problems of stowage planning, dual cycling, and cargo discharge time estimation, inspired and motivated by DFDS, one of the largest short sea RoRo shipping companies in Europe. Thanks to our close collaboration, primary inefficiencies are identified and problems are formulated in the industry setting. Mathematical models, a heuristic, and a statistical framework have been proposed and tested on real data. Results indicate that this thesis has a significant impact on improving sustainability, in particular, fuel and emission reduction of RoRo shipping industry.

The thesis has demonstrated how optimization and statistical methods can contribute to solving complex industrial problems. This is believed to be of great interest to both the maritime community and the data science community. The work resulted in four research articles: three published and one under review. Finally, the thesis closes with a conclusion and future work relevant to both communities in order to build a more sustainable the RoRo shipping industry.

Resumé

Maritim transport er rygraden i den globale handel. I Europa er short-sea-roll-on/roll-off (RoRo) shipping en dominerende transportform på grund af dens fleksibilitet og sammenkobling med andre transportformer. Branchen står over for mange udfordringer for at overholde internationale regler og forblive konkurrencedygtige, og derfor er der et behov for forskning der undersøger ineffektivitet og foreslår løsninger, der bidrager til RoRo-industrien, da området mangler yderligere forskning. Ph.d.-afhandlingen har således til formål at bidrage til bæredygtig RoRo-drift med fokus på stowage gennem digitaliserings- og optimeringsmetoder. Princippet er at udvikle løsninger, der kan implementeres og integreres i planlægningsværktøjer til at støtte beslutningstagere i industrien.

Specifikt undersøger denne afhandling problemerne med stowage planning, dual cycling og estimering af cargo discharge time inspireret og motiveret af DFDS, et af de største short-sea-RoRo-rederier i Europa. Takket være vores tætte samarbejde identificeres primære ineffektiviteter, og problemer formuleres så tæt på virkeligeheden som muligt. Matematiske modeller, en heuristik og en statistisk ramme er blevet foreslået og testet på reelle data. Resultaterne indikerer, at vores arbejde har en betydelig indvirkning på forbedring af bæredygtighed, især reduktion af brændstofsforbrug og udledning af CO_2 i RoRo-industrien.

Afhandlingen har vist, hvordan optimerings- og statistiske metoder kan bidrage til at løse komplekse problemer fra industrien. Dette menes at være til stor interesse for både det maritime samfund og data science samfundet. Arbejdet resulterede i fire forskningsartikler: tre offentliggjorte og en under gennemgang. Endelig afsluttes afhandlingen med en konklusion og fremtidigt arbejde, der er relevant for begge samfund for at opbygge en mere bæredygtig RoRo-industri.

Preface

This PhD thesis has been submitted to the Department of Materials and Production, Aalborg University in partial fulfillment of the requirements for acquiring the degree of Philosophiae Doctor (PhD). The work has been conducted from May 2018 to April 2021 under the supervision of Associate Professor Niels Gorm Malý Rytter and Associate Professor Line Blander Reinhardt. An online external research collaboration with Professor Kjetil Fagerholt at the Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology was part of the PhD study.

The PhD project is part of the ECOPRODIGI project, in collaboration with one of the largest Roll-on/Roll-off (RoRo) shipping companies - DFDS, a leading loading computer provider - Kockumation among others. ECOPRODIGI project aims to increase eco-efficiency in the Baltic Sea region maritime sector through digitalization in close cooperation between industry and research organizations. The PhD study has been financially supported by the Interreg Baltic Sea Region Programme and Aalborg University.

The thesis is structured in two parts: Part I – Introduction and Part II – Papers. Part I consists of four sections as follows: Section 1 introduces the background of the thesis with an outline. Section 2 provides a general understanding of RoRo shipping and its opportunities and challenges. Section 3 dives into the details of the PhD study and its contribution both academically and industrially, followed by a conclusion and discussion on future work in Section 4. Part II contains a collection of four peer-reviewed research articles.

Beizhen Jia 贾贝箴
Copenhagen, Denmark, July 9, 2021

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First of all, I am deeply grateful to my main supervisor Niels Gorm Malý Rytter for giving me the opportunity of pursuing a PhD, for your valuable guidance and unwavering support throughout the years. I have learned so much from you both professionally and privately. I would not have been who I am now if it were not for you. Tarragona - Sines/Lisbon, Rotterdam, Hamburg, Tallin, Turku, Gothernburg, Leeds Castle, Vestfold, Vilnius, Manila, Denmark.

The same gratitude goes to my co-supervisor Line Blander Reinhardt for your dedication, support, and insightful feedback at every stage of the project. Thanks for believing in me even more than myself. Your positive attitude has made my PhD journey such a pleasant experience. You are so cool, woman.

I would like to express special thanks to Professor Kjetil Fagerholt for hosting my external research "stay", virtually due to corona. It has been a great pleasure and motivation working with you, for your dedication, knowledge and constructive feedback have been extremely inspiring and helpful during the last phase of my PhD study.

Thanks to all my co-authors for a great collaboration on several fruitful research articles. Thanks to all my wonderful ex-colleagues at the section of sustainable production.

I have also been extremely lucky to be able to collaborate with DFDS. Thank you Mads Bentzen Billesø and your colleagues for being so supportive, innovative, and sharing. Thanks to all the partners in ECOPRODIGI.

I am forever grateful for all my friends in Denmark, China, wherever in the world, despite of corona, time, distance. Thanks for making my life so wonderful. Thanks for always being there, sharing, listening, and inspiring.

This thesis would not have been possible without my wonderful boyfriend Matthias Als, for your unconditional support, consistent patience, and endless encouragement. You are the optimal solution to my boyfriend multi-objective optimization problem, 0.0% gap. Thanks to my beloved cat Noah, thanks for being so fluffy and retarded and making me smile every day.

最后，我想感谢我亲爱的爸爸贾文华和妈妈任荣敏。我是一个自私的女

儿，谢谢你们无条件地支持和理解我在国外追寻自己想要的生活。你们永远是我最坚强的后盾，我避风的港湾。我爱你们。

Thanks to everyone who has appeared in my life.

Contents

Part I

Introduction

Introduction

1 Introduction

Maritime transport is the backbone of global trade, transporting a total volume of 11.08 billion tons in 2019, accounting for 80% of the global trade [35]. Maritime transport can be divided into several market segments based on the vessel type: oil tankers, bulk carriers, general cargo ships including roll-on roll-off (RoRo) cargo ships, container ships, and other ships. In Europe, due to its many peninsulas and islands, maritime transport plays an important role in intra-EU trade besides the road, rail, and air transport, accounting for 29.2% of a total 3353 billion tkm, 70.1% by weight and 46.7% by value in 2018 [8]. Maritime transport is cost efficient and environmentally friendly per ton mile compared to other modes of transport. Short sea shipping is the maritime transport service offered on relatively short distances, in contrast to the intercontinental cross-ocean deep sea shipping [9]. Short sea RoRo shipping, among others, is a dominant transportation mode in Europe for its flexibility and connectivity to other modes of transportation. Compared to the container shipping sector, RoRo shipping has not gained much attention from researchers until recently. However, the RoRo shipping industry also faces challenges in order to comply with international regulations and stay competitive.

The PhD study aims to investigate solutions that can optimize the inefficiencies of various operations in short sea RoRo shipping with a focus on cargo stowage.

1.1 ECOPRODIGI

The PhD study is part of the EU Interreg project ECOPRODIGI, aiming to bring eco-efficiency and digitalization to the maritime industry by designing and piloting digital solutions under close collaboration between industry end-users, technology vendors, and research organizations [1]. Therefore, the PhD study is conducted in close collaboration with DFDS - one of the biggest RoRo shipping companies in Europe, Kockumation - a leading sup-

plier in maritime applications, and other relevant industrial partners within the ECOPRODIGI project. The objective of the PhD study is to develop prototypes of optimization and statistical models that can be implemented into planning tools used by decision makers to improve the efficiency and sustainability of the RoRo shipping industry.

1.2 Thesis Outline

The thesis consists of two parts: Part I introduces the background of the thesis in Section 1, provides a general understanding of RoRo shipping and its opportunities and challenges in Section 2, dives into the details of the PhD study and its contribution both academically and industrially in Section 3, and concludes in Section 4. Part II consists of a collection of four research articles disseminating the findings of the PhD study as follows.

- Paper A [19]

  Jia B., Fagerholt K., Reinhardt L.B., Rytter N.G.M. (2020) "Stowage Planning with Optimal Ballast Water." In: Lalla-Ruiz E., Mes M., Voß S. (eds) Computational Logistics. ICCL 2020. *Lecture Notes in Computer Science*, vol 12433, pp. 84–100. Springer, Cham.

- Paper B [18]

  Jia B., Fagerholt K. (2021) "Step-wise Stowage Planning of Roll-on Roll-off Ships Transporting Dangerous Goods." *Maritime Transport Research*, vol. 2, p.100029. Elsevier Ltd.

- Paper C

  Jia B., Tierney K., Reinhardt L.B., Pahl J. (2021) "Optimal Dual Cycling Operations in RoRo Terminals." Submitted.

- Paper D [20]

  Jia B., Rytter N.G.M., Reinhardt L.B., Haulot G., Billesø M.B. (2019) "Estimating Discharge Time of Cargo Units – A Case of Ro-Ro Shipping." In: Paternina-Arboleda C., Voß S. (eds) Computational Logistics. ICCL 2019. *Lecture Notes in Computer Science*, vol 11756, pp. 122–135. Springer, Cham.

2 RoRo Shipping

This section aims to provide readers a general understanding of the RoRo shipping industry from two perspectives. Firstly, the industry characteristics

are described in detail from three aspects: the cargo units, the ships, and the terminals in Section 2.1. Secondly, some of the common opportunities and challenges the RoRo shipping industry is facing are discussed in Section 2.2.

2.1 Industry Characteristics

Cargo Units

Depending on the cargo itself or the equipment the cargo is transported in, cargo units can be cars, trucks, trailers, and containers. The majority of cargo units onboard short sea RoRo ships are trailers, which is also the focus of the thesis. A typical trailer is shown in Figure 1; such stand-alone trailer without a truck is called an *semi-trailer* or *unaccompanied trailer*. Terminal tractors, also called *tugs*, are used to load and unload unaccompanied trailers. Depending on the content of the cargo, there are general, refrigerated, and dangerous cargo units. Refrigerated cargo units are transported in reefer trailers, which are temperature controlled and suitable for perishable cargo, such as fruit and vegetables that need to be kept fresh on arrival. Reefer trailers are required to be placed where electrical plugs are accessible. Dangerous goods are categorized into various classes according to the International Maritime Dangerous Goods (IMDG) Code [16]. Dangerous cargo units require correct labeling of the content, packaging, and segregation, meaning the placement of any two dangerous cargo units needs to satisfy the minimum distance required in the IMDG Code based on their classes.

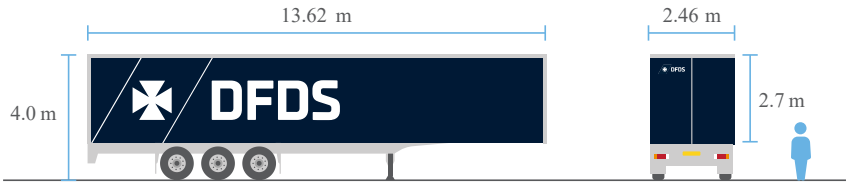

Fig. 1: Trailer Dimensions. Source: [6]

Trailers are with wheels, and therefore can not be stacked as containers, and thus the space efficiency is lower. On the other hand, trailers provide more flexibility and connectivity which most other transport modes can not compete with.

RoRo Ships

RoRo ships typically have multiple decks. Each deck is divided into several lanes horizontally, and each lane fits the width of a standard sized trailer. The capacity of RoRo ships is measured in lane meters. A typical short sea RoRo ship is shown in Figure 2. RoRo ships usually have a main ramp located at the back of the ship, serving as a connecting bridge between the shore and the ship. Loading and unloading operations of trailers are conducted through the *main ramp*. The deck that is directly connected with the main ramp is usually called the *main deck*. In addition, decks within the ship are connected through internal ramps.

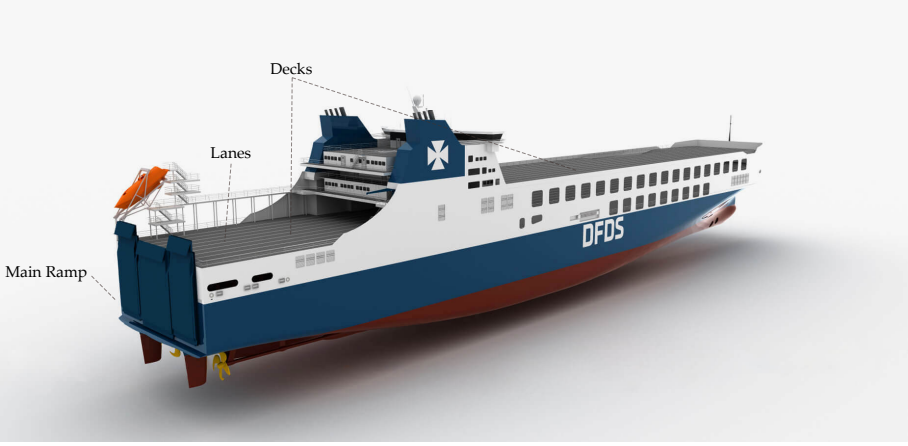

Fig. 2: A RoRo Ship. Source: [5]

RoRo ships are subject to strict regulations in order to reduce airborne emissions when sailing in the Emission Control Areas (ECAs), such as the North Sea and the Baltic Sea. Shipowners can choose to bunker the expensive low sulfur fuel oil or install scrubbers on board to clean the exhaust gas before emitting it into the atmosphere. The installation is an expensive initial investment however it allows the shipowners to bunker a cheaper alternative.

As always the utmost importance is on the seaworthiness of the ship, meaning the ship is complied with the safety and stability regulations and ready to sail.

RoRo Terminals

RoRo Terminals, in contrast to container terminals with stacked containers, often have a fishbone layout with trailers standing next to each other, as shown in Figure 3. At the entrance of a terminal is the gate, which registers information of which trailer enters the terminal (*gate-in*) and leaves the

Fig. 3: A RoRo Terminal. Source: [7]

terminal (*gate-out*). There are several factors determining the placement of a trailer, such as which voyage or ship the trailer belongs to, if the trailer is an import or export cargo, and if the trailer contains cargo with special needs e.g. refrigerated and dangerous cargo.

As mentioned earlier, trailers cannot be stacked and thus are less space efficient. Therefore, timely pick-up and delivery of cargo units from customers are critical to the terminal efficiency to reduce congestion and increase space utilization.

2.2 Challenges and Opportunities

The RoRo shipping industry is facing several challenges as well as opportunities, which are further elaborated from four perspectives: flexibility and convenience, environmental regulations, safety at sea, and digitalization and integration.

Flexibility and Convenience

Compared to short sea container shipping and road transportation, RoRo shipping has many advantages over its competitors. RoRo shipping provides the possibility of transporting goods from A to B without additional cargo handling. It offers customers flexibility and convenience that allows a smooth

connection with road transportation from origins to destinations. For example, door-to-door delivery with RoRo service from Turkey to Europe requires 6 days on average, whereas with container service it requires 20 days [33]. Moreover, RoRo shipping reduces truck drivers' working time compared to pure road transportation, thus more safety with regards to road accidents resulting from long and exhausting driving. RoRo shipping offers a fixed and reliable schedule with a relatively fast sailing speed in order to achieve a short voyage time. Moreover, it also provides the possibility of transporting odd sized cargo and heavy machinery which are otherwise challenging to transport. The above mentioned points are proven to have a critical impact on the maritime transport choice [4] [24] [37].

Environmental Regulations

The marine environment has been the focus of the International Maritime Organization (IMO). The International Convention for the Prevention of Pollution from Ships (MARPOL) was originally introduced in 1973 to prevent marine pollution by oil, supplemented by various amendments. Although shipping is one of the most energy efficient ways to transport cargo, air pollution from ships can contribute to worsened global air quality and environmental problems cumulatively over time. MARPOL Annex VI was added in 1997 for the purpose of minimizing ship emissions such as SOx, NOx and etc, followed by a revised Annex VI with significantly more strict limits on airborne emissions including the introduction of emission control areas (ECAs) [15]. The environmental measures have posed great challenges to ship owners, leaving them with two options: adopting expensive low sulfur fuel oil or installing scrubbers on board. However, opportunities also emerge as it requires a transformation of the conservative and traditional way of operations in the shipping industry. This is extremely important since short sea RoRo shipping companies mostly operate in ECAs that require strict restrictions on ship emissions. Optimization in fuel efficiency through various operations in routing, planning, cargo handling and etc. is required. Moreover, the ambitious GHG emission reduction [14] requires even more actions to be done such as exploring the possibilities of renewable energies and implementing advanced technologies and integration in order to be more competitive.

Safety at Sea

Ship safety and stability is of utmost importance at all time, not only at sea but also in port. Therefore, it is critical to have a good stowage plan that takes into account the distribution of cargo weight and ballast water to ensure good stability before, during, and after loading and discharging of cargo units on board. Moreover, in the case of heavy weather, lashing is required

so the trailers will not move from side to side, creating a great risk of stability problems during sailing. Studies on improving lashing can be found here [34] [22]. Last but not least, safe segregation of dangerous goods subject to the IMDG Code is required by IMO. Planning the stowage of dangerous goods can be a complex and challenging process.

Digitalization and Integration

Digitalization has been the keyword and focus of the shipping industry. More and more data is being collected and processes are being digitalized or even automated by either solutions developed in house or by software and technology vendors. However, given the fact that many critical and fundamental data sources are yet to be collected; that many work processes remain manual; and that there is a lack of some sort of standardization in the industry, it is a challenge to integrate all the processes in the maritime value chain with different levels of digitalization and automation, resulting in inefficiencies and environmental impact.

3 Integrated Cargo Logistics

The focus of the PhD study is sustainable RoRo shipping through optimization of cargo stowage and related operations. This section describes the contribution of the thesis as follows. Section 3.1 lists all the activities related to data collection from DFDS, including site visits at the terminals, both online and physical meetings, seminars, and data files, which serve the fundamentals of the PhD project. An end2end cargo stowage process is described in detail in Section 3.2, and inefficiencies are identified. A general literature review is provided in Section3.3, followed by the research contributions of the PhD study in Section 3.4, presenting how some of the inefficiencies can be tackled and the contribution to the literature. Section 3.5 lists all the dissemination activities conducted during the course of the PhD study.

3.1 Data Collection and Project Timeline

Data collection in this project covers two areas: domain knowledge and quantitative data. Domain knowledge has been gained through multiple terminal visits, meetings with the terminal management, the crew on board, and staff at the head office, ECOPRODIGI project seminars as well as relevant documents on ships, terminals, and operations. Continuous inputs and feedback from our industrial partners have contributed significantly to the success of the project. Quantitative data has been collected from the company's systems and database.

3.2 End2End Cargo Stowage Process

Stowage is the process of assigning locations on the ship to a list of cargo units to be transported. Cargo stowage is of great importance as it has a significant impact on its related operations. The process starting from gate-in of a cargo unit ending at gate-out of the cargo unit is defined as the *end2end cargo stowage process*, which interfaces with the booking process and in principle covers gate-in, yard positioning, stowage planning, load planning, cargo loading, vessel departure, vessel operations, vessel arrival, discharge planning, yard positioning, pick-up and gate-out processes [1] (Figure 4). This section describes in detail the operation in each process, their challenges and opportunities in integrated logistics, and finally how the focus area of the PhD study has been chosen.

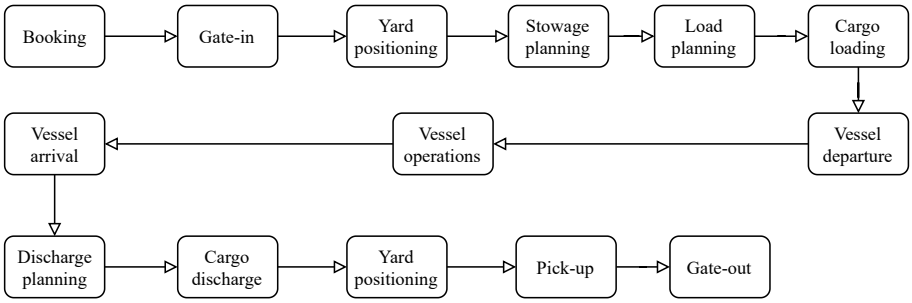

Fig. 4: End2End Cargo Stowage Process

Customers make a booking for their trailer(s) to be transported through various booking channels provided by the shipping company. Customers are supposed to deliver the trailer to the terminal at a certain time prior to the ship's departure, which is known as the *cut-off time*. The cut-off time can vary from one hour to up to several hours depending on the route and type of cargo unit. For example, the cut-off time for dangerous goods is usually earlier than that for standard trailers. During the gate-in process, each trailer is assigned a position on the yard. This information is updated and stored in the database. The stowage planner then needs to make a stowage plan based on the booking list and the status of cargo presence in the terminal, and afterwards a load planning such as how many tugs should be deployed to which decks, is performed. The cargo is then loaded according to the stowage plan supported by the load plan. Once all the cargo units are loaded, the ship can depart given all stability and safety conditions are in place. The ship arrives at the destination port and is ready to discharge all the cargo units on board, following a discharge plan. Discharged cargo units are positioned at the yard and are available for the customers to pick up, gate out of the terminal, and continue to deliver to the next destination in the logistics chain,

which concludes the end2end cargo stowage process.

However, there are many challenges throughout the process. First and foremost, the competitive industrial environment makes it very difficult for shipping companies to enforce the booking agreements, experiencing that cargo units arrive earlier or later and even do not show up for their booked departures. This results in the lack of arrival time and status of booked cargo units for the operating shipping companies. Moreover, cargo weight and dimensions are not validated at the gate due to the fact that cargo is usually charged by the length of the trailer instead of weight. Even though a position is assigned to a trailer upon gate-in, the precise location where the trailer is parked in reality may still be wrong, which is not updated accordingly in the terminal system. This can be problematic during the loading process when tug masters need to find certain trailers as it is time-consuming and therefore slows down the loading process. Current industrial practice is usually to work with a high-level, preliminary, and manual stowage plan presenting roughly the number of trailers on each deck or area on the deck, therefore there is no precise information of each cargo unit onboard the ship. Thus it is challenging for the loading computer to calculate the exact measurements for stability and safety. To comply with safety requirements, additional ballast water is therefore taken on board to make sure the vessel can leave with desired trim and stability. Moreover, customers lack information on the available pick-up time of their trailers, resulting in both long waiting times for the customers at the terminal and also possible congestion inside and outside the terminal area.

Challenging as it may be, opportunities appear with great potential of improvement to reduce inefficiency in the processes to become more competitive. The key question guiding this work becomes clear: can we gain eco-efficiencies in the end2end cargo stowage process through digitalization and optimization?

To tackle the inefficiencies and gain more competitiveness, the industry can implement hardware and software solutions to improve the quality of data capture in the future. For example, the lack of arrival time and status of booked cargo units can be improved by installing tracking devices on the trailers or developing phone apps with incentives for the drivers to log their estimated arrival time. Inaccurate cargo weight and dimensions can be validated at a smart gate, equipped with weight-in-motion sensors and various functional cameras to identify incoming drivers' number plates and trailer numbers to skip the manual gate-in process. Wrong parking locations of trailers on the yard can be validated and updated in the system by the use of camera or drone technology, which can also be utilized onboard the vessel to track the position of cargo units loaded onboard each deck and also to monitor the cargo operations and cargo conditions during sailing.

On the basis of a good data source, the industry can also improve effi-

ciency through statistical and optimization techniques that convert data into valuable knowledge to develop a better decision support system for cargo stowage and operations, that is integrated into daily processes. This is also the focus and contribution of this PhD study, which will be further elaborated in Section 3.4 after reviewing relevant literature in the field of RoRo shipping in Section 3.3.

3.3 Literature Review

This section aims to provide a general overview of the literature in RoRo shipping with reference to terminal operations and stowage planning. To the best of the author's knowledge, no review paper has been made in this area so far. RoRo shipping has attracted more and more attention from researchers in recent years, though not to the same extent as container shipping. We refer readers with an interest in container shipping to this literature review [36] and the following update [32] on terminal operations, and this book [17] on stowage planning.

Terminal Operations

Some researchers have studied the performance of RoRo terminal operations via simulation modeling with different focus areas. A discrete event simulation (DES) model has been developed to identify potential bottlenecks of RoRo terminals for better decision making and resource allocation [21]. Another study aims to develop a DES model to analyze the performance of a Souther Mediterranean RoRo terminal, with reference to the ship turnaround time, which, according to the results from experiments, are significantly affected by inter-arrival time, unloading/loading time, number of cars and number of trucks [23]. Another study also tries to develop a DES model to evaluate the impact of the daily operational decisions on planning and operational efficiency in RoRo terminals, focusing on vehicle handling. A cost function is defined to assess the decisions in terms of both logistic and environmental costs [13]. Furthermore, terminal capacity has been investigated by using a simulation modeling method [29] and calculated estimations [25] [31] since it is closely related to not only terminal performance but also strategic terminal planning.

Other researchers have also tried to investigate the terminal traffic. For example, one paper forecasts the daily RoRo freight traffic at ports by a hybrid model combining empirical mode decomposition, permutation entropy, and artificial neural networks [26]. A good forecast of traffic flow at ports can serve as inputs to decision support systems for better resource planning.

Stowage Planning

Maritime stowage planning problems in the context of RoRo shipping have started to gain more and more attention in recent years. The RoRo ship stowage problem has been introduced for the first time by Øvstebø et al. for deep sea car carriers that serve multiple ports on the journey [27]. A mixed integer programming (MIP) model has been developed with the objective to maximize the revenue intake. Decisions such as which cargo to carry, the number of vehicles in each cargo order, and where to stow the vehicles are considered in this paper. A heuristic solution approach is designed and compared with the exact method. Later on, the same group of researchers extended the study to include routing and scheduling decisions simultaneously [28]. The proposed heuristic solution is shown to be able to handle realistic size instances. However, dividing the decks into lanes as done in [27] can potentially limit good solutions. Therefore, Hansen et al. propose a new and more realistic version of MIP model for the RoRo ship stowage problem for one deck (2DRSSP) which can be viewed as a two-dimensional packing problem [12]. The generated stowage plans can be evaluated by a shortest path based heuristic developed in another study [10]. The 2DRSSP has been further studied and extended in [11]. A novel MIP model is proposed with a new approach of modeling the shifting aspect. The model is solved using an adaptive large neighborhood search heuristic proposed in this paper. Based on some latest research on RoRo stowage planning problem, Puisa [30] proposes a MIP model with three practical improvements, i.e. ship stability, fire safety, and cargo handling efficiency. The model aims to maximize the revenue and minimize the shifting cost as previous research studies focusing on deep sea RoRo ships.

Studies have also been done to optimize stowage on vehicle ferry to optimize revenue [2] and improve packing efficiency [3].

3.4 Research Contribution

Based on the literature review and extensive discussions with the collaborating company, this thesis aims to tackle three aspects of problems within the end2end cargo stowage process: stowage planning with optimal ballast water (Paper A and B with IMDG cargo), loading and unloading efficiency through dual cycling optimization (Paper C), and unavailable arrival information by estimating cargo arrival time (Paper D). This section presents in detail the contribution of each paper to both academic research and industrial application.

Stowage Planning

Paper A studies the problem of stowage planning in short sea RoRo shipping with a focus on stability and applicability of the stowage optimization model. First, we propose a new perspective to design the stowage models taking into consideration the integration with loading computers. We present a novel mathematical formulation of the RoRo ship stowage problem with the inclusion of ballast water, where stability requirements are satisfied by means of good weight distribution of cargo units instead of using excess ballast water, i.e. causing additional fuel consumption while sailing according to admiralty coefficient. A discretization method is introduced to linearize the quadratic constraint caused by the inclusion of ballast water. The objective is to generate an optimal stowage plan with minimal ballast water intake to reduce unnecessary fuel consumption. We test a real life case with empirical data collected from the shipping company. The result shows 57.69% ballast water reduction, equivalent to 6.7% reduction in fuel and CO_2 emission, indicating significant savings and potential to apply the model in real life. Additional tests are conducted on instances with various weight distribution and discretization levels, showing these two parameters have no significant impact on the computation time.

Paper B extends the problem formulation from Paper A with the presence of dangerous cargo units, which require complex segregation rules to ensure safety at sea. We propose a step-wise planning approach to incorporate industrial experts' inputs for generating a more robust and flexible stowage for plan RoRo ships. The approach consists of three steps, which are individually formulated as a (mixed) integer programming model solved by a commercial solver Gurobi. Step 1 maximizes the number of dangerous cargo units to transport subject to the segregation rules according to the IMDG Code. Step 2, which is optional, maximizes the distance among the dangerous cargo units selected in Step 1 to ensure maximal safety. Finally, Step 3 minimizes the ballast water intake to ensure stability and safety of the ship, based on the model developed in Paper A. We generate 30 sample instances based on a large amount of real data from the collaborating shipping company. Results from the computational study show great potential in improving safety and reducing fuel consumption and CO_2 emission (as indicated in Paper A) for RoRo shipping companies to implement the step-wise stowage planning approach and integrate it into daily operations.

Dual Cycling Operation

In this paper, we seek to improve the efficiency of loading and discharging operations by introducing the concept of dual cycling for RoRo ships. Dual cycling is the concept of loading while discharging cargo units. Paper C

presents the novel RoRo dual cycling problem with an integer programming (IP) formulation. The objective is to minimize the total operational time on loading and discharging of cargo units. The NP-completeness of the problem is proven by a reduction from a general machine scheduling problem. We propose a generalized random key algorithm (GRKA) as the solution approach and evaluate its performance against the IP model solved by commercial solver Gurobi on both 4 industrial and 40 generated instances with different deck layouts. Results show that the GRKA heuristic approach solves all cases to optimality or near optimality in just seconds of computational time. Our empirical results show the total operational time can be reduced significantly, equivalent to an estimate of 25% less fuel consumption and CO_2 emission. We believe there is a potential of integrating our approach into terminal operations for decision support given the fast computational time and the significant improvement in shortening vessel turnaround time at the port.

Cargo Arrival Time Estimation

Another inefficiency is the lack of cargo arrival information for customers to pick up their trailers in time, causing reduced truck utilization, longer waiting time, and lower satisfaction for the customers; reduced yard space utilization, and potential congestion in the terminal. Paper D aims to address this problem with a data-driven module-based framework for estimating the discharge time of individual cargo units. The framework consists of three modules: Module 1, which estimates the loading position on board based on loading timestamps; Module 2, which takes the input from Module 1 and estimate the discharge sequence; and Module 3, which derives the discharge time based on the discharge sequence from Module 2 and a discharge speed based on historical data. The framework is tested against real data provided by the collaborating shipping company. We present results for the performance of both individual modules and the overall framework. The overall result shows that the modular framework is capable of estimating the discharge time of each individual trailer within one-hour accuracy for up to 70% of all cargo units. The proposed modular framework applies simple and understandable logic and thus can be easily applied and customized to different voyage routes, vessels, and shipping companies, indicating great potential for industrial implementation and integration of the framework into daily operations.

3.5 Dissemination Activities

Presentations

The research conducted during the PhD project has been presented in the following conferences and workshops.

- Presentation titled *Cargo Stowage Optimization in Ro-Ro Shipping* at the 1st EURO Young Workshop, 2019, Seville, Spain;
- Presentation titled *Estimating Discharge Time of Cargo Units in Ro-Ro Shipping* at the 27th Annual Conference of the International Association of Maritime Economists (IAME), 2019, Athens, Greece;
- Presentation titled *Estimating Discharging Time of Cargo Units - A Case of Ro-Ro Shipping* at the 10th International Conference on Computational Logistics (ICCL), 2019, Barranquilla, Colombia;
- Presentation titled *Optimal Dual Cycling Operations in Short-Sea RoRo Terminals* at a seminar held at Technical University of Denmark, 2019, Kongens Lyngby, Denmark;
- Presentation titled *Eco-efficiency and Digitalization in Ro-Ro Shipping* at the 4th AIROYoung Workshop - New Advances in Optimization, Machine Learning an Data Science, 2020, Bolzano, Italy;
- Online presentation titled *Stowage Planning with Optimal Ballast Water* at the 10th International Conference on Computational Logistics (ICCL), 2020, Twente, the Netherlands.

Co-supervisions

Co-supervision of 2 master projects and 10 bachelor projects on various study programs at Aalborg University Copenhagen. Supervised topics include forecasting, machine learning, and statistical process control for problems related to maritime operations and logistics.

Other Activities

- Terminal and ship visits at Vlaardingen, the Netherlands (2018, 2019), Esbjerg, Denmark (2018, 2019), Gothernburg, Sweden (2018);
- Participation at 3rd AIROYoung Workshop - Advanced Methods in Optimization and Data Science, 2019, Rome, Italy;
- Organization of the stowage workshop with guests and participants from UK, DTU, DFDS and Kockumation, 2019, Copenhagen, Denmark;

- Research Visit about Smart Deck at Tallinn University of Technology, Maritime Academy and Port of Tallinn, 2019, Tallinn, Estonia;
- Participation in Applications of Optimization, 2019, Copenhagen, Denmark
- Article titled *Digitalisation of Integrated Logistics Chain in Roll-on/Roll-off Shipping* published in ORbit magazine, issue 34, 2020;
- Peer-reviewed abstract titled *Eco-efficiency potential from digitalizing cargo stowage and operations in RoRo Shipping* submitted and accepted by the 29th Annual Conference of the International Association of Maritime Economists (IAME), 2021, Rotterdam, the Netherlands.

4 Conclusions and Future Work

This section concludes the thesis with a summary of the main contributions of this PhD study and potential future research directions. The work related to the thesis has been disseminated in international conferences, various workshops and seminars, and peer-reviewed journals.

4.1 Conclusions

The PhD study contributes to the field of digitalization and optimization in the short sea RoRo shipping industry with a focus on sustainability from several aspects: novel problem definition, modeling, solution approach, and industrial application. In general, we have shown how statistical and mathematical optimization methods can have a significant impact on improving efficiency and sustainability in the short sea RoRo shipping industry. In particular, we have addressed the following three problems: stowage planning, dual cycling, and cargo discharge time estimation.

In order to present readers with an overview of the contributions across articles contained in this thesis, we attempt to quantify the relative significance from various indicators shown in Table 1. The level of significance is represented by the number of "+" from low to high.

Table 1: Thesis Contribution.

Contribution	Stowage Planning		Dual Cycling	Cargo Arrival Time
	Paper A	Paper B	Paper C	Paper D
Novelty of Problem	+++	+++	+++	+++
Terminal Performance			+++	+++
Reduced Fuel Consumption/Emissions	++	++	+++	+
Safety and Stability	+	+++		
Readiness for Implementation	++	++	+	+++

Novelty of Problem

The first main contribution is the introduction of three novel problem formulations in the short sea RoRo shipping. Paper A proposes a novel mathematical formulation of the stowage optimization model with the inclusion of ballast water and better stability formulation. Paper B, extended from Paper A, introduces the concept of dangerous goods into the stowage planning process and proposes a step-wise planning approach. Paper C introduces the novel concept of dual cycling, meaning discharging trailers while loading simultaneously in order to reduce the total time spent on discharging and loading operations. The last paper, Paper D investigates the problem of estimating cargo discharge time in order to provide customers timely information for better logistics planning and proposes a statistical based estimation framework.

Terminal Performance

From a terminal's perspective, the thesis contributes with models that might improve terminal efficiency and asset utilization, reduce terminal congestion, and shorten ship turnaround time in port.

For a ship with fixed sailing schedules, the shorter the turnaround time, the longer time the ship can sail at sea, i.e. slow steaming which can reduce the fuel consumption quadratically. Paper C aims to reduce the ship turnaround time at port by optimizing the loading and discharging process with the concept of dual cycling. Results based on empirical data suggest an estimated reduction of 88 minutes in turnaround time, equivalent to nearly 25% potential reduction in fuel consumption and related airborne emissions through slow steaming. Shorter ship turnaround time leads to lower terminal resource costs and the possibility to accommodate more ships.

Paper D proposes a framework to estimate the discharge time for individual cargo units. A timely cargo arrival information enables customers to plan an efficient cargo supply chain, thus reduces truck congestion and emissions inside the terminal and improved customer satisfaction.

Reduced Fuel Consumption/Airborne Emissions

One way for shipping companies to stay competitive is to minimize the operational cost, the biggest part of which is fuel consumption. Reduced fuel consumption also means less airborne emissions, which complies with strict international environmental regulations and thus contributes to a better environment. Paper A and B introduce stowage optimization models that minimize the intake of ballast water, which can potentially reduce fuel consumption and CO_2 emissions by 6.7% based on an industrial test case. Paper C demonstrates an estimated reduction in fuel consumption and emissions by

around 25% through dual cycling optimization. In addition, both Paper C and D potentially reduce fuel consumption and emissions by reduced truck waiting time, which is not able to be quantified in this study.

Safety and Stability

Safety and stability is a critical but complex issue. We have addressed not only ship safety and stability and also specifically cargo safety. Paper A promotes the integration of the loading computer and stowage planning process and includes better stability constraints with the inclusion of ballast tanks. Paper B extends the focus of ship stability and safety to cargo safety, in particular, the segregation of dangerous cargo units to comply with the regulations and potentially even reduce the risk of danger such as fire and explosion.

Readiness for Implementation

How well can a model or a framework be integrated with other systems is an important aspect to consider for industrial implementation. With a practical mindset, we have tried to meet industry requirements for solutions, especially the connection between systems and operations in order to develop models and frameworks that can be easily implemented.

Paper A and C present models which can enable a higher degree of automation than Paper B and D with regards to the need of human intervention in the work process. Paper B's step-wise stowage planning model provides the possibility of interaction with stowage planners at each stage, which gives more robustness and applicability but also less automation at the same time. Paper D has the lowest degree of automation readiness, which is natural for a statistics based framework solution. Note that this thesis aims to develop solutions, which are to become part of or integrated into decision support tools used by staff onboard / onshore as part of daily work processes, and therefore mainly support humans in making more informed decisions instead of replacing human decisions.

Despite Paper D being the least automated solution, it has a great potential of being integrated into tools used to support daily operations due to the significant performance and simplicity of the framework. To the authors' knowledge, further investigation and testing of the framework have been conducted by the collaborating company. Paper A and Paper B, on the other hand, requires further work before the models can be implemented, in particular, the handling of cargo uncertainty and the ability of the loading computer software to integrate. Paper C requires the most work of all due to the discretization of time in the problem formulation despite its high level of automation. Future work on potential improvements to the proposed solutions in this thesis is further discussed in the following section.

4.2 Future Work

In this thesis, a number of new problem formulations were introduced with proposed solution methods that demonstrate significant improvement in inefficiencies. However, both the models and solution methods presented can potentially be improved, such as better problem formulation and faster solution approach from an academic perspective; and considerations on the potential for implementation and integration in real-life daily operations from an industrial perspective. Ideas for potential improvement of the work completed in the thesis are listed as follows:

- Paper A and B investigate the short sea RoRo ship stowage planning problem. Some details which were simplified and linearized due to the complexity of the problem can be potentially improved by using a better approximation, such as the stability calculations. Optimal intake of ballast water can significantly reduce fuel consumption, as demonstrated in Paper A. However, the trim of the ship also has a significant impact on fuel consumption, which should be taken into consideration. Regarding computational performance of the models, the possibility of constructing a heuristic approach for Step 2 in Paper B is worth investigating, in order to improve both the computational time and solution quality so that it becomes more attractive to be integrated into the planning tool in real life. Moreover, it would also be interesting to study the robustness of the model with regard to changes in the amount, size, weight distribution of cargo units, in order for the model to be implemented in the cargo stowage work processes in real life. The integration with the loading computer and other data sources and validation with stowage planners and crew onboard are also critical aspects to consider for implementation.

- Paper C addresses dual cycling for RoRo ships to improve loading and discharging efficiency. Our proposed heuristic is of high quality with regards to both fast computational time and solution optimality, which makes it realistic for our approach to be integrated into planning tools for decision support. A key limitation of this work is the assumption that time is discretized. To improve the potential of implementation, we suggest future work on the realism of modeling relating to the time discretization for loading and discharging tasks. Moreover, it would also be interesting to research the impact of dynamic or realtime information on the robustness of the solution.

- Paper D describes the problem of discharge time for individual cargo units onboard a RoRo ship and proposes a module based estimation approach. The bottleneck lies in Module 3, which can potentially be

improved by more accurate calculation of discharge speed or modeling discharge time using e.g. machine learning to improve the accuracy.

Most of the proposed solution approaches in this thesis are (mixed) integer programming models solved by the commercial solver Gurobi. It would also be interesting to investigate the choice between mathematical modeling and the heuristic approach, especially in the industrial setting.

Moreover, there are still many important problems with inefficiencies in the end2end cargo stowage process which require to be modeled and solved in order to be implemented and integrated into real life. However, this can not be achieved without the industry or relevant international organizations establish standardization such as data sharing, verified weight, enforced contract, etc.

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Part II

Papers

Paper A

Stowage Planning with Optimal Ballast Water

Beizhen Jia, Aalborg University

Kjetil Fagerholt, Norwegian University of Science and Technology

Line Blander Reinhardt, Roskilde University

Niels Gorm Malý Rytter, Unversity of Southern Denmark

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Abstract

Stowage planning is at the essence of a maritime supply chain, especially for short sea Ro-Ro ships. This paper studies stowage optimisation of Ro-Ro ships with a focus on stability constraints and the applicability of models. The paper contributes to short sea Ro-Ro ship stowage in two ways. First, we propose an integrated approach of designing stowage models with the consideration of loading computers. Second, we present a mathematical formulation of the Ro-Ro Ship Stowage Problem with Ballast Water with a discretisation method, to generate an optimal stowage plan which meets stability requirements by means of the weight of cargoes instead of excess ballast water, i.e. excess fuel consumption. Computational tests based on empirical data indicate significant savings and potential of model application in the real world. Preliminary results show 57.69% ballast water reduction, equivalent to 6.7% fuel savings and CO_2 reduction. Additional tests on instances with various cargo weight distribution and discretisation levels are conducted, and finally, improvements are suggested for further research considerations.

Keywords: Stowage optimisation, Ballast water, Maritime transportation, Environmental impact.

1 Introduction

Roll-on/Roll-off (Ro-Ro) short sea shipping (SSS) has become one of the most important means in Europe for transportation of passengers and cargoes. Ro-Ro ships carry vehicles and passengers travelling with own journey plans as well as cargo units being trailers, cars, heavy machinery, containers, or anything that goes onto a rolling equipment. Trailers and rolling cargoes are transported either accompanied or unaccompanied by a (truck) driver. Compared to other means of intra-European transport, like for example, container shipping, rail or pure road transport, Ro-Ro SSS has the advantage of being well integrated into the entire cargo supply chains from door to door. Short sea container shipping requires several modal shifts (road, rail, ship etc.), has longer transit times and low flexibility due to less frequent departures, and implies more document handling in comparison with Ro-Ro SSS.

The European Ro-Ro SSS market is growing [1], but also becoming increasingly competitive with currently approximately 100 short sea operators in Europe [2]. Several Ro-Ro companies have recently expanded their fleet capacity via ordering new mega Ro-Ro ships. One example is DFDS which recently ordered 6 x 6700 lane metre Ro-Ro ships to be delivered to their routes in 2019-2020 [3]. The increase in Ro-Ro tonnage, combined with recent Brexit and Corona virus developments, is likely to impact ship utilisation and rate levels going forward. Also the industry must comply with environmental regulations and International Maritime Organization (IMO)'s 2030 and

2050 targets for greenhouse gas emissions [4]. New ship designs, propulsion technologies and fuel alternatives are in progress to meet long term requirements, but in parallel cost control and energy efficient ship operations will be a strategic priority for existing Ro-Ro operators. A key element will be reduction in fuel consumption and costs on the sea leg via adjusting speed, trim, reduced deadweight etc. To achieve this, it is critical for ships to be stowed optimally before departing from port, which implies maximising cargo load, reducing ballast water intake and thereby deadweight without compromising stability, strength or safety requirements. Ship stowage is a key part of Ro-Ro SSS operations, and it includes a whole set of maritime related subprocesses from when a cargo unit gates into the terminal until when it gets picked up at the destination terminal. It is critical that the entire process is understood well to be able to plan and execute optimal stowage for Ro-Ro ships. In addition to what was mentioned above, high quality stowage planning also ensures efficient load and discharge processes at the terminal, and shortening of the port stay which again enables the ship to slow down and save fuel on the sea leg.

Through interviews with selected terminal managers, stowage planners, ship officers and other relevant stakeholders from one of the largest Ro-Ro shipping companies in Europe, the end-to-end cargo stowage process is defined as a process of a series of cargo-related activities including booking, gate-in, yard positioning at loading port, stowage planning, loading, discharging, yard positioning at destination port and gate-out.

As illustrated in Figure A.1, stowage planning acts as the core activity in the process. It takes booking information and cargo arrival status as input to the planning. The booking information offers a list of cargo booked for the departure with detailed cargo information, such as cargo type, transportation unit type, dimensions and weight, well in advance. In addition, cargo arrival status confirms the presence of booked cargo in the terminal on the day, due to the fact that no-show is a common phenomenon in shipping industry. Therefore, before making a stowage plan, the planner needs to know how much of the booked cargo have actually shown up, so that he does not plan stowage for cargo that will never show up and makes timely decision to pull forward optional cargo if the ship's capacity is not fulfilled, thus maximising the space utilisation onboard.

Once the load list is updated, a stowage plan is made with consideration of ship stability and cargo characteristics. The stowage plan includes a plan for positions of all cargo to be loaded onboard the ship to ensure a good handling of cargo with regards to special requirements for dangerous goods, refrigerated goods, and goods with lashing needs. The loading operation is conducted according to the stowage plan, and it gets updated if there is any changes happening during the loading operation. Based on the updated stowage plan, the discharge operation is performed at the destination port,

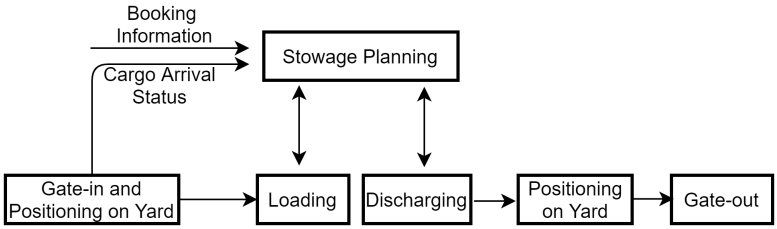

Fig. A.1: The Ro-Ro shipping End2end Stowage Process.

and customers can pick up cargo units according to the pick-up time and position in the yard. Finally, customers gate out with their cargo and usually continue road transportation to the next destination.

From above, it becomes visible that stowage planning interacts with all activities happening in the end-to-end cargo stowage process. Hence, it is essential to make a good stowage plan, as it impacts ship utilisation, fuel consumption, safety at sea and the ability to execute load and discharge operations efficiently. Moreover, it can also be used to derive accurate information of when cargo is available for pick-up by customers at the destination port [5].

2 Literature Review

Stowage planning of Ro-Ro ships has not attracted the same attention from researchers in operations research and optimisation as has container ships. Øvstebø et al. [6] were the first to introduce the Ro-Ro ship stowage problem (RSSP). For a set of mandatory and optional cargoes and a given route with multiple port calls, reflecting the situation of deep sea car carriers, the problem was to determine which additional cargoes to carry and how to stow all carried cargoes on board the ship in order to maximise the profit of the journey. Cargo consisted of a number of homogeneous vehicles. Decks were divided into several lanes which also explained why only rolling moment and vertical forces were constrained in the model for stability considerations. The paper proposed a mixed integer programming (MIP) approach as well as a heuristic algorithm to solve the RSSP. According to the authors, realistic size instances with 5-10 mandatory cargoes could be solved to optimality by MIP, while the heuristic worked better without stability constraints.

Hansen et al. [7] focused on the operational decisions related to the stowage of Ro-Ro ships visiting multiple ports. The paper restricted the stowage problem to a single deck and considered it as a special version of a 2-dimensional packing problem with some additional considerations. In addition, it also considered the shifting of cargoes to make an entry/exit path if needed dur-

ing loading and unloading operations. Several versions of new MIP formulation for the problem were presented with the consideration of reducing the need of shifting. The goal was to stow all mandatory cargoes and as many optional cargoes as possible while trying to avoid shifting. Since it was focused on a single deck, stability constrains were therefore not included in the model. Furthermore, the model used a grid representation of the deck instead of dividing it into several lanes, which the authors thought may restrict finding of good solutions. The paper concluded that the model works well with small-size instances and suggested further research of a faster algorithm for realistic-size problem instances and eventually for not only one single deck but the whole ship.

Following their previous work [7], Hansen et al. [8] presented the stowage plan evaluation problem to determine which vehicles to shift at each port call, in order to minimise the extra time spent on shifting. For a given set of alternative stowage plans, the goal was to find the best plan of all with the minimal shifting time. A shortest path based heuristic was proposed for solving the problem and it showed that solution method was powerful for its fast computing time and high success rate in determining a better plan.

The above mentioned papers were focused on deep sea Ro-Ro ships, such as car carriers that operate globally with multiple port calls on the sailing route. The problems were usually considered with two types of cargoes, mandatory and optional. The objective was therefore focused on revenue related decisions, such as how many optional cargoes could be stowed, less shifting cost, and etc. Stability constraints were simplified and limited for the ease of modelling, and not included at all in the case [7] where only one deck is considered. Such handling of stability constraints might be due to the fact the RSSP with deep sea car carriers is more robust to changes in terms of cargo weight. There is limited variation for car weights. Thus it becomes more relevant for deep sea car carriers to focus on shifting costs along multiple ports on the route in their stowage planning. Nonetheless, when planning stowage for short sea Ro-Ro ships, stability is of utmost importance due to high variance of cargo weights. The difference of cargo weights can have a significant effect on ship's stability in many aspects.

Based on the state-of-art research on Ro-Ro stowage optimisation problem, Puisa [9] proposed three practical improvements, namely ship stability, fire safety and cargo handling efficiency. The author proposed a new grid method to discretise the stowage location onboard for accurate ship stability and strength calculation. Fire safety was ensured by adding additional constraints to high risk cargoes, average headroom and cargo spacing. With the argument that it was not a realistic solution to penalise cargo shifting with a cost as proposed by previous researches, elimination of such was proposed in the paper for a swift loading and unloading operation with multiple port calls. The study included different cargo types with the same weight within a

type which might not be the case of containers and trailers for example. The test instance size was small with most cargoes being optional. So it is difficult to say the running performance when solving realistic sized problems. The study extended stability calculations with stricter and more constraints. However, without the inclusion of ballast tanks in the calculation, limits for stability constraints should be adjusted to the cases without ballast tanks.

Integration of various operations to improve terminal efficiency has been studied by some researchers in containers shipping, such as ship loading problems where stowage planning is taken into consideration as an input to the model [10] [11] [12], and stowage planning integrated with the quay crane scheduling [13].

Rethink of the stowage problem. No matter how fast the algorithm works or how much revenue the objective function can achieve, stability is always the prerequisite of a stowage plan. Without it, a ship can not sail. Therefore, it is mandatory to calculate stability for every ship departure to ensure its seaworthiness, which is enforced by IMO. Every ship has a loading computer onboard which connects to sensors that collect all information needed to calculate stability of the ship. Once all cargoes are loaded, ship officers will try to adjust the amount of ballast water in each tank to reach the desirable stability. This usually ends up with ships carrying around with excess ballast water, in other words, excess fuel consumption.

Therefore, the contribution of this paper is twofold - first, to introduce the integrated approach of stowage planning with considerations of loading computers, which has not been studied so far to the authors' knowledge, and second, to include ballast water optimisation in RSSP with the purpose of generating a stowage plan that reduces fuel consumption and at the same time provides a better stability condition that is closer to the loading computer requirements.

3 Integrated Stowage Planning

Stowage planing for Ro-Ro ships is typically done through a stowage module in combination with onboard loading computer software. A stowage module can be as advanced as stowage optimisation models or as simple as Excel sheets. Loading computers provide deck officers the ability to validate whether a given stowage plan complies with maritime authorities' stress and stability requirements. A ship is required to be seaworthy at any given moment in order for her to sail. At each ship departure, during and after finishing loading, the hull strength and stability of the ship are calculated and if necessary modified by adjusting the amount of water in ballast tanks to meet stability requirements. Currently in the market for Ro-Ro ships, there are several loading computer systems available, such as Kockumation's Loadmaster,

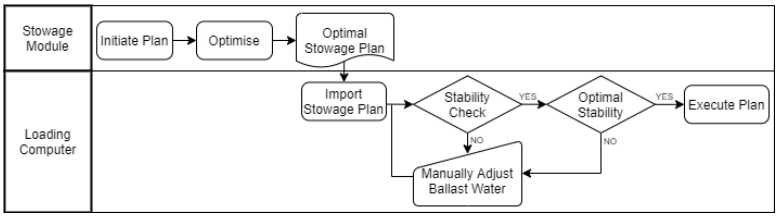

Fig. A.2: Traditional stowage planning and interaction with loading computers.

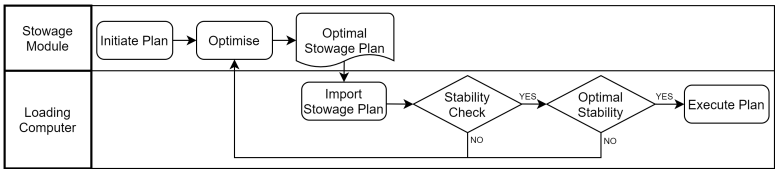

Fig. A.3: Envisioned future approach for stowage planning with integration of loading computers.

NAPA's Loading Computer, Navis's MACS3 and Autoship's Autoload.

The common and traditional approach of designing stowage plans, as illustrated in Fig.A.2, starts with a stowage module generating an initial stowage plan, optimises if possible and then sends it to the loading computer onboard to check the stability of the plan. If it passes the loading computer's stability requirement, the plan can be executed in the loading process. Otherwise, the ship officer or stowage planner manually adjusts the plan by adding ballast water and/or moving cargoes around to achieve desired stability. It is usually the case that the plan does not fulfil the stability requirement from the loading computer, especially when the stowage module provides an optimal plan with bad stability condition to the loading computer. In the case of a stowage model with simplified stability constraints, it may perform excellent in finding optimal solutions according to the objective function. Nonetheless, it may result in undesirable overall performance due to the fact that manual adjustment can be expensive regarding the excess amount of ballast water which is translated to excess fuel consumption.

We propose an integrated approach of stowage planning as decision support, illustrated in Fig. A.3. Compared with the traditional approach, the difference is that the loading computer is integrated into the planning phase, meaning that when the optimal plan does not pass stability check, instead of manual adjustment, the information is sent back to the module with additional constraints added to re-optimise and re-generate a new optimal solution. In this approach, there is continuous communication and interaction between the stowage module and the loading computer to improve the plan for it to satisfy stability requirements in the end. The envisioned future ap-

proach is automated to the extent that the integration with the loading computer allows. Anyways, these iterations can be expensive, and hence should ideally be eliminated or minimised. Therefore stability constraints should be set as close to reality as possible for the stowage module to generate a good plan subject to a certain objective function while keeping stability within required limits or even optimal stability. In this paper, we focus on designing the stowage model with considerations of the integration with loading computers instead of the whole iterative process, which highly depends on the development of loading computers.

4 Ro-Ro Ship Stowage Problem with Ballast Water

Let us assume that a given Ro-Ro ship transporting two types of cargoes: general trailers (TRAs) and refrigerated trailers (TRARs). TRAs can be loaded anywhere, whereas TRARs can only be loaded at designated slots that have power connection through the ship. The ship has a fixed number of decks with various weight limits. In the case of short sea Ro-Ro ships, the majority of cargoes are standard trailers. For the sake of simplicity, we assume cargoes are homogeneous in dimensions with the same length, width, and height, however, different in weight. All cargoes are mandatory and available at the loading port, unaccompanied by drivers after delivered to the terminal. A number of tug masters are assigned for loading and unloading tasks between ship and shore. Cargoes are loaded onto and discharged from the ship through the main ramp usually located at the aft of the ship. Movement of cargoes within the ship is conducted through narrower ramps located on the side of the ship in between decks. For this characteristic of Ro-Ro ship, cargoes need to be loaded and discharged following precedence relations based on their positions on board.

In order to generate a stowage plan that is more likely to pass stability requirements in the loading computer, it is important to include stability measurements from three dimensions, namely vertical, transverse and longitudinal forces imposed on the ship, measured through metacentric height (GM), heel and trim values as shown in Figure A.4. These values are complicated to calculate and are dependent on various factors according to naval architecture [14]. Therefore, they are represented by the composite vertical centre of gravity ($\overline{VCG}$) from the keel (KG), transverse centre of gravity ($\overline{TCG}$) from midship and longitudinal centre of gravity ($\overline{LCG}$) from aft perpendicular to mimic the stability as close to reality as possible.

The vertical distance between composite $\overline{VCG}$ to the metacentre is GM, which is calculated by the equation $KG + GM = KM$, where KM is the height of metacentre from keel and can be found in the hydrostatic table from the ship builder. For the simplicity of the model, KM is treated as a constant. GM

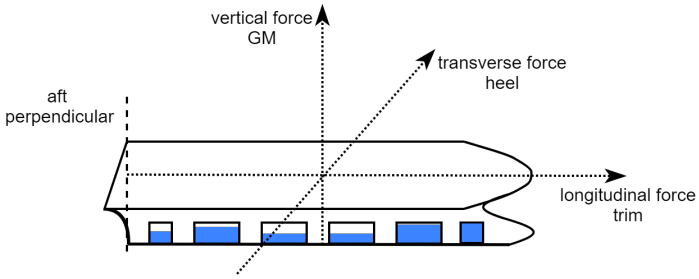

Fig. A.4: Ship stability illustration.

is one of the most important measurement when it comes to stability. GM is always positive to make sure that ships have the ability to bring themselves back to the upright position. Ship designers usually produce and define a set of values of minimum GM (GM_{min}) that meet all intact and damage stability criteria. If the actual GM value is higher than GM_{min}, then in most cases, other stability requirements will also be satisfied [15]. On the other hand, a very large GM meaning that the ship returns to the upright position too fast. At this stage, it has too much stability and becomes stiff, which can cause damage to cargoes and discomfort of crew. Therefore, a maximum GM (GM_{max}) value should be enforced as well. Hence, KG should satisfy $KM - GM_{max} \leq KG \leq KM - GM_{min}$.

Another two important parameters of stability are $\overline{TCG}$ and $\overline{LCG}$. $\overline{TCG}$ is an estimation of how much the ship heels, to ensure the ship does not roll too much to one side due to imbalanced heavy load. $\overline{LCG}$ is of similar concept to $\overline{TCG}$ but works in longitudinal direction, and serves as an estimation of trim to make sure the ship does not have a too heavy nose or bottom sitting in the water. Both $\overline{TCG}$ and $\overline{LCG}$ are constrained to a limit range to achieve close-to-zero heel and trim. Note that trim is a more complicated matter which has an impact on fuel consumption. However, it has a non-linear relation to displacement, draught and speed of the ship, hence, trim optimisation is left out in this article.

Ballast tanks are located at the bottom and along both sides of the ship, as illustrated in Figure A.4. There are two different types of ballast tanks on board - heeling tanks and regular tanks. Most of the ships have an anti-heeling system which is designed to balance the ship continuously and automatically with heeling tanks to minimise the angle of heel during loading and unloading operations. The total amount of water in all heeling tanks are required to be within a certain range in order to provide sufficient anti-heeling capability when the ship is heeled within a certain range of angles. However if it is beyond the ability of the anti-heeling system, then the amount of water

in regular tanks needs to be adjusted to ensure stability. For carrying the same cargo load, the more ballast water a ship carries, the deeper it sits in the water due to the extra deadweight, the more fuel is consumed. In other words, fuel consumption has a positive correlation with the amount of extra ballast water a ship carries.

For a given Ro-Ro ship, transporting a set of cargoes from one loading port to one discharging port, we present an optimisation problem dealing with where to stow each cargo on board so that the ship can sail with a minimal amount of ballast water while still respecting the ship's stability requirements. We consider decisions such as the placement of individual cargo on board with regards to its weight and stowing restrictions, and the amount of ballast water in each tank. In order to integrate with loading computer, we introduce the inclusion of ballast tanks as well as more complete and accurate stability constraints introduced above, in order to achieve overall efficiency of stowage planning with a goal of reducing fuel consumption. We define this problem as Ro-Ro Ship Stowage Problem with Ballast Water (RSSPBW).

5 Mathematical Formulation

We start this section by introducing a list of notation, before presenting the mathematical formulation for the RSSPBW described in Section 4. This formulation contains non-linear stability constraints due to the introduction of ballast water. Therefore, we propose a method of linearising these constraints resulting in a binary integer linear programming formulation.

Indices

c	cargo unit
d	deck
s	slot
i	ballast tank

Sets

$\mathcal{C}$	set of cargo units
$\mathcal{C}^{\mathcal{R}}$	subset of refrigerated units
$\mathcal{D}$	set of decks
$\mathcal{S}$	set of slots
$\mathcal{S}_d$	subset of all slots on deck $d \in \mathcal{D}$
$\mathcal{S}_d^{\mathcal{R}}$	subset of all refrigerated slots on deck $d \in \mathcal{D}$
$\mathcal{T}$	set of ballast tanks
$\mathcal{T}^{\mathcal{H}}$	subset of regular ballast tanks

$\mathcal{T}^{\mathcal{B}}$	subset of heeling ballast tanks

Parameters

$H^{max/min}$	limiting water volume required in all heeling tanks
T_i^{max}	maximum volume capacity for ballast tank i
C_c^W	individual weight of cargo unit c
$D_d^{W,max}$	maximum allowable weight on deck d
C_c^R	= 1 if cargo unit c is refrigerated, 0 otherwise
D_d^H	height of deck d
L^W	lightweight of the ship
L^{VCG}	VCG of lightship
T_i^{AoB}	Area of the base for ballast tank i
T_i^{TCG}	TCG of ballast tank i
T_i^{LCG}	LCG of ballast tank i
C_c^{VCG}	VCG of individual cargo unit
$S_s^{VCG/TCG/LCG}$	VCG/TCG/LCG of slot s
$KG^{max/min}$	maximum/minimum limiting KG value
$\overline{TCG}^{max/min}$	maximum/minimum limiting $\overline{TCG}$ value
$\overline{LCG}^{max/min}$	maximum/minimum limiting $\overline{LCG}$ value
ρ	sea water density, unit ton/m^3

Variables

x_{cds}	(binary) = 1 if cargo c is loaded on deck d at slot s
t_i	(continuous) the mass of water in ballast tank i
KG	composite VCG from keel
$\overline{TCG}$	composite TCG from midship
$\overline{LCG}$	composite LCG from aft perpendicular

5.1 Mathematical Formulation

$$\min \sum_{i \in \mathcal{T}^{\mathcal{B}}} t_i \tag{A.1}$$

$$\sum_{d\in\mathcal{D}}\sum_{s\in\mathcal{S}_d} x_{cds} = 1 \quad c\in\mathcal{C}, c\notin\mathcal{C}^R \tag{A.2}$$

$$\sum_{d\in\mathcal{D}}\sum_{s\in\mathcal{S}_d^{\mathcal{R}}} C_c^R x_{cds} = 1, \quad c\in\mathcal{C}^R \tag{A.3}$$

$$\sum_{c\in\mathcal{C}} x_{cds} \leq 1, \quad d\in\mathcal{D}, s\in\mathcal{S}_d \tag{A.4}$$

$$\sum_{c\in\mathcal{C}}\sum_{s\in\mathcal{S}_d} C_c^W x_{cds} \leq D_d^{max}, \quad d\in\mathcal{D} \tag{A.5}$$

$$\rho H^{min} \leq \sum_{i\in\mathcal{T}^{\mathcal{H}}} t_i \leq \rho H^{max} \tag{A.6}$$

$$KG^{min} \leq KG \leq KG^{max} \tag{A.7}$$

$$\overline{TCG}^{min} \leq \overline{TCG} \leq \overline{TCG}^{max} \tag{A.8}$$

$$\overline{LCG}^{min} \leq \overline{LCG} \leq \overline{LCG}^{max} \tag{A.9}$$

$$x_{cds} \in \{0,1\}, c\in\mathcal{C}, d\in\mathcal{D}, s\in\mathcal{S} \tag{A.10}$$

$$0 \leq t_i \leq \rho T_i^{max}, i\in\mathcal{T} \tag{A.11}$$

$$KG = \frac{\sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}}\sum_{s\in\mathcal{S}_d}(S_s^{VCG}+C_c^{VCG})C_c^W x_{cds} + L^W L^{VCG} + \sum_{i\in\mathcal{T}} t_i \frac{t_i}{\rho T_i^{AoB}}}{\sum_{c\in\mathcal{C}} C_c^W + L^W + \sum_{i\in\mathcal{T}} t_i} \tag{A.12}$$

$$\overline{TCG} = \frac{\sum_{i\in\mathcal{T}} t_i T_i^{TCG} + \sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}}\sum_{s\in\mathcal{S}_d} x_{cds} C_c^W S_s^{TCG} + L^W L^{TCG}}{\sum_{c\in\mathcal{C}} C_c^W + L^W + \sum_{i\in\mathcal{T}} t_i} \tag{A.13}$$

$$\overline{LCG} = \frac{\sum_{i\in\mathcal{T}} t_i T_i^{LCG} + \sum_{c\in\mathcal{C}}\sum_{d\in\mathcal{D}}\sum_{s\in\mathcal{S}_d} x_{cds} C_c^W S_s^{LCG} + L^W L^{LCG}}{\sum_{c\in\mathcal{C}} C_c^W + L^W + \sum_{i\in\mathcal{T}} t_i} \tag{A.14}$$

The objective of the model (A.1) minimises the total amount of ballast water carried onboard a ship in order to reduce the fuel consumption caused by excess ballast water. Constraints (A.2) and (A.3) ensure that each cargo is loaded exactly once at a slot for general cargo and refrigerated cargo respectively. Whereas constraints (A.4) make sure that each slot will only have at most one cargo loaded. For ship safety and stability, constraints (A.5) make sure that the total weight of cargoes loaded on each deck does not exceed the maximum weight limit per deck. Constraint (A.6) keeps the total amount of water in heeling tanks within a safe margin so that the tanks have sufficient capability to heel the ship. Lastly, vertical, transverse and longitudinal stability calculations are presented in equation (A.12), (A.13) and (A.14), and are constrained through constraints (A.7), (A.8) and (A.9), respectively. Due to the inclusion of ballast tanks and the amount of water inside as decision variables, VCG of ballast tanks becomes a function of the decision variables as well. For a given ballast tank, its VCG depends on the volume of water inside, and its shape, or its area of base if the tank is shaped vertically straight. The model assumes the latter, as also shown in Equation (A.12). Lastly, decision variables are bounded by (A.10) for binary indicator x_{cds}, and by (A.11) for both types of ballast tanks, whose upper limits are taken from

ship builders.

5.2 Linearisation

As can be observed that constraints (A.7), (A.8) and (A.9) are non-linear when substituted with equation (A.12), (A.13) and (A.14), respectively, not only due to the division but also the quadratic function of decision variables t_i in equation (A.12).

To eliminate the division existing in all three constraints, we simply multiply each constraint with its lower fraction, which is the sum of all weights including the ship itself. It is naturally positive, hence does not have any impact on the signs of the inequalities. It is however trickier when it comes to linearising the quadratic function in equation (A.12) - the product of the amount of water in the ballast tank and its vertical centre of gravity which is again determined by the amount of water whether the tank empty, full or in between. We propose a discretisation method using the following additional notations listed. In the discretisation method, we divide each tank i into several filling levels denoted by a set of discrete points $k \in \mathcal{K}_i$ and use binary variables y_{ik} to indicate whether the tank is filled to a certain level k. Each point or filling level corresponds to an amount of water T_{ik}^{VOL} and a VCG value T_{ik}^{VCG} when tank i is filled to the level k.

Indices	k	discretisation point, fill level of ballast tank
Sets	$\mathcal{K}_i$	set of discretisation point for ballast tank i
Parameters	T_{ik}^{VOL}	volume of ballast tank i if filled at level k
	T_{ik}^{VCG}	VCG of ballast tank b if filled at level k
Variables	y_{ik}	(binary) = 1 if ballast tank i is filled at level k

An example of the discretisation method is illustrated in Figure A.5. Let us look at one of the ballast tanks on board, tank i, which is located right above the keel. The maximum amount of water tank i can carry is 100 m^3 and its maximum VCG value is 10 metres. The tank is divided into three levels denoted by a set of points $\mathcal{K}_i = \{0, 1, 2\}$. At filling level $k = 0$, tank i is empty and therefore its corresponding VCG is 0 metres. A half filled tank i corresponds to a filling level of $k = 1$, with a VCG of 5 metres. Lastly a filling level of $k = 2$ meaning that the tank is full with 100 m^3 of ballast water inside and a VCG of 10 metres. In the case illustrated here, the tank is filled to level $k = 1$, represented by binary variables $y_{i2} = 1$, and $y_{i0} = y_{i1} = 0$. As mentioned above, the discretised tank values corresponding to filling level $k = 2$ are 50 m^3 of ballast water and a VCG of 5 metres. Therefore, the gravity moment of the tank i becomes the following linear calculation:

$$\sum_{k \in \mathcal{K}_i} \rho T_{ik}^{VOL} T_{ik}^{VCG} y_{ik} = \rho(0 \times 0 \times 0 + 50 \times 5 \times 1 + 100 \times 10 \times 0) = 250\rho \ (t\text{-}m)$$

The method represents the decision variables t_i, and their corresponding VCG in a discrete manner and replaces them in the original formulation in Section 5.1 so that the quadratic product can be linearised. The amount in ballast tank t_i, their

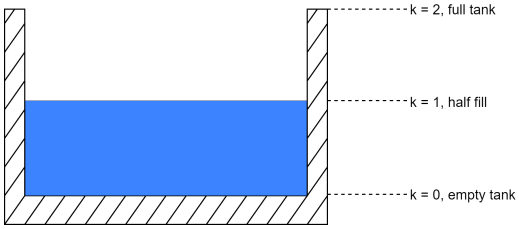

Fig. A.5: Tank discretisation.

corresponding VCG, and their gravity moment are now represented as

$$t_i = \sum_{k \in \mathcal{K}_i} \rho T_{ik}^{VOL} y_{ik} \qquad i \in \mathcal{T} \tag{A.15}$$

$$T_i^{VCG} = \sum_{k \in \mathcal{K}_i} T_{ik}^{VCG} y_{ik} \qquad i \in \mathcal{T} \tag{A.16}$$

$$t_i T^{VCG} = \sum_{i \in \mathcal{K}_i} \rho T_{ik}^{VOL} T_{ik}^{VCG} y_{ik} \qquad i \in \mathcal{T} \tag{A.17}$$

Constraint (A.7) is then linearised and rewritten as the following:

$$\begin{aligned} &KG^{min}(\sum_{c \in \mathcal{C}} C_c^W + L^W + \sum_{i \in \mathcal{T}} \sum_{i \in \mathcal{K}_i} \rho T_{ik}^{VOL} y_{ik}) \leq \\ &\sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} (S_s^{VCG} + C_c^{VCG}) C_c^W x_{cds} + L^W L^{VCG} + \sum_{i \in \mathcal{T}} \sum_{k \in \mathcal{K}_i} \rho T_{ik}^{VOL} T_{ik}^{VCG} y_{ik} \\ &\leq KG^{max}(\sum_{c \in \mathcal{C}} C_c^W + L^W + \sum_{i \in \mathcal{T}} \sum_{i \in \mathcal{K}_i} \rho T_{ik}^{VOL} y_{ik}) \end{aligned} \tag{A.18}$$

By substituting t_i with formula (A.15) in all other appearance in the original formulation and constraint (A.7) with A.18, a new linearised formulation of RSSPBW is presented.

6 Computational Results

We collected empirical data from one of the largest short sea Ro-Ro shipping companies in Europe. One departure has been selected as the benchmark in this study due to the complexity of working with the loading computer. The departure was from Vlaardingen, the Netherlands to Immingham, the UK. The ship deployed for the route has a capacity of 4076 lane meters with two heeling tanks and 20 regular ballast tanks in various sizes. Empirical data regarding the departure consisted of a stowage plan carried out by the dispatcher and the crew, a list of cargo information, and a file from the loading computer on board containing the ship's condition upon departure. Limits for the stability constraints were roughly estimated based on zero trim condition with the help of an naval architect working with the loading computer. For this specific ship, the limits applied in the model are [11, 12.5], [87.83, 93.61] and [-0.5, 0.5] for KG, LCG and TCG respectively. The linearised RSSPBW was run in Julia

Table A.1: Ballast and fuel consumption saving results based on real stowage plan and sailing condition.

Parameters	unit	orig.	opt.	opt.s	opt.orig.s
Ballast water	amount (ton)	3448.5	911.4	1458.9	2115.5
	saving in (ton/%)	0.0/0.00	2537.1/73.57%	1989.6/57.69%	1333.0/38.65%
Stability	GM (metre)	1.51	1.43	1.23	1.28
from loading	Trim (metre)	0.00f	1.93a	0.91a	0.06a
computer	Heel (degree)	0.1s	1.8s	1.5s	0.4s
Fuel consumption	amount (ton)	10404.7	9520.3	9707.6	9946.9
*annual	saving (ton/%)	0.0/0.00	884.4/8.5%	697.1/6.7%	457.8/4.4%
	monetary saving	$0	$502339	$395953	$260030
CO_2 impact	emission (ton)	32412.0	29657.0	30240.4	30985.9
*annual	reduction (ton)	0	2755.0	2171.6	1426.1

with Gurobi optimiser on a window laptop with Intel(R) Core(TM) i7-7820HQ CPU @ 2.90GHz and 16.0 GB RAM. The optimal solution was found in 65 seconds with an input size of 251 cargoes with a total weight of 6976 tons and 10 discretisation levels of ballast tanks.

Preliminary results on ballast water savings and stability conditions are shown in Table A.1. The original stowage plan (orig.) collected from the empirical data carried 3448.5 tons of ballast water, whereas the optimal solution (opt.) from the linearised RSSPBW minimised the amount of ballast water down to 911.4 tons with a saving of 2537.1 tons, accounted for almost 75% of the original amount. However, the optimal solution provided a plan that is heavily trimmed by the aft with a risky GM and not approved by the loading computer due to the stability requirement. For the sake of the performance and comparison, we improve the optimal solution by manually adjusting the amount of ballast water on board to meet the loading computer's requirement (opt.s). The result when the ship is within stability is still astonishing - over half the original ballast intake was cut off. Moreover, we also improved the plan a step further by adjusting the ship to match the stability condition in the original stowage plan with a close-to-even trim and heel (opt.orig.s). Once again, we are still able to save 38.65%, which is equivalent to an amount of 1333 tons saving of the original amount of ballast water. Furthermore, to translate ballast savings into fuel consumption savings and CO_2 reductions, we roughly estimated the fuel consumption by using admiralty coefficient [16], average fuel consumption and CO_2 emission of a ro-ro ship close to the empirical ship [17], route distance [18] and an average bunker price of $568 per metric ton for MGO in Rotterdam in 2019 [19]. For one ship sailing on the selected route with a daily departure, the annual savings in fuel consumption are 697.1 and 457.8 tons for the cases where stability requirements are satisfied. Their respective monetary savings are $348,550 and $228,903. Moreover, a saving in fuel consumption has a positive impact on our environment. As presented in the table, CO_2 emission can be reduced significantly with an amount of 2171.6 tons. Note that the savings in "opt.s" and "opt.orig.s" are only minimal since they were based on manual improvement from a non-expert.

The preliminary results show that the RSSPBW has a significant benefit on ballast savings with stability constraints and integration with loading computer, even though it is based on only one departure. Setting the right limits for stability constraints in the

Table A.2: Test instances and results.

Instance	% of cargo weigh between				$\lvert\mathcal{K}_i\rvert$ = 10		$\lvert\mathcal{K}_i\rvert$ = 50		$\lvert\mathcal{K}_i\rvert$ = 100	
	5-15	15-25	25-35	35-45	t	$t^{'}$	t	$t^{'}$	t	$t^{'}$
inst1	25	25	25	25	2.63	2.82	2.21	2.30	2.16	2.20
inst2	20	30	30	20	2.78	2.86	2.46	2.50	3.26	3.33
inst3	30	20	20	30	1.72	1.77	1.68	1.74	3.26	3.28
inst4	10	40	40	10	2.27	2.32	2.99	3.05	3.17	3.28
inst5	40	10	10	40	2.27	2.28	2.38	2.42	2.74	2.77
inst6	10	20	30	40	110.38	9.28	31.66	18.65	37.32	8.44
inst7	40	30	20	10	1.70	1.62	2.53	2.45	2.72	2.60
inst8	50	50	0	0	2.30	2.18	1.67	1.61	2.48	2.39
inst9	0	50	50	0	16.77	4.70	38.03	15.26	9.64	2.19
inst10	0	0	50	50	63.48	8.52	17.52	8.20	17.2	3.49

linearised RSSPBW is a complicated matter involving one to master the knowledge of navel architecture. A better set of limits will definitely contribute to a ship condition closer to ideal stability. Furthermore, a larger set of discretisation points provides a higher level of granularity for the filling levels and in turn improves the flexibility of the model satisfying the stability constraints. However, it might be expensive. In order to evaluate the impact of different discretisation levels on the running time, we performed the following tests. Based on the above empirical load list, we generated 10 instances with different cargo weight distribution and run them against three discretisation levels $|\mathcal{K}_i| = \{10, 50, 100\}$ $\forall i$ to examine the performance variation, displayed in Table A.2. In addition, we compare the running time when it solves to optimality (t) with the running time when it is terminated by 1% gap ($t^{'}$), equivalent to less than 2 tons ballast water.

Most instances can be solved to optimality within 4 seconds regardless of the discretisation levels. For cases that are difficult for the model to find the optimal solution, such as inst6, inst9 and inst10, a larger discretisation level can significantly improve the running time as assumed above, but at the same time a too large discretisation level can be costly as indicated in the test results of inst6, where the running time was improved significantly from 110s to 31s from a discretisation level of 10 to 50, while with $|\mathcal{K}_i|$ increased from 50 to 100, the performance dropped. No obvious pattern has been found on the correlation between discretisation level and running time. There are several other deciding factors such as the strictness of stability constraints, the granularity of tanks and the cargo distribution as well. However, for cases where optimality is difficult to achieve, getting close to the lower bound with 1 % gap can be done at a much lower computational cost. This indicates the ease of implementing the model in the real world, namely fast running time providing a close-to-optimum solution.

7 Conclusion and Discussion

This paper analyses the problem of stowage planning in short sea Ro-Ro shipping and proposes an integrated approach to model and solve stowage and stability problems.The new approach requires better formulation of stability constraints and the

inclusion of ballast water compared to previous methods. The idea is to generate an optimal stowage plan which uses the weight of cargoes to satisfy stability requirements instead of using excess ballast water which is translated into excess fuel consumption. The paper defines a Ro-Ro ship stowage problem with ballast water and presents a quadratic mathematical formulation with the objective to optimise the amount of ballast water onboard. A discretisation method is applied to linearise the quadratic constraints due to the introduction of ballast tanks. The linearised model is then tested against empirical data collected from the collaborating company. Computational results on the selected departure indicate significant potential for ballast savings, showing the relevance of the model's application in the real world. Furthermore, additional tests on instances with various cargo weight distributions and discretisation levels are conducted, and results show no significant correlation among the factors.

Our preliminary study result from this research clearly indicates the industry potential of our integrated stowage approach and model which delivered between 4.4% and 6.7% of savings in fuel consumption and emissions. Due to the complexity of the problem, some details were simplified and compromised compared to reality, which can be further improved by a more complete and better formulated set of constraints. For example, additional deadweight elements, such as storage and fuel tanks can be included for a more accurate stability calculation; free surface movement can be implemented by penalising partially filled tanks; trim optimisation can be added since it has an obvious impact on fuel consumption etc. In addition, other discretisation methods such as piecewise linear functions might improve the solution without significantly increase computational costs. Another aspect which we suggest for future research is to analyse the robustness of the model, subject to changes of cargo amounts, mix and weight. As mentioned, the unpredictability of cargo amounts and composition, makes it difficult to apply our model in daily processes without making it more robust. Lastly, even though the majority of cargo is homogeneous in dimensions, cargo in reality differ in sizes compared to standard trailers. Future research and models for stowage planning can therefore also improve practical relevance by including this aspect.

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Paper B

Step-wise Stowage Planning of Roll-on Roll-off Ships Transporting Dangerous Goods

Beizhen Jia, Aalborg University

Kjetil Fagerholt, Norwegian University of Science and Technology

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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, 6,210 persons injured and 21,392 ships involved [1]. 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 [2] 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 Figure B.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"

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

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. B.1: General Segregation Table [2]

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 [3], 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. [4] consider stack segregation in the slot planning problem. [5] 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 [6] and an update [7] on the topic of container terminal operation including stowage planning. Moreover, [8] 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 [9–12]. Other studies have also put more focus on the stability and safety side of the stowage planning. [11] proposes three improvements to the optimization of RoRo stowage, namely finer approach to ship stability, fire safety, and cargo handling efficiency. [3] 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 [13, 14]. 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 [3], 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 [3]. 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 7, 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 8.

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 $N^S = \sum_{d \in \mathcal{D}} |\mathcal{S}_d|$. 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 $\mathcal{C}$, 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 $\mathcal{C}^D$ and a subset of general cargo units $\mathcal{C}^G$. 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, $\mathcal{C}_{cn}$ 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 $\mathcal{C}_{cn}$ 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: $\mathcal{C}^{D,M}$ is the set of mandatory dangerous cargo units, $\mathcal{C}^{D,O}$ is the set of optional dangerous cargo units, where $\mathcal{C}^{D,M} \cup \mathcal{C}^{D,O} = \mathcal{C}^{D}$. $\mathcal{C}^{G,M}$ is the set of mandatory general cargo units, $\mathcal{C}^{G,O}$ is the set of optional general cargo units, where $\mathcal{C}^{G,M} \cup \mathcal{C}^{G,O} = \mathcal{C}^{G}$. Each cargo unit c is contained in a standard sized trailer with a specific weight C_c^W and each deck d has a maximum allowable weight $D_d^{W,max}$ 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 $\mathcal{T}^{\mathcal{H}}$ and a subset of regular ballast tanks $\mathcal{T}^{\mathcal{B}}$. 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 T_i^{max}. 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 [15], 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 [3] and the text book by [16].

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 Figure B.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 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:

$$\max \sum_{c \in \mathcal{C}^{D,O}} \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} x_{cds} \tag{B.1}$$

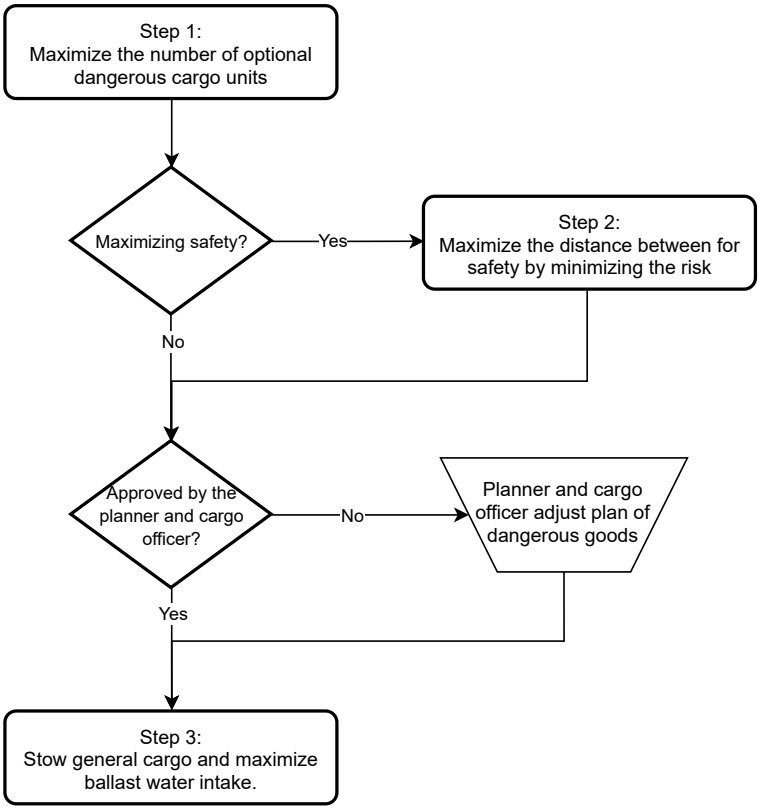


Fig. B.2: Step-wise stowage optimization process with the presence of dangerous goods

subject to:

$$\sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}_d} x_{cds} = 1, \quad c \in \mathcal{C}^{D,M} \tag{B.2}$$

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

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

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

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

Objective function (B.1) maximizes the number of optional dangerous cargo units that are are carried on board the ship. Constraints (B.2) make sure that all the mandatory dangerous cargo units are loaded, while constraints (B.3) ensure that each slot contains at most one (dangerous) cargo unit. Constraint (B.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 (B.5). If dangerous cargo unit c is placed in slot s on deck d, then no cargo unit $c' \in \mathcal{C}_{cn}$ can be loaded at any slot $s' \in \mathcal{S}^N_{dsn}$. Binary requirements for the variables are imposed through constraints (B.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 $\mathcal{C}^{D'}$ 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 $\mathcal{C}^{G',O}$. Thus, by updating relevant cargo sets, we have the followings: $\mathcal{C}^{G'} = \mathcal{C}^{G,M} \cup \mathcal{C}^{G',O}$ and $\mathcal{C}' = \mathcal{C}^{G'} \cup \mathcal{C}^{D'}$.

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) and a risk minimization formulation (Section 3.2).

Distance formulation

We define $D_{dsd's'}$ as the distance between 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 as follows:

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

The objective function (B.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:

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

subject to:

$(B.5)$

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

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

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

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

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

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

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

The model additionally requires the segregation constraints (B.5) introduced in Section 3.1. Constraints (B.9) require that all the dangerous cargo units selected in Step 1 are placed in a slot. Constraints (B.10) ensure that each slot contains at most one cargo unit. Constraints (B.11), (B.12) and (B.13) link the new binary variables y with the original decision variables x. Constraints (B.11) ensure that if slot s does not contain dangerous cargo unit c, $y_{dsd's'}$ is forced to be 0, similarly with constraints (B.12). Constraints (B.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 (B.14) and (B.15).

Risk formulation

Even though the distance formulation in Section 3.2 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:

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

subject to:

$$(B.5)$$
$$(B.9)$$
$$(B.10)$$
$$y_{dss'} \leq \sum_{c \in \mathcal{C}^{D'}} x_{cds}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{B.17}$$
$$y_{dss'} \leq \sum_{c' \in \mathcal{C}^{D'}} x_{c'ds'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{B.18}$$
$$y_{dss'} + 1 \geq \sum_{c \in \mathcal{C}^{D'}} x_{cds} + \sum_{c' \in \mathcal{C}^{D'}} x_{c'd's'}, \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_{d'} \tag{B.19}$$
$$x_{cds} \in \{0,1\} \quad c \in \mathcal{C}^{D'}, d \in \mathcal{D}, s \in \mathcal{S}_d \tag{B.20}$$
$$y_{dss'} \in \{0,1\} \quad d \in \mathcal{D}, s \in \mathcal{S}_d, s' \in \mathcal{S}_d \tag{B.21}$$

The structure of the constraints in the risk formulation resembles that of the distance formulation in Section 3.2. Segregation is enforced through constraints (B.5) introduced in Section 3.1. The risk formulation shares the same constraints (B.9) and (B.10) that ensure dangerous cargo units are loaded exactly once and that each slot can not load more than one cargo unit respectively. Constraints (B.17), (B.18) and (B.19) link the new linear variables y with the decision variables x. Unlike the distance formulation, constraints (B.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 (B.20) and (B.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 [3] and shown as below:

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

subject to:

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

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

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

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

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

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

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

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

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

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

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

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

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

Given by the stowage of the dangerous cargo units (either from Step 1 or Step 2), the Step 3 objective (B.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 (B.23) make sure that all the general cargo units will be assigned a slot on board, and constraints (B.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 (B.25) limit the total weight of cargo units loaded on each deck. The heeling capability is guaranteed in constraint (B.26) so that the tanks have sufficient forces to heel the ship. Lastly, vertical, transverse and longitudinal stability calculations are presented in equations (B.30), (B.31) and (B.32), and are limited by constraints (B.27), (B.28) and (B.29), respectively. Lastly, domains for decision variables are given by constraints (B.33), (B.34) and (B.35).

Equation (B.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 [3]. 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:

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

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

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

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

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

By updating t_i with constraints (B.36) in the original formulation and replacing constraint (B.27) with constraint (B.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 [3]. 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 B.1. No segregation is needed between dangerous cargo units and general cargo units.

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

Table B.1: IMDG segregation rules for four classes

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 B.1:

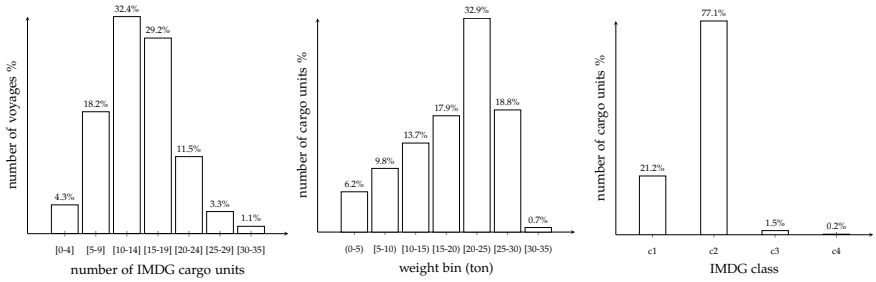
1. 3 meters
2. 6 meters
3. 36 meters
4. 48 meters

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 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 Figures B.3a, B.3b and B.3c, respectively.



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

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

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 B.2.

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

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

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 B.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 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 B.3 for comparison. Each step of optimization has been given a time limit of 3600 seconds. 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 (B.7) of the distance formulation in Section 3.2. The distance between slots on different decks is set as 48 meters 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 $d = 1, 2, ..., |\mathcal{D}|; s = 1, 2, ..., |\mathcal{S}_d| - 1; s' = s + 1, ..., |\mathcal{S}_d|$. 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 B.3. Small instances with a total number of dangerous cargo units less than 10 are solved to optimality in less than 15 seconds. 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.

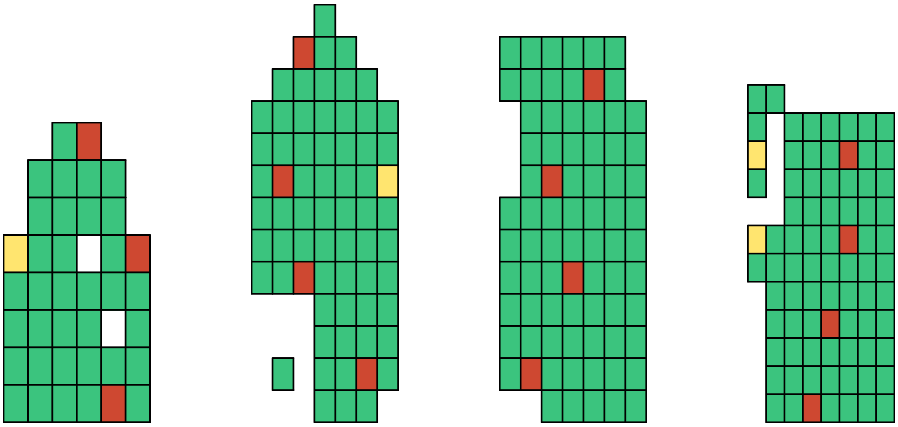
Instance			Full optimization							Partial optimization		
			Step 1	Step 2				Step 3		Step 1	Step 3	
id	m/o	c1/c2/c3/c4	Time	Time	Gap	Δ d.	Δ c. d.	Time	Obj.	Time	Time	Obj.
1	3/0	3/0/0/0	0	0	0.0%	0.0%	0.0%	10	0	0	3	0
2	4/0	0/4/0/0	0	1	0.0%	4.3%	14.3%	12	0	0	3	0
3	5/0	0/5/0/0	0	1	0.0%	5.4%	20.5%	6	0	0	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

Table B.3: Computational results. Solution times are in seconds.

The results in Table B.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 1) and then minimize the ballast water intake (Step 3), all 30 instances are solved to optimality within less than 30 seconds. 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.

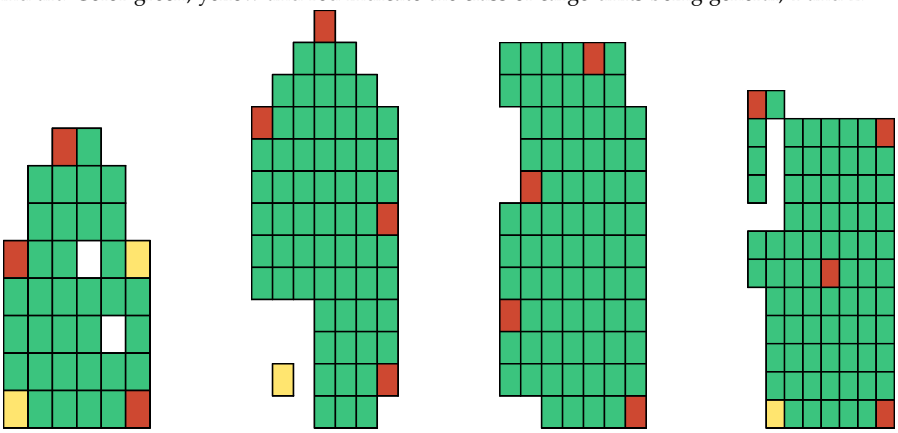
In the case of full optimization, which ensures even more safety regarding the segregation of dangerous cargo units, the instances with few dangerous cargo units can be solved to optimality within reasonable time. However, it takes a significant amount of time to solve the model in Step 2 for the instances 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 Figure B.4 for partial optimization and Figure B.5 for full optimization. As stated in Table B.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.



(a) lower hold **(b)** main deck **(c)** upper deck **(d)** weather deck

Fig. B.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.



(a) lower hold **(b)** main deck **(c)** upper deck **(d)** weather deck

Fig. B.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.

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% [3]. 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.

Acknowledgements

The research was partially supported by ECOPRODIGI project funded by Interreg Baltic Sea Region Programme. We wish to thank our industrial collaborator DFDS for their openness to share, innovation mindset, and valuable support throughout the conduct of research. We are grateful for the two anonymous reviewers for their valuable comments.

A Appendix - 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, $\mathcal{T} = \mathcal{T}^{\mathcal{B}} \cup \mathcal{T}^{\mathcal{H}}$
$\mathcal{T}^{\mathcal{B}}$	set of regular ballast tanks
$\mathcal{T}^{\mathcal{H}}$	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
T^{max}_i	maximum volume of ballast tank i
T^{VOL}_{ik}	volume of water inside ballast tank i when filled at level k
T^{VCG}_{ik}	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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Paper C

Optimal Dual Cycling Operations in RoRo Terminals

Beizhen Jia, Aalborg University

Kevin Tierney, Bielefeld University

Line Blander Reinhardt, Roskilde University

Julia Pahl, University of Southern Denmark

The paper has been submitted.

The layout has been revised.

Abstract

Roll-on roll-off (RoRo) shipping plays an important role in freight transport on the European continent, and is faced with the challenge of reducing its CO_2 emissions while increasing its efficiency. Dual cycling, in which loading and discharging processes are carried out simultaneously, achieves this goal by reducing the turnaround time of vessels in port and thus the CO_2 output of handling equipment in port and fuel consumption through slow steaming at sea. Optimizing the dual cycling operations on RoRo vessels has not yet been investigated in the literature. This paper presents the novel RoRo dual cycling problem (RRDCP), and formulates it using integer programming (IP) with the objective to minimize the total makespan of discharging and loading operations. We further prove that the RRDCP is NP-complete by a reduction from a general machine scheduling problem, and introduce a novel heuristic to solve the problem called a generalized random key algorithm (GRKA). We evaluate the IP model and GRKA approach on both generated and industrial instances, showing that the GRKA heuristic finds optimal or near-optimal solutions to real-world problems in just seconds. We provide managerial insights on industrial instances, which indicate that our approach leads to a reduction in fuel consumption and CO_2 emissions of up to 25% for RoRo operations.

1 Introduction

Short sea *roll-on roll-off* (RoRo) shipping is an central transportation mode in Europe, especially in countries with long shorelines or a large number of islands. In particular, in nations such as Italy, Denmark, Norway, Sweden, and Greece, the share of national seaborne transport is relatively high, ranging from 14% to 26% in 2019 [1, 2]. RoRo shipping is commonly operated in liner shipping mode, i.e., according to fixed schedules where vessels transport a wide range of "rolling" general cargo, such as cars, trucks, heavy rolling machinery, trailers with or without an engine, etc. (see also [3]). Furthermore, RoRo shipping can substitute emission-intensive transport modes such as trucks [4], making RoRo shipping a potential path to increased sustainability in the EU.

Reduced turnaround times of vessels are both critical for vessel operators as well as for ports in terms of cost effectiveness [5, 6]. This is achieved not only through streamlined administrative services, but also by effective planning for time-efficient discharging and loading operations [7]. This translates into port efficiency [5, 8], which permits vessels to sail slower during their sea voyages. Since the fuel consumption of vessels is roughly cubic in the vessel speed [9], slower speeds can lead to significantly increased fuel efficiency and, thus, reduced CO_2-emissions. Moreover, more efficient terminals have increased availability and better utilization of yard space that allows for higher throughput rates and better overall competitiveness [2].

In this paper, we model and solve the *RoRo dual cycling problem* (RRDCP). The RRDCP is concerned with discharging and loading trailers in a minimal amount of time from a RoRo vessel subject to precedence constraints on the discharging and loading order. To the best of our knowledge, this is the first time that a model has been formulated for dual cycling in RoRo shipping. To this end, our paper presents the following novel components.

- We provide an integer programming model of the RRDCP.
- We reduce a general machine scheduling problem to the RRDCP.
- We introduce a new metaheuristic paradigm that generalizes biased random key genetic algorithms [10] and solve the RRDCP to near optimality in just a few seconds.

Our models and experimental analysis are based on real-world data from a European RoRo shipping company. Based on this data, we perform a managerial assessment of dual cycling using our technique and show that optimizing dual cycling operations on RoRo vessels can lead to a fuel consumption reduction.

The rest of the paper is organized as follows. We provide a brief problem description in Section 2, followed by a review of related literature in Section 3. The RRDCP and IP model is defined and formulated in Section 4 followed by a discussion on its complexity from a scheduling point of view in Section 5. In Section 6 a random key heuristic is introduced and the results are presented in Section 7. We conclude the paper with a discussion and outlook in Section 8.

2 Problem description

RoRo shipping can encompass a wide variety of rolling cargo. In this work, we focus mainly on unaccompanied trailers that are loaded and discharged using tugs. We note, though, that our algorithms and approach likely generalize to other types of RoRo cargo. A RoRo vessel is made up of multiple decks, with each deck having different height and weight restrictions (see also [11]). The main deck has one or more external ramps connected to the shore that serve as the bridge on to and off the vessel. Most RoRo vessels only have one external ramp connected to the main deck as this requires less port infrastructure for servicing vessels. Cargo needs to pass over the external ramp connected with the main deck and is transported to other decks through internal ramps. Once a ramp is free of cargo, the loading and discharging of the connected decks can take place simultaneously and independently. Hence, it is sufficient to analyze each deck individually for planning loading and discharging operations.

For arriving vessels, a loading plan is developed at the terminal. The loading plan indicates the positions on board the vessels that are to be filled with specific trailers and ensures the vessels' stability while underway. Loading and discharging operations are subject to precedence rules, which are based on safety requirements and the layout of a specific deck. For example, a trailer cannot be discharged before the trailer in front of it and the trailer in front of it to the starboard side are both discharged. However, when loading, trailer positions belonging to the lane farthest starboard will have the trailer in front of it and the one in front of it to the port side as their precedence constraints; see Figure C.1. For instance, trailer position 1 can only be discharged if trailer 5 and 6 have both been discharged. For trailer position 12, which is in the most starboard lane, the trailer can only be loaded if trailers 7 and 8 are already on board the vessel. Moreover, trailer positions can not be loaded if the trailer already in that position has not yet been discharged.

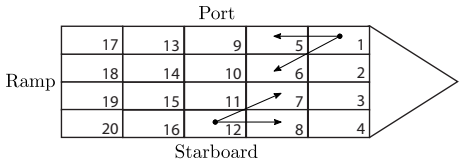


Fig. C.1: Simplified Deck Illustration Showing the Precedence Constraints for discharging Position 1 and Loading Position 12.

The traditional way of handling unaccompanied cargo in short sea RoRo shipping is to deploy a number of *tugmasters* driving tugs, which are highly maneuverable trucks, to discharge each single trailer from the vessel to the yard and to load export trailers from the yard to the vessel once the overall discharging operation is finished. As a result, tugmasters travel empty 50% of the time which is highly inefficient in terms of utilization time and energy consumption. Figure C.2 shows data from a case study with our industrial partner that quantifies the activity time for RoRo cargo operations at the terminal. The figure presents the discharge and loading times for 11 voyages collected from a leading RoRo shipping company. The average total operational time indicates that almost 11 hours are spent on loading and discharging operations, where approximately 2 hours are used for discharging and 9 hours for loading operations. Note that the loading time is proportional to the working efficiency, the imbalance in number of trailers to be discharged and loaded, whether or not not cargo is present at the terminal on time, and break times required by the labor union.

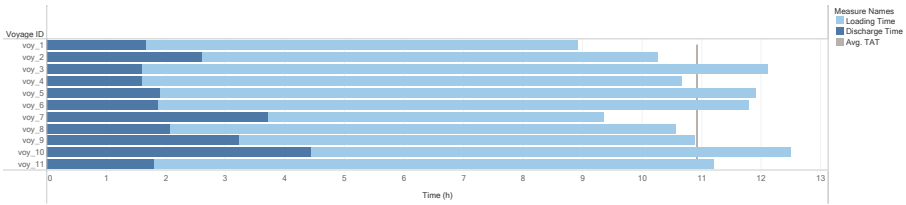


Fig. C.2: Turnaround Time at Terminal.

Reducing the number of empty tug trips has a direct impact on reducing vessel turnaround times. This can be achieved by dual cycling. In dual cycling, after loading a trailer, tugs drive to a trailer to be discharged and take it off the vessel. Figure C.3 illustrates the difference between two cargo handling strategies, with Figures C.3(a) and C.3(b) displaying the options for trailer handling without and with dual cycling, respectively. Although the advantages of dual cycling are obvious, it is not possible to perform it with every discharge and load operation. RoRo vessels must first be emptied sufficiently to start dual cycling. This heavily depends on the size and structure of the vessel decks where trailers are located.

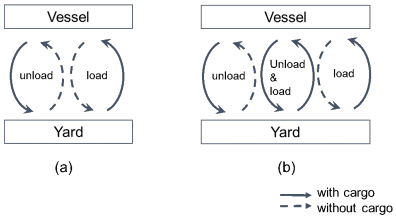


Fig. C.3: Illustration Created to Show the Comparison between Traditional Cargo Operation Strategy (a) and Dual Cycling Strategy (b).

3 Literature review

Within seaborne transport the area of liner shipping has been subject to a significant amount of research. With regards to discharging and loading vessels, the literature has focused mainly on minimizing container handling times, driving distances of port material handling equipment, as well as reducing empty moves of various kinds of container terminal equipment [7]. Recently, interest in RoRo operations has grown, but nonetheless, only a limited number of areas within the RoRo field have been examined. For instance, the area of RoRo stowage is investigated regarding both optimizing stability and energy efficiency [12], as well as packing and shifting costs [13]. Moreover, [14] analyze and estimate the discharge time of cargo units on a RoRo vessel based on different loading positions. Besides theses areas, there is research dealing with routing and scheduling of RoRo vessels [15] as well as analysis of effects of sulphur emission limits on RoRo operations provided by [16].

Dual cycling has mainly been established in the area of container handling. For instance, the quay crane double cycling problem (QCDCP) at container terminals has been investigated previously by many researchers who typically focus on the optimization of a single quay crane. The first academic paper addressing QCDCP is provided by [17]. The problem solved concerns the optimal load ordering of container stacks assuming non-preemptive stack operations. In their study, a simple scenario is investigated and formulated as a two-machine flow shop scheduling problem. They argue that their problem can be solved by Johnson's rule [18]. Although [17] consider both loading and discharging operation as unit time operations, they do not consider precedence relations in their problem. [17] only take into account one crane operating on a single row of a vessel.

The model from [17] has been extended in a number of ways. [19] find a general rule for the optimal starting point of dual cycling for a QCDCP for a single crane to avoid delays to the start of dual cycling due to containers blocking each other. [20] formulate a MIP model and develop a local search-based heuristic for the general QCDCP also including hatch covers in their problem. [21] review the weaknesses of a selection of existing models for the multi-QCDCP and call attention to real-world requirements that need to be included as constraints in models to enhance their applicability. In [22], the problem considered by [17] is transformed to a problem with stack-wise precedence constraints. The problem with stack-wise precedence can be converted into m precedence chains, where m is the number of stacks and each con-

tainer has at most one predecessor and at most one successor. [22] develop a polynomial time algorithm for this single crane case that shares similarities with a simple lane case of the problem considered here with only a single tug operating. With the same concept for the purpose of improving loading and unloading efficiency, double cycling in RoRo shipping requires researchers' attention. One could relate the problem to a multi-QCDCP with empty crane moves and more complex precedence constraints not restricting operations to one bay or stack. Thus the two problems are very different in essence and to the best of our knowledge the complexity of the RoRo dual cycling problem is unknown.

In addition to the problem-specific focus of dual cycling research for quay cranes, its relation to machine scheduling has been investigated. [17] point out that the dual cycling problem is a type of machine scheduling problem, see, e.g., [23] for an overview. This provides us with inspiration for reducing machine scheduling to the RRDCP, which we discuss further in Section 5 on the complexity of RRDCP.

4 RRDCP Statement and Mathematical Formulation

We move from our general description of the short-sea RoRo problem in Section 2 to describe the RRDCP in more detail and formulate it mathematically. We first discuss assumptions necessary for modeling the RRDCP in terms of the spatial layout of the vessel and the precedence constraints, followed by an IP model.

4.1 RRDCP Assumptions

A deck is divided into slots that fit standardized trailers in terms of their size. We assume the trailers are homogeneous in size, but note that in reality the lengths and heights may vary. Irregular-sized cargo can be treated as taking multiple slots and easily incorporated by altering the precedence matrix. In addition, we consider only unaccompanied trailers since self-driving units do not require extra labor.

The handling of unaccompanied trailers is performed by a tug driver with a tug. The related tug operations can be divided into five types of actions. A tug driver at one stage can either:

1. drive from the quay to the vessel with a trailer (loading),
2. drive from the quay to the vessel without a trailer,
3. drive from the vessel to the quay with a trailer (discharging),
4. drive from the vessel to the quay without a trailer, or
5. stay idle on quay.

Each action requires a single unit of time. The reason for this is that it greatly simplifies the checking of precedence constraints and the overall modeling of the problem, as we do not need to consider time as a continuous property. Furthermore, some trailers will take more or less time to load or discharge than others, and it is difficult to predict since the time varies from trailer to trailer depending on the driver,

traffic on board and in the terminal, weather conditions, trailer location on board, etc. We abstract from various factors in this article, but discuss the applicability of the model further in Section 8.

We assume that tugs do not interfere with each other while pulling trailers to or from the vessel, i.e., adjacent trailers may be loaded or removed within a single time unit. All tugs start on the quay and must drive on to the vessel. In reality, tugs are assigned to specific decks, and once a deck is emptied, the tug can be assigned to another deck. However, since we model decks independent from each other, we assume a fixed number of tugs over the planning horizon of a deck. Note that tugs are not allowed to idle on the vessel and the number of tugs that can service the vessel is limited and fixed throughout the overall discharging/loading operation. We further note that there is a maximum number of tugs allowed on a deck at any given time to prevent collisions and the safety of the vessel. We abstract from pauses for drivers as union regulations are different from port to port.

The objective of the RRDCP is to minimize the total operational time of loading and discharging a vessel, i.e., makespan minimization subject to precedence rules. The precedence rules are described with a precedence matrix $\mathcal{P}$ for discharging and loading of the form $(i, i') \in \mathcal{P}$ and $(j, j') \in \mathcal{P}$, respectively. That is, trailer i must be discharged before i' can be discharged, and trailer j must be loaded before j' can be loaded. Furthermore, a trailer cannot be loaded into its designated position on the vessel until the trailer in that slot is discharged. However, the discharge and loading of a trailers in the same designated position may take place in the same time step.

4.2 Mathematical Formulation

Sets and Parameters

$\mathcal{S}$	Set of trailer positions to be discharged from vessel to quay, indexed by i
$\mathcal{Q}$	Set of trailer positions to be loaded from quay to vessel, indexed by j
$\mathcal{T}$	Set of time steps, $\mathcal{T} = \{1, \ldots, \lvert\mathcal{S}\rvert + \lvert\mathcal{Q}\rvert\}$, indexed by t
$\mathcal{P}$	Set of trailer handling precedence pairs, as described above.
k	Total number of tugs

Variables

x_{it}	Equals one if trailer (position) $i \in \mathcal{S}$ is discharged in time step $t \in \mathcal{T}$ and zero otherwise.
y_{jt}	Equals one if trailer (position) $j \in \mathcal{Q}$ is loaded in time step $t \in \mathcal{T}$
wsq_t, wqs_t	Number of tugs traveling from/to vessel to/from quay without a trailer in time step $t \in \mathcal{T}$, respectively.
wqq_t	Number of tugs idling on the quay in time step $t \in \mathcal{T}$
u	Makespan

Objective and Constraints

$$\min z = u \tag{C.1}$$

s.t.

$$u \geq ty_{jt} \qquad \forall j \in \mathcal{Q}, t \in \mathcal{T} \tag{C.2}$$

$$u \geq tx_{it} \qquad \forall i \in \mathcal{S}, t \in \mathcal{T} \tag{C.3}$$

$$u \geq (|\mathcal{Q}| + |\mathcal{S}|)/k \tag{C.4}$$

$$u \leq 2(|\mathcal{Q}| + |\mathcal{S}|) \tag{C.5}$$

$$\sum_{t \in \mathcal{T}} x_{it} = 1 \qquad \forall i \in \mathcal{S} \tag{C.6}$$

$$\sum_{t \in \mathcal{T}} y_{jt} = 1 \qquad \forall j \in \mathcal{Q} \tag{C.7}$$

$$\sum_{t \in \mathcal{T}} tx_{it} \leq \sum_{t \in \mathcal{T}} (t-1) x_{i't} \qquad \forall (i, i') \in \mathcal{P} \tag{C.8}$$

$$\sum_{t \in \mathcal{T}} ty_{jt} \leq \sum_{t \in \mathcal{T}} (t-1) y_{j't} \qquad \forall (j, j') \in \mathcal{P} \tag{C.9}$$

$$\sum_{t \in \mathcal{T}} tx_{it} \leq \sum_{t \in \mathcal{T}} ty_{it} \qquad \forall i \in \mathcal{S} \tag{C.10}$$

$$\sum_{i \in \mathcal{S}} x_{it} + wsq_t = \sum_{j \in \mathcal{Q}} y_{jt-1} + wqs_{t-1} \qquad \forall t = 2, \ldots, |\mathcal{T}| \tag{C.11}$$

$$\sum_{i \in \mathcal{S}} x_{it} + wsq_t + \sum_{j \in \mathcal{Q}} y_{jt} + wqs_t + wqq_t = k \qquad \forall t = 1, \ldots, |\mathcal{T}| \tag{C.12}$$

$$\sum_{i \in \mathcal{S}} x_{it} \leq k/2 \qquad \forall t = 1, \ldots, |\mathcal{T}| \tag{C.13}$$

$$\sum_{j \in \mathcal{Q}} y_{jt} \leq k/2 \qquad \forall t = 1, \ldots, |\mathcal{T}| \tag{C.14}$$

$$\sum_{j \in \mathcal{Q}} y_{j1} + wqs_1 + wqq_1 = k \tag{C.15}$$

$$x_{i1} = 0 \qquad \forall i \in \mathcal{S} \tag{C.16}$$

$$wsq_1 = 0 \tag{C.17}$$

$$x_{it}, y_{jt} \in \{0, 1\} \tag{C.18}$$

$$wsq_t, wqs_t, wqq_t, u \in \mathbb{Z}_{\geq 0} \tag{C.19}$$

The objective (C.1) is to minimize the total operational time of the loading and discharging of a vessel, i.e., the makespan. It is defined as the latest time in which either a loading or discharging operation occurs in constraints (C.2) and (C.3). Note that tx_{it} and ty_{jt} equal the time when the trailer i or j is discharged or loaded, respectively, and zero otherwise. Furthermore, constraint (C.4) provides a lower bound on the makespan if all tugs were able to perform dual cycling on all tasks. We impose an upper bound on the makespan through constraint (C.5), which is the time used for single cycling with one tug.

Constraints (C.6) and (C.7) make sure that each trailer position is discharged and loaded only once, respectively. Constraints (C.8) to (C.10) enforce the precedence restrictions between loading-loading, loading-discharging, and discharging-discharging operations, respectively. Alternative formulations of the precedence constraints are possible, but we note that this one has the best performance. Constraints (C.11) and (C.12) link tug movement with the loading and discharging operations. The maximum

number of tugs on board at each time step, usually set as half of the total number of working tugs, is enforced by constraints (C.13) and (C.14). Finally, we assign starting values to the variables in the first time step in constraints (C.15), (C.16) and (C.17). Note that y_{j1} being zero is implied if no loading is possible for dual cycling from the beginning.

5 Complexity of the RRDCP

As mentioned previously, to the best of our knowledge there is no study of the complexity of the RRDCP. In the following, we show that the decision version of the RRDCP is NP-complete by reduction from a general scheduling problem generally denoted by $P|prec, p_j = 1|C_{max}$ [24]. To do this, we first formally define the RRDCP as a scheduling problem. We are given the following sets and parameters:

(a) A set $\mathcal{J}$ of loading and discharging tasks that must be completed $\mathcal{J} = \{j_1, \ldots, j_h, j_{h+1}, \ldots j_n\}$, where h is the number of loading tasks and $n - h$ is the number of discharging tasks with the additional sets $\mathcal{J}_l = \{j_1, \ldots, j_h\}$ and $\mathcal{J}_d = \{j_{h+1}, \ldots, j_n\}$,

(b) a partial order $\prec$ on $\mathcal{J}$,

(c) a unit time duration for each loading task and discharge task (including the transportation of the cargo from port to vessel and from vessel to port, respectively), denoted by $W(j_i) = 1$,

(d) a number of tugs that each can complete at most one task j_i at a time t.

(e) a change cost $C_{lm} \in \{0, 1\}$ in which a tug performing a loading task j_l followed by a loading task $j_m, l, m \leq h$ must use one unit time $C_{lm} = 1$ to drive empty from the vessel to the port between the two tasks. Furthermore, a tug performing a discharge task j_p followed by a discharge task j_q must also use one unit time $C_{pq} = 1$ to drive empty from the port to the vessel between the two tasks. This is also called a sequence dependent setup time.

Given these sets and parameters, we can now describe the RRDCP as follows:
(D1): *General dual-cycling decision problem*. Given (a),(b),(c),(d), (e), and a completion time t does a total function $f(j) \longrightarrow \{0, ...t-1\}, \forall j \in \mathcal{J}$, exist such that:

(i) if $j \prec j'$, then $f(j) + W(j) \leq f(j')$ (precedence constraints are satisfied),

(ii) $\forall j \in J, f(j) + W(j) \leq t$ (all tasks are completed before the time t),

(iii) for $0 \leq i < t$, there are at most k elements in $\mathcal{J}$ for which it holds that $f(j) \leq i < f(j) + W(j)$ (ensure at most k tugs are used), and

(iv) if $f(j) + W(j) = f(j')$ then ($j \in \mathcal{J}_l$ and $j' \in \mathcal{J}_d$) or ($j \in \mathcal{J}_d$ and $j' \in \mathcal{J}_l$).

[25] determine the complexity of different scheduling problems with precedence constraints, although none of problems consider sequence dependent setup times included in (D1). Minimizing the makespan is denoted as C_{max} by [25], where in this case C_{max} is greater than the completion time of any job j. Thus $C_{max} \leq f(j) + W(j)$ for all $j \in \mathcal{J}$.

The aim of the dual cycling problem is to find the minimum completion time of the last tug. To show that the dual-cycling problem is NP-complete, we consider

the scheduling problem. This is done here by considering the scheduling problem defined by [26] and later denoted $P|prec, p_j = 1|C_{max}$ by [24]. To prove that (D1) is NP complete, we make a reduction to the decision scheduling problem which in [26] is defined as follows:

We are given the following sets and parameters:

(a) a set $\mathcal{J} = \{j_1, \ldots, j_n\}$ of jobs.

(b) a partial order $\prec$ on $\mathcal{J}$.

(c) a weight function $W(j_i) = 1$.

(d) a number of processors k is represented by the number of tugs used.

(S1): *The scheduling decision problem*. Given (a),(b),(c) and (d), does a total function $f(j) \longrightarrow \{0, ...t-1\}, \forall j \in J$ exist?

[24] prove that (S1) is NP-complete by reduction from the clique problem.

The reduction from (S1) to (D1) is straightforward. We simply set $C_{lm} = 0$ for all l and m thus making (e) from (D1) redundant. It is also straight forward to see that a solution to this problem would also present a solution to (S1) and that the translation between the problems can be done in linear time. Furthermore, (D1) is clearly in NP, as a solution to D1 can be trivially checked for correctness in polynomial time. Thus we have shown that (D1) is NP-complete when the number of tugs are provided as input. However, if the number of tugs to use is considered as a decision variable, the problem is still open as noted by [23]. As with all NP-complete problems, special cases of the problem can be polynomial time solvable and as mentioned by [26], polynomial time algorithms might exist for specific numbers of tugs. Such polynomial time algorithms have been proven to exist for problems with two machines [26]. Moreover, special graph structures may also lead to polynomial time algorithms [27].

In conclusion, an m parallel machine scheduling problem for unit time jobs with arbitrary precedence constraints is NP-complete. Therefore, the RRDCP is NP-complete. However, for cases satisfying conditions of a bounded path and limited degree in the precedence graph, polynomial time algorithms exist [28]. In RRDCP problems the degree is often limited to between two and eight. However, bounding the path length can be more challenging.

6 A Random-Key Heuristic for the RRDCP

Our heuristic approach to solving the RRDCP is based on the fact that constructing a feasible solution is possible in linear time. Our heuristic is a generalization of the biased random-key genetic algorithm (BRKGA) metaheuristic (see [10]), in which we replace the genetic algorithm with a different metaheuristic method. We describe a heuristic approach, which we call a generalized random-key algorithm (GRKA), for solving the RRDCP. After describing the GRKA framework, we discuss the RRDCP-specific *decoder* required by the GRKA, which is a parameterized, greedy construction heuristic. Finally, we present some complexity results regarding the decoder indicating that not all RRDCP problems are actually hard.

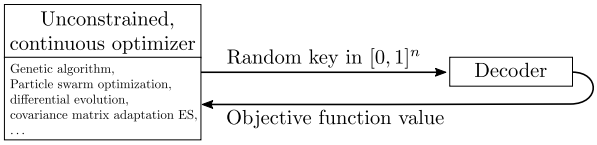


Fig. C.4: Overview of the GRKA Method.

6.1 GRKA

The GRKA consists of two components, as shown in Figure C.4: an unconstrained, continuous optimizer (despite the name, unconstrained, continuous optimizers support lower and upper bounds on the variable domains) and a decoder. The unconstrained optimizer must be able to solve a continuous optimization problem in which the objective function is given by a black box (i.e., there is no derivative) and the input is constrained to within the hypercube $[0,1]^n$. Numerous algorithms exist for this task, such as particle swarm optimization (PSO) [29], differential evolution (DE) [30], covariance matrix adaptation evolutionary strategies (CMA-ES) [31], or the GA used in the BRKGA [10].

The central component of the GRKA is the *random key*, which is a vector of values in the range $[0,1]$. The random key connects the problem-independent optimizer to the problem-specific *decoder*, in that the optimizer queries the value of the objective function from the decoder for a given random key. The decoder is a parameterized construction heuristic, and the only set of parameters it accepts is the random key. The decoder must use the information given in the random key to create a solution to the problem. For example, in the traveling salesperson problem, each node could be assigned to an entry in the random key and the decoder would build a tour by sorting the nodes by the value of their random key entry and adding them to the tour in that order. The optimizer can thus influence the tour's construction by raising or lowering the random key entry of each node.

A key advantage of random-key heuristics over other types of metaheuristics is that they make it possible to solve discrete, constrained optimization problems with continuous optimizers in an unconstrained setting. A further advantage is that the problem modeler does not need to think about metaheuristic details and can instead focus on specifics of the problem at hand. A disadvantage is that delta evaluation (i.e., incremental evaluation) of the objective function is not possible, meaning fewer solutions can be explored than in local search techniques.

6.2 RRDCP Decoder

We design an RRDCP decoder that accepts a random key with a length equal to the number of trailers to discharge and load. The decoder works by iteratively checking whether there are any trailers that can be discharged or loaded without violating the precedence constraints, and loading/discharging as many as possible according to the position of the tugs. The decoder prefers trailers with a lower random key entry if there are more trailers to load/discharge than tugs available. The available tugs are divided into two groups and it is assumed that these two groups switch positions on

the vessel in each time step, i.e., one group drives on the vessel and the other one drives off. To simplify the algorithm, we assume the total number of tugs k is even, however the algorithm works for any number of tugs.

Algorithm 1 accepts the random key, R and the parameters S, Q, P, k as defined in the mathematical model. First, the random key is adjusted to the range $[0, 1)$ so that it can be used for sorting in the following step. Next, all trailers to be loaded and discharged are inserted into the priority queues D^S and D^Q, respectively, with the priority of each entry equal to the number of descendants in the precedence graph P plus the value of the random key. Note that ties in the random key are unlikely due to the precision of the floating point numbers, but should they occur, they can be broken arbitrarily.

Algorithm 1 Greedy RRDCP Decoder.

1: **function** RRDCP-DECODER(R, S, Q, P, k)
2: Remap R to the range $[0, 1)$
3: $D^S \leftarrow S$, sorted by $|\{(i, i') \in P \mid i \in S\}| + R(i)$ (ascending)
4: $D^Q \leftarrow Q$, sorted by $|\{(j', j) \in P \mid j \in Q\}| + R(i)$ (ascending)
5: $t \leftarrow 1$ ▷ Time counter
6: **while** $|D^S| > 0$ **or** $|D^Q| > 0$ **do**
7: $U \leftarrow$ Pop the top $\min\{|D^S|, k/2\}$ dischargeable trailers from D^S ▷ Unload step
8: Update D^Q and D^S for all $u \in U$
9: $L \leftarrow$ Pop the top loadable $\min\{|D^Q|, k/2\}$ trailers from D^Q ▷ Load step
10: Update D^Q for all $l \in L$
11: $t \leftarrow t + 1$
12: **return** t

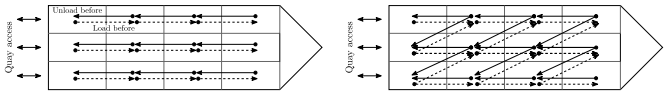
The main loop of the construction approach begins on line 6, which iterates until all trailers are loaded or discharged. On the following line, we pop the top $k/2$ *dischargeable* trailers, or however many are left, from the priority queue and insert them into U for processing. A trailer can be discharged if all trailers preceding it in P are already discharged (i.e., its priority value in the priority queue is less than one). With the trailers in U discharged, we can now update the priority queues, thus decrementing the priority value of any trailer connected to a trailer in U in the precedence graph.

Having determined which trailers will be discharged, we now check whether we can perform any loading operations on line 9. As with discharging, we only load trailers that are ready to be loaded according to the precedence graph. The construction procedure continues until every trailer is loaded and discharged, incrementing the time at the end of each iteration, and returning the time t as the objective function value.

6.3 Special Cases and Lower Bounds

In this section, we investigate a few special cases of the RRDCP in which a simple, polynomial time algorithm can solve the RRDCP optimally, as well as lower bounds on the number of time steps. While the cases we show on their own are not necessarily realistic, many real problems could contain these cases as subproblems once some trailers are loaded and discharged. We focus in particular on two cases of the RRDCP in which we assume the vessel has m *lanes*, each with a capacity of n trailers with $n \geq m$, and that there are an even number $k \leq m$ of tugs available. Assume the vessel is accessed at the beginning of each lane. With an even number of tugs, we always cycle half of the tugs on/off the vessel in each time step as in the decoder. This means the first step is always to drive $k/2$ tugs on to the vessel and let $k/2$ tugs idle at the quay. We ignore this step in our calculations of the number of steps below.

Figure C.5 shows the two cases we examine in this subsection. In the *simple lanes* setting, as shown in Figure C.5a, the precedence graph only contains arcs within a single lane between adjacent trailers. The precedence constraints in simple lanes just ensure that lanes are discharged in the order of the trailers in the lane, and loaded in reverse order and each lane's precedence graph is disjoint from other lanes. Figure C.5b shows the *adjacent lane* setting, in which to discharge a trailer, both the trailer preceding it in the lane and the preceding trailer in the lane immediately to the left must be removed first. This precedence constraint structure is rather realistic, however we note real instances have varying lane lengths and obstacles, which we do not consider here.



(a) Simple lanes. **(b)** Adjacent lane precedence.

Fig. C.5: Simplified, but Still Realistic RRDCP Problems.

We first introduce two propositions related to when dual cycling can first begin, and how many loading steps still must be performed after dual cycling ends.

Proposition 6.1. *There are at least $n-1$ time steps of discharging before dual cycling begins.*

Proposition 6.2. *There are at least $n-1$ loading after the last dual cycle occurs.*

Both propositions follow from the lane length n: dual cycling can only start once an entire lane is empty, and the last lane is loaded when there is nothing left to discharge. Note that in both cases we have $n-1$ and not n since dual cycling begins/ends with the last slot in a lane.

Simple Lanes

We now prove a lower bound on the number of time steps necessary for the simple lanes case, and show that for even k where $m \mod (k/2) = 0$, the lower bound

represents the number of steps in the optimal solution. Let T_{mnk} be the minimum number of time steps required to fully discharge and load a vessel in the simple lanes case with k tugs.

Theorem 6.1. *For simple lanes with even k, $n \geq m$, $T_{nmk} \geq n + \left\lceil \frac{nm}{k/2} \right\rceil - 1$*

Proof. Proof From Proposition 6.1 there are at least $n-1$ time steps before any dual cycling can occur. Clearly it is not possible to perform better than discharging the remaining $mn - n - 1$ slots during dual cycling and thus while loading. There are nm slots remaining to be loaded. Since we can load at most $k/2$ trailers at each time step, it will take at least $\frac{nm}{k/2}$ time steps until all trailers are loaded. It is not possible to perform a fractional time step, therefore we must round this value up and get $\lceil \frac{nm}{k/2} \rceil$. Combining the first $n-1$ discharges with the loading while discharging the remaining, we get $T_{nmk} \geq n + \left\lceil \frac{nm}{k/2} \right\rceil - 1$. □

Theorem 6.2. *Let k be even and let $m \mod (k/2) = 0$ then for simple lanes, $T_{nmk} = n + \frac{nm}{k/2} - 1$*

Proof. Proof Since $k < m$ it is clearly possible to discharge the first $k/2$ lanes in parallel. This takes $n-1$ steps (Proposition 6.1), dual cycling then begins by discharging the next $k/2$ lanes while loading the first $k/2$. This pattern repeats until there are no more lanes to discharge. The final $k/2$ lanes can be loaded in parallel. Since we load $k/2$ trailers in every time step starting from time step $n-1$ until all trailers are loaded, we require $\frac{nm}{k/2}$ time steps until they are all loaded. Thus, $T_{nmk} = n + \frac{nm}{k/2} - 1$. □

We now have an algorithm that provides an optimal number of time steps when m is divisible by $k/2$. When m is not divisible by $k/2$, we note that the optimal solution is generally only a few time steps away from the bound shown above, but we do not prove these cases.

Adjacent Lanes

In the adjacent lane case, we must consider the discharge and load order imposed by neighboring lanes. The trailers are discharged and subsequently loaded in a pattern that can be best described as a triangle. We note that our bound is not tight; there are many cases where an extra time step or two are necessary because not all $k/2$ tugs can be used in every time step. We leave this as an open problem, but note that we do not believe finding the optimal solution is computationally difficult on these problems.

Theorem 6.3. *For adjacent lanes with even k, $n \geq m$, $T_{nmk} \geq \frac{m(2n-m+1)}{k} + \left\lceil \frac{nm}{k/2} \right\rceil - 1$.*

Proof. Proof The lower bound on the number of moves in the adjacent lane case has two terms representing discharging and loading. As in our previous proofs, we need to know how many discharges are performed until we begin double cycling. To

discharge the last trailer in the first lane, we must discharge both the "triangle" of trailers m rows above it, and the $n-m$ by m rectangle of trailers. Mathematically, there are $m(n-m)$ trailers in the top rectangle, and $\frac{m(m+1)}{2}$ trailers extending up from the last slot in the first lane. We divide this numbers of trailers through by our available tugs and get $\frac{m(n-m)}{k/2} + \frac{\frac{m(m+1)}{2}}{k/2}$. In the same time step as the last discharge of the first lane we can begin dual cycling. There are nm trailers to load, meaning we need at least $\lceil \frac{nm}{k/2} \rceil$ time steps. Putting all these terms together, and subtracting one since they overlap by one time step for dual cycling, we get the following, which we can simplify into the following inequality: □

$$T_{nmk} \geq \frac{m(n-m)}{k/2} + \frac{\frac{m(m+1)}{2}}{k/2} + \left\lceil \frac{nm}{k/2} \right\rceil - 1 = \frac{m(2n-m+1)}{k} + \left\lceil \frac{nm}{k/2} \right\rceil - 1$$

7 Computational Results

In this section, we report the computational results of the GRKA compared with standard solver solutions for the RRDCP. We first describe the test instances and their precedence rules, followed by computational results on various combinations of deck layouts and trailer precedence. We also address the magnitude of benefits from conducting dual cycling operations in real life using empirical data at the end of the section. The mathematical model is coded in the Julia Language with JuMP [32], solved in Gurobi 9.0 [33] with default settings. The GRKA is coded in Python 3. All tests are run on machines with dual 16 core Intel Xeon E5-2670 processors at 2.6 GHz with 64 GB of memory in total.

7.1 Test Instances

Vessels can have vastly different configurations for the stowage of trailers, thus we design a benchmark of 40 instances to consider varying sizes and properties of the vessels. The benchmark of instances, the data generator, and our heuristic solution procedure will be made available on github upon publication of this work. The 40 test instances are generated with a lane structure through a combination of ten different deck layouts and four sets of precedence rules. Deck layouts are randomly generated of various sizes from 67 trailers to 113 trailers. These are based on two classes of deck layouts, denoted by M and L, where M represents a deck layouts with a maximum capacity of 79 trailers in 13 rows in the longest lane, and a deck width of 7 lanes at the widest row. The class L represents deck layouts with a maximum capacity of 113 trailers in 15 rows in the longest lane and 9 lanes on the widest row. We assume the ramp for accessing the trailers is at the back of the vessel, i.e., the stern, although we note that on our industrial instances access from the midship and the bow is also realistic. We categorize each instance as $\{M, L\}$-B-$\{N, S, O\}$, where B is the number of blocked slots, e.g., due to support pillars, and the final parameter $\{N, S, O\}$ describes whether there are no blocked slots (N), blocked slots in the shape of a square (S), or a blocked slot structure difficult to describe (O).

Table C.1: Precedence of Slot (r,c) in Various Precedence Rules.

Rule	discharging	Loading	Precedence.
m	(r+1,c)	(r-1,c)	Front slot.
mp	(r+1,c),(r+1,c-1) or (r+1,c+1)	(r-1,c),(r-1,c+1) or (r-1)(c-1)	Front and its immediate port slots.
ms	(r+1,c),(r+1,c+1) or (r+1,c-1)	(r-1,c),(r-1,c-1) or (r-1,c+1)	Front and its immediate starboard slots.
mps	(r+1,c),(r+1,c-1) and/or (r+1,c+1)	(r-1,c),(r-1,c+1) and/or (r-1,c-1)	Front, its immediate port and starboard slots.

We provide four sets of general rules set up for testing regarding the structure of the precedence constraints based on a general understanding of the discharging and loading operations. Table C.1 provides the rules. Note that the rules do not apply to the first row for loading and the last row for discharging since nothing blocks them from being loaded or discharged, respectively. Moreover, regarding rules mp, ms and mps, for trailers located at the most port or starboard side, the blocking slots are the front and the front to a feasible side, to ensure a safety space of two slots in front of the trailer being loaded or discharged. An example of the precedence relations based on rule ms is illustrated in Figure C.6. As stated above for rule ms, additional clearance is needed from the starboard side of trailers. Therefore, for trailers loaded at slots 5-7, the preceding slots are (9,10), (10,11) and (11,12), respectively. As for the trailer on the most starboard side at slot 8, the blocking slots are 12 and 11.

In addition to our generated instances, we also collect instances based on a short sea RoRo vessel operating from Vlaardingen, Netherlands to Immingham, United Kingdom. The vessel contains four decks: the lower hold (lh), main deck (md), upper deck (ud), and weather deck (wd), each with different capacities, layouts and ramp positions. Each industrial instance is denoted by *deck name-capacity-ramp location*. Precedence constraints are developed based on a combination of rules illustrated in Table C.1, with additional inputs from the stowage planner at the company. We assume full loading and discharge for both generated and industrial instances. All instances are solved with four tugs.

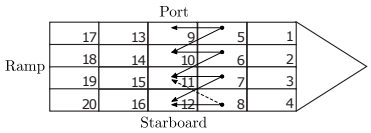


Fig. C.6: Example of discharging with Rule ms.

7.2 Computational Experiments

We now present the computational results on our test instances. Table C.2 shows the minimum solution value of Gurobi and GRKA with several different options for the continuous optimizer: BRKGA [10], PSO [29], DE [30], random construction, and CMAES [31]. We chose these continuous optimizers for the GRKA as they represent a wide range of effective strategies for continuous black-box optimization. We allow Gurobi to have 48 wall hours of solving time with up to 8 threads, while all runs of

GRKA are performed single threaded with up to 60 seconds of CPU time, although it never needs more than 10 seconds. We run GRKA five times for each instance and continuous optimizer combination and report the best value. We note that the performance of the GRKA is relatively stable over the five runs. However, given the low CPU time of the approach, it is clearly feasible to run multiple copies of GRKA in parallel and take the best value.

We first note that CMAES matches or exceeds the best solution found by Gurobi on all instances except one in only a few seconds of CPU time, compared to the hours of time needed by Gurobi. Furthermore, Gurobi finds no solution on six instances of the dataset, further emphasizing the need for a heuristic.

Using GRKA with the random setting, i.e., the decoder is just run with random input until the timeout is reached, results in solutions that are not far away from the best found by CMAES or Gurobi. This is likely due to the fact that at least some parts of the problem are easy to solve. In other words, once some decisions are made about the order some trailers are loaded/discharged, the rest of the problem is likely solvable to optimality almost regardless of the random key values. Nonetheless, the advantage of using CMAES or one of the other optimizers is clear, as they are able to focus on key choice points and find correct decisions that lead to high quality solutions.

7.3 Empirical Analysis

We further investigate the impact of dual cycling optimization by benchmarking the heuristic results of the four industrial instances against the current operational mode, i.e., single cycling, as shown in Table C.3. It is clear that dual cycling creates significant savings in the number of tug moves. The larger the deck is, the higher the degree of dual cycling is possible. In the case of the studied vessel, dual cycling reduces the total tug moves by 71, which is equivalent to a time savings of 355 minutes when assuming 5 minutes per move. Note the time savings are distributed across the four tugs in operation, resulting in an average savings of more than 88 minutes, thus enabling an equally sized reduction in turnaround time.

A shorter turnaround time gives vessels more time and flexibility during their sea voyage, and thus can reduce fuel consumption and CO_2 emissions through slow steaming. Recall that the admiralty coefficient A is a constant for a given vessel that approximates the relationship of displacement ∇, vessel speed V and engine power P [34]:

$$A = \frac{\nabla^{\frac{2}{3}} \times V^3}{P} \tag{C.20}$$

The amount of fuel consumed can be estimated by the power used and vessel speed can be approximated by voyage distance and time at sea. Thus, fuel savings through slow steaming can be estimated for any given displacement, resulting in this case in a fuel and emission reduction of nearly 25%. Shorter turnaround times also lead to lower labor costs and potentially more vessels can be accommodated at existing berths. Furthermore, high tug utilization with less empty movements indicates less fuel consumption and emission from the tugs, shorter working hours for the tug drivers and less labor costs for the terminal operators.

Table C.2: Minimum Value Found over Five Runs of Each Metaheuristic Implemented in GRKA and a Single Execution of the Gurobi Solver.

Instance	Ruleset	BRKGA	PSO	DE	Random	CMAES	Gurobi	CMAES gap to Gurobi
M-0-N	m	**52**	53	**52**	53	**52**	**52**	0.000
	mp	68	68	68	68	68	68*	0.000
	mps	80	80	80	80	80	80	0.000
	ms	68	68	68	68	68	68	0.000
M-9-S	m	47	47	47	47	**46**	**46**	0.000
	mp	60	60	60	60	60	60	0.000
	mps	72	72	72	72	72	72*	0.000
	ms	62	62	62	62	62	62*	0.000
M-11-O	m	**45**	46	46	46	**45**	**45**	0.000
	mp	58	58	58	58	58	58*	0.000
	mps	68	68	68	68	68	68	0.000
	ms	59	59	59	59	59	59*	0.000
M-19-O	m	**44**	45	45	45	**44**	**44***	0.000
	mp	58	58	58	58	58	58	0.000
	mps	68	68	68	68	68	68	0.000
	ms	61	61	61	61	61	61*	0.000
L-0-N	m	72	**71**	73	73	**71**	72*	-0.014
	mp	**96**	**96**	97	97	**96**	-	-
	mps	114	114	114	114	114	-	-
	ms	**96**	**96**	97	97	**96**	-	-
L-20-S	m	**60**	61	61	61	**60**	**60***	0.000
	mp	**76**	**76**	**76**	77	**76**	**76***	0.000
	mps	94	94	94	94	94	94*	0.000
	ms	82	82	82	82	82	82*	0.000
L-24-O	m	59	59	59	59	**57**	58*	-0.017
	mp	**72**	**72**	73	**72**	**72**	**72***	0.000
	mps	90	90	90	90	90	90*	0.000
	ms	79	79	79	79	79	79*	0.000
L-16-O	m	63	63	63	63	**62**	63*	-0.016
	mp	84	84	84	84	84	-	-
	mps	98	98	98	98	98	98*	0.000
	ms	84	84	84	84	84	-	-
L-18-O	m	61	61	62	61	**60**	**60***	0.000
	mp	75	75	75	75	**74**	83*	-0.108
	mps	93	93	93	93	93	93*	0.000
	ms	82	**81**	82	82	82	82*	0.000
L-20-O	m	**56**	**56**	**56**	57	57	**56***	0.018
	mp	**69**	**69**	**69**	**69**	**69**	70*	-0.014
	mps	84	84	84	84	84	-	-
	ms	**75**	**75**	**75**	**75**	**75**	76*	-0.013
lh-38-stern	Industry	38	38	38	38	38	38	0.000
md-67-stern		**58**	**58**	59	**58**	**58**	59*	-0.017
ud-77-midship		**62**	63	63	64	**62**	**62***	0.000
wd-80-bow		60	61	61	61	**59**	**59**	0.000

Note. Gurobi runs that did not find the optimal solution are marked with a star *.

Table C.3: Empirical Results and Estimated Time Savings.

Instance	Total Operational Time		Savings	
	Single Cycle	GRKA(CMAES)	Moves	Time*
lh-38-stern	45	38	7	35
md-67-stern	71	58	13	65
ud-77-midship	82	62	20	100
wd-80-bow	90	59	31	155

Note. Estimated with 5 minutes per move.

8 Conclusion

In this paper, we address dual cycling for RoRo vessels. We presented a mathematical formulation of the RRDCP in the form of an integer programming problem, and showed that the decision version of the RRDCP is NP-complete. Since the integer program we developed requires significant time to solve, we introduce a novel heuristic based on generalizing the BRKGA as our solution approach. We showed that our approach can solve real instances to optimality in many cases, and near optimality in the rest, using only several seconds of CPU time. We further presented the benefit of implementing dual cycling with our algorithm in an industrial case. The empirical results show a significant saving in tug moves and turnaround time, allowing for an estimated reduction in fuel consumption and CO_2 emission by 25%. Given the speed of the heuristic, we expect that our approach can easily be integrated into companies' systems and terminal operations for decision support.

For future work, we intend to investigate how to increase the model realism with regards to the time discretization in our model. Assuming that time is discretized, with each tug movement taking one unit of time regardless of the cargo type and cargo location on board or in terminal, is a key limitation of this work. Future work will thus examine alternative time discretizations or removing the discretization entirely. Another aspect that will be considered is the robustness of the solution with regards to dynamic or realtime information.

Acknowledgement

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Paper D

Estimating Discharge Time of Cargo Units – A Case of Ro-Ro Shipping

Beizhen Jia, Aalborg University

Niels Gorm Malý Rytter, Aalborg University

Line Blander Reinhardt, Roskilde University

Gauvain Haulot, DFDS

Mads Bentzen Billesø, DFDS

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Abstract

Ro-Ro shipping is a dominant form of short sea freight transport. Ro-Ro ship operators are today unable to provide customers with precise information about when trailers are available for pick-up by customers on the terminal despite vessel arrival times being well known in due time. This results in reduced truck utilization, longer waiting time for drivers, less efficient yard space utilization, potential terminal congestion and dissatisfied customers. In this paper the cargo unit discharge time estimation problem of Ro-Ro ship-ping is solved in collaboration with a European short-sea Ro-Ro shipping company. A module-based framework using statistical analysis for estimating the discharge time is proposed and tested. The initial framework is able to estimate the earliest pick-up time of each individual truck or trailer within 1 hour accuracy for up to 70% of all cargo. The results of the study show potential for improving performance and accuracy. Further investigation and testing is currently ongoing by the case company based on the results from this study.

Keywords: Cargo Discharge Time Estimation, Short Sea Shipping, Terminal Operations, Integrated Logistics Chain, Industry Implementation.

1 Introduction

Roll-on/Roll-off (Ro-Ro) shipping is a large part of the maritime freight transport of coastal communities and also deep sea due to the versatility of most Ro-Ro vessels. For over 1.8 billion tonnes of goods transported through short-sea ship-ping (SSS) in European Union in 2017, Ro-Ro units accounted for 13.6% with only 1% less than cargo transported through containers [1]. In Europe the Ro-Ro shipping is very dominant, due to the extensive coastal line compared to the landmass of Northern, Western and Southern Europe. The fact that this landmass consists of a large amount of peninsulas makes the short-sea Ro-Ro shipping an attractive alternative to land based and container transport and in some cases such as the British Isles there does not exist a land based alternative. Ro-Ro vessels consist of two major types: deep-sea going Ro-Ro vessels which are commonly car carriers travelling across continents, and short-sea Ro-Ro vessels that transport mostly trailers and heterogeneous cargo sometimes with a mixture of passengers as well. The short-sea vessels are in Europe strongly present between countries separated by sea but located closer to each other such as the North Sea, Baltic Sea and Mediterranean areas. Ro-Ro SSS like short-sea container transport generally operates with fixed schedules servicing often just two ports although in occasions the routes can include from 3 to 10 port calls in a round trip even though longer routes are more common in short-sea container transport. Although Ro-Ro vessels have a much smaller capacity than container vessels the Ro-Ro vessels have the advantage of a larger choice of ports due to container vessels crane requirement. The main competitors for Ro-Ro vessels are road transportation and short-sea container shipping and it is important to remain competitive which implies offering client a short transit time and reliable schedules. However speeding up the vessels increases the bunker consumption significantly. Increasing the bunker consumption is both costly and also not applicable with the International Maritime Organization (IMO) announced goals for reducing CO_2 emission in maritime transportation with

50% by 2050. The European Commission has set ambitions for enhancing the further development of SSS through three actions, one of which is improved integration of SSS in full logistics chains [2]. The integration includes among others the loading and discharge of Ro-Ro vessels. These processes can take up to long hours depending on the vessel size thus leaving a large time interval for the first trailer available for pick-up to the last one available at a given destination port. Lack of information can result in customers' trucks waiting around at the terminal for hours for a trailer or terminal congestion caused by trailers taking up the limited terminal space longer than actually required.

2 Background

Today the information about trailers availability for pick-up at the yard is often released after the discharge of all the cargo from the Ro-Ro vessel. In order to increase customer satisfaction without increasing operational costs, one option is to provide customers with the planned discharge time for their trailers or general cargo so that they can avoid waiting for the discharge of all the cargo before retrieving it. Being able to provide customers with information about availability of individual trailers for pick up at yard in due time, e.g. several hours before vessel ETA, can enable customers to increase the utilization of their logistics assets and resources. Moreover it can reduce the congestion at the gate and the surrounding road network as all customers are not arriving to the terminal to pick up their trailers at the same time. Meanwhile, reduced 'turnaround' time of trailers in the terminal means a better utilization of the yard with more throughput. However despite extensive effort spent on stowage planning and execution Ro-Ro shipping companies are today unable to produce and deliver this information to their clients.

Researchers have previously investigated the challenge of terminal congestion in relation to truck arrival, however most of the research so far has been focused on the segment of container shipping rather than the Ro-Ro sector. Moreover the focus of the research has been on investigating problems of terminal congestion due the unpredictable arrival time of trucks for pickup of import cargo, which impacts resource allocation at terminals and implies inefficiencies for ports and haulage companies. For container terminals, research on improving efficiency of landside drayage operations has proposed implementing Truck Appointment System (TAS), gate extended hours and pricing policies to control truck arrival rates to handle these challenges [3]. For example the impact of TAS on truck-related port emissions, turn-around time, congestion and air pollution has been studied extensively [4, 5]. Furthermore, there are some studies investigating the use of optimization methods to support TAS [6–8]. For example Phan and Kim have proposed a solution for negotiations of truck arrival time among trucking companies and terminal [9]. Reinhardt et al. applied several optimization techniques to solving the bottleneck of the inland transport of containers connecting customers and terminals for more efficient liner shipping operations [10, 11].

If we zoom out and consider the overall flow of logistics operations at terminals, it is interesting to observe that most research is focusing on TAS and truck arrivals.

Thus investigating options for predicting discharge time of individual cargo units (containers) at terminals as a way forward attempting to improve terminal operations and customers' processes has been overlooked. In a situation where a ship operator or terminal is able to predict the available pick-up time of the individual cargo units, a TAS with better accuracy and reliability could be developed which would result in reduced terminal congestion. For container shipping, the challenge of predicting cargo availability for pickup might be difficult to embrace due to variability of stowage situations from ship to ship, however for Ro-Ro shipping this issue might be more addressable as loading and dis-charge procedures across decks, lane sections etc. can be assumed more regular and stable across voyages. In general, but in particular from the perspective of Ro-Ro shipping we consider estimating the discharge time of cargo units as an overlooked topic when solving terminal congestion problems and logistics efficiency problems. Quality estimation will enable TAS and truck arrival management systems to perform much better. It is also an issue so far not studied for Ro-Ro terminals, where we mainly identified a few studies focused on simulation and decision support for terminal capacity planning and operational execution [12–17]. In this paper we have in collaboration with a European short-sea Ro-Ro ship-ping company identified the discharge time estimation problem for Ro-Ro ship-ping, developed a module-based framework for estimating the time available for customers' pick-up of individual trailers. We have completed a subsequent evaluation of accuracy of the methods on data collected from actual discharge cases, and compared the results with different time windows.

The remaining of this paper continues with defining the discharge time problem for Ro-Ro vessels in section 3, followed by a description of the framework structure in section 4. In section 5, we present a case study on its application and discuss the results. Finally, we conclude the paper and point out directions for future research.

3 Problem Description

The Ro-Ro cargo unit discharge time problem is a challenge involving various stakeholders of the cargo logistics chain, as shown in Fig. D.1. A cargo unit can be either unaccompanied or accompanied depending on if there is a truck and driver travelling with the cargo. Unaccompanied cargo requires tugs in order to be placed on/off board. All cargo are loaded under the instruction of a dispatcher (or foreman), who manually creates an overall stowage plan and controls cargo flows in an import/export terminal. When a vessel arrives at a terminal, a local dispatcher plans the discharge of the vessel for both types of cargo. Once all cargo is discharged from the vessel and onto the terminal, import customers are able to pick up their unaccompanied cargo and complete the rest of the logistics chain. One of the pain points for both terminals and customers is that the import customers do not have information of the available pick-up time for their cargo in advance as this is assumed difficult to provide by the Ro-Ro vessel operators for multiple reasons.

First, different unit types require a different amount of time to be fastened to or be released from the vessel. For example, it's faster to lock / unlock the trestles attached to standard trailers, whereas mafis and cassettes require longer time due to

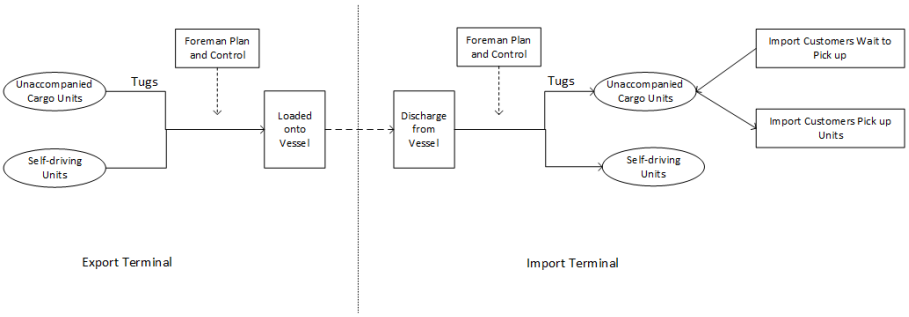

Fig. D.1: Ro-Ro cargo logistics chain at terminal

their special operational requirements (heavy weight, gooseneck, translifter, lashing etc.) Besides this, general cargo, hazardous cargo, refrigerated cargo, livestock, bulk can also be transported. They have dedicated zones or warehouses where they are supposed to be discharged to inside the terminal. Refrigerated cargo must be plugged in, therefore the area where they are stored in the terminal is usually on the edge or furthest away. Same goes for bulk cargo, like steel and wood. Hence the cycle time is much longer for the above mentioned cargo, compared to standard trailers. Where the unit is loaded onboard a vessel also influences the discharge time as a unit can be discharged only when all units which stand in front of it are discharged in order to make a path out. Moreover it requires more time for tugs to travel to the weather deck, which is the top deck of a vessel, than the time required to pick up a trailer on the main deck. Therefore, it is the relative position of a unit on a deck and the deck that determines the discharge time. When a vessel arrives at a terminal, it also takes some time to set up the ramp and arrange tug masters before discharging the first unit. If the vessel is early or late according to the schedule, it will have an impact on the exact time when units is being discharged, and in the case where multiple vessels arrive in one time slot it will also have an impact on the schedule of the tug usage. Tug availability is one of the most important factors determining the discharge speed of a vessel, hence, the discharge time. The more tug masters are assigned to the vessels, the faster the vessel gets discharged. However, depending on the day of the week and the number of vessels arriving, the tug availability fluctuates throughout the discharging process. Day of week is an external factor that has an impact on the number of tugs to be used. It indirectly influences the discharge speed by directly influencing the number of tugs scheduled for the discharge process. Weekends and weekdays with more vessels arrivals will have less tugs scheduled for each vessel's discharge, hence lowering down the speed. The tug availability is not a fixed number of workers as illness and other issues may affect the number of tugs available, thus making it difficult to model and plan. Moreover, extreme weather requires extra lashing of the units for safety reasons during sailing. When it comes to the time of discharge, bad weather can slow down the tug masters' driving speed, and it requires extra time to release the lashing on the units before they can get discharged. Having captured the influence of these factors or variables enables us to model the discharge time of each unit as a function of unit type or type group, cargo type, position, vessel

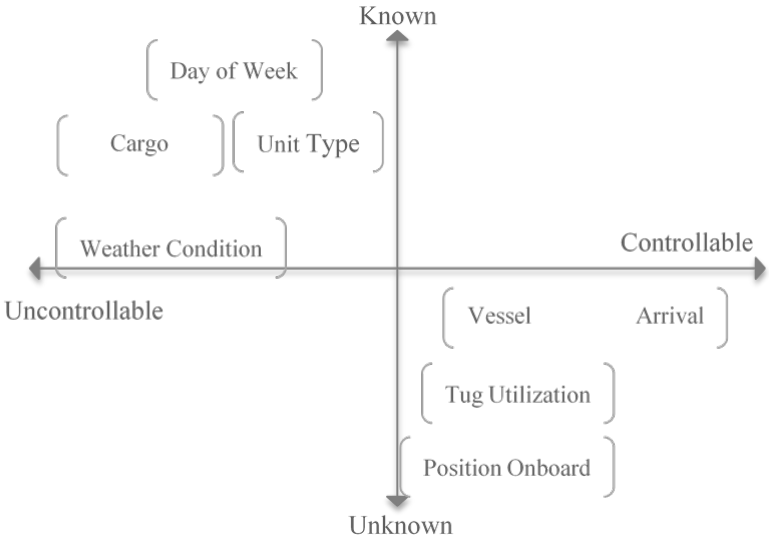

Fig. D.2: Categorization of potential variables for cargo unit EDT

arrival condition, tug availability, day of week, and weather condition.

$$EDT_{unit} = F(t, c, p, v, n, d, w)$$

EDT_{unit}	discharge time per unit
t	unit type
p	position onboard
v	vessel arrival condition
n	tug availability
d	day of week
w	weather condition

The factors influencing the discharge time of the unit are at the same time the challenges affecting the model of estimated discharge time (EDT). The challenges are of different risk types, as shown in the risk matrix in Fig. D.2, depending on the availability of knowledge and the ease of control of the factors. As can be seen, the factors fall into two major quadrants by the time of vessel departure – known but uncontrollable; unknown but controllable. Some information is known but uncontrollable, like day of week, cargo type, unit type, and weather condition. Regarding weather condition, one could argue that it is known through weather forecasts but it can also be considered slightly unknown due to inaccuracy or uncertainty of weather forecasts in general. It is for this study considered a piece of known information as operational

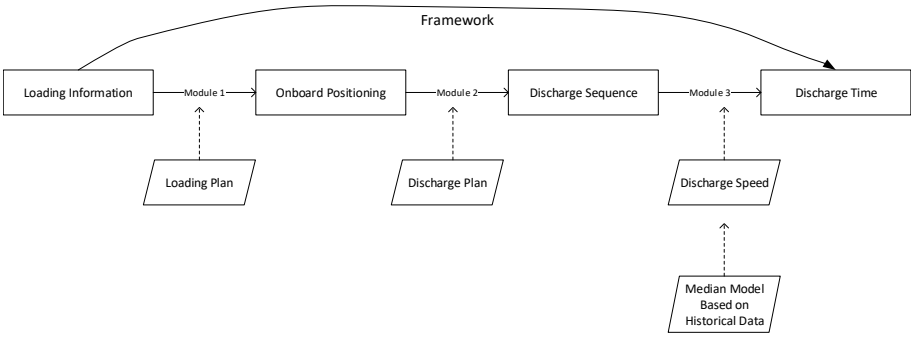

Fig. D.3: The Modular Discharge Time Framework

efficiency is not sensitive to slight weather changes, and that weather forecast is sufficient to catch significant weather shifts. Whereas already by the time of loading, some of the factors are unknown, however still controllable which means that the information could be captured with certain degree of human intervention. This includes position on board, tug availability, and vessel arrival condition. These three factors have the highest influence on the discharge time of a unit. However the challenges in estimating the discharge time are, to the authors' knowledge, lack of traceability where the unit is loaded on board; shifting tug usage; and uncertain discharge sequence deck-wise but also position-wise within a deck. Furthermore, the challenges when implementing solutions to control these factors are the standardization of loading and discharge processes across routes and voyages with consideration of human participation and business complications stemmed from customer requirements.

4 Framework

To estimate individual discharge times of the cargoes from the loading information, this paper propose a modular framework for the Ro-Ro cargo discharge time estimation problem (Fig. D.3). The framework consists of basic statistical methods and logics combined in different modules to form the framework for delivering a good discharge time estimation. The framework consists of three modules:

Module 1. : The loading position is estimated from loading information such as loading timestamps, standardized loading sequence and its position (first in last out).

Module 2. : Estimates the discharge sequence from the estimated loading position provided by module 1 (furthest in last out).

Module 3. : Estimates the discharge time based on the discharge sequence generated in module 2 with certain discharge speed.

The combination of three modules constitutes the Ro-Ro cargo discharge time estimation framework, and the overall accuracy depends on the performance of each module. Depending on what information is available in the operation, the discharge

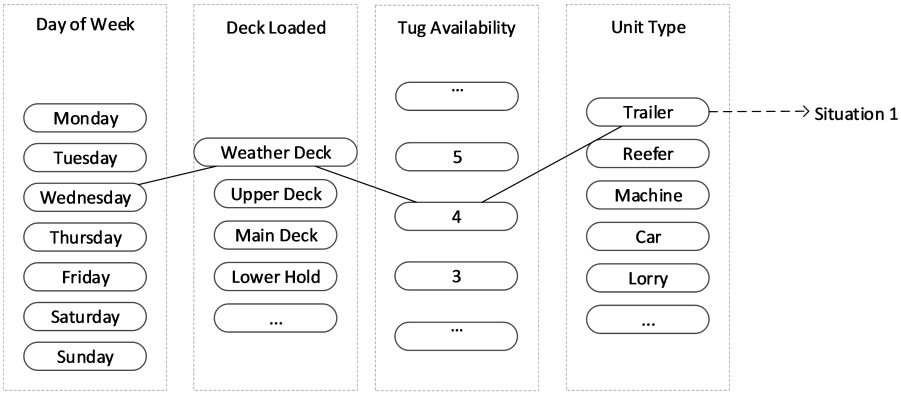

Fig. D.4: Example of a Discharge Situation

time estimation can be constructed with only one or two modules. For example, if the company makes a detailed stowage plan and executes accordingly, the first module will be omitted as real loading positions of cargoes will be available as input to module 2. In this paper, we are more interested in the cases where loading positions are not recorded when vessel departs and thus unknown, which is also close to situations experienced in real-life operations.

For the first two modules, a fixed loading and discharge plan is assumed, which means that the vessel loads and discharges in a specific sequence, however, a limited number of usually minor shifts in position in the plan is possible in reality. The third module estimates the discharge time based on the estimated discharge sequence and discharge speed which arose as a sub-problem.

4.1 Discharge Speed

As discussed in section 3, the discharge speed is influenced by various different factors. To find the discharge time in module 3 we have constructed a model which we call a situational median model to estimate discharge speed for different discharge situations. A situation is a combination of various factors that have a significant influence on the discharge speed, such as unit type, week day, tug availability and deck loaded. An example of a situation is illustrated in Fig. D.4, and it is a situation where the discharge happens on a Wednesday, for trailers on the weather deck with four tugs working simultaneously.

Each situation is connected to a discharge speed based on historical data, assuming no significant changes of processes, equipment or systems in the relevant time horizon. Let S be the set of situations, and V be the set of discharge speed, where $v_i \in V$ is the discharge speed of situation $i \in S$. The Binary variable x_{ni} equals to 1 if i is the situation of the nth discharged unit, and 0 otherwise. Discharge time for one unit is defined as the time interval between the current discharging unit and the

previously discharged unit. It is formulated as below:

$$\nabla^{i}_{EDT(n)} = DT^{i}_{n} - DT^{i'}_{n-1} \qquad i, i' \in S \tag{D.1}$$

DT^{i}_{n} is the discharge timestamp of the nth discharged unit, and $n-1$ is the previous unit in the discharge sequence. The situation i of $\nabla^{i}_{EDT(n)}$ is determined by the situation of the discharging unit n such as unit type, deck, weekday, and tug availability and is thus independent of the situation of unit $n-1$. This means that each discharge unit has its independent speed calculated from the situation i of the unit.

The situational median discharge speed equation is the median of discharge time intervals categorized by different situations from historical voyages. The discharge speed of situation i is irrelevant to the unit's discharge sequence n. Thus we can define the situational median speed v_i as:

$$v_i = median(\cup \nabla^{i}_{EDT}) \qquad i \in S \tag{D.2}$$

The estimated discharge time of the nth unit is the sum of the time needed to discharge individual unit from the first in the discharge sequence up until the nth, based on the unit's situation. And it is formulated as:

$$EDT_n = \sum_{m=1}^{n} \sum_{i=1}^{|S|} v_i x_{mi} \tag{D.3}$$

The framework is configured with more details from the industry case which is tested and evaluated with real data in the next section.

5 Case Study

5.1 Description of the Case Problem

The problem and the framework are further researched in a case study with a Ro-Ro shipping company that operates short-sea transportation in Europe. The chosen route of the study is a 15-hour voyage from Vlaardingen, the Netherlands to Immingham, England, with two identical vessels servicing a daily schedule.

A three-week data collection was conducted in collaboration with the company. Loading and discharging operations were instructed by foreman, based on the standardized sequence plans per deck. For module 1, an example of the loading sequence of main deck drawn by a foreman is given in Fig. D.5. The first trailer loaded is estimated to be in position 1 and the last one loaded in position 63. If this were a discharge plan in module 2, position 63 would be estimated to be the first discharged and etc. Exact loading positions have been captured for frame-work validation. In addition, a nine-month historical data starting from January 2018 was retrieved from the company's database for the situational median dis-charge speed model. No significant changes in the process was made throughout the selected nine-month and three-week period. The majority of the data is automatically logged through booking and terminal management systems. For each unit, information on time of loading, time of dis-charging, deck loaded, unit type etc. is available. However due to changes

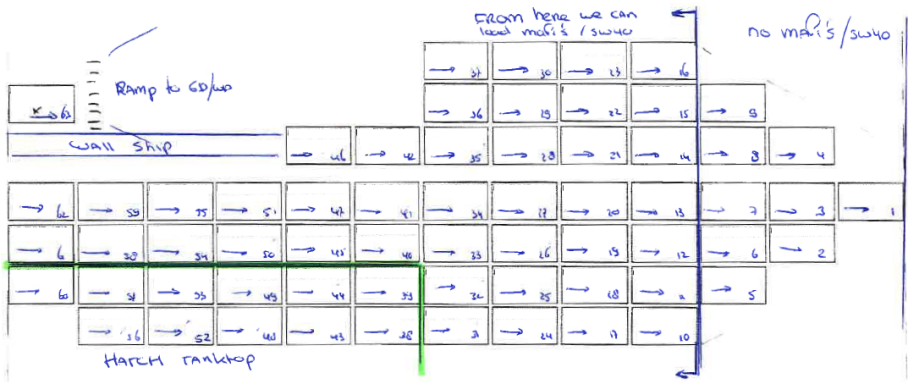

Fig. D.5: Example of the loading plan of the main deck. Source: DFDS Vlaardingen

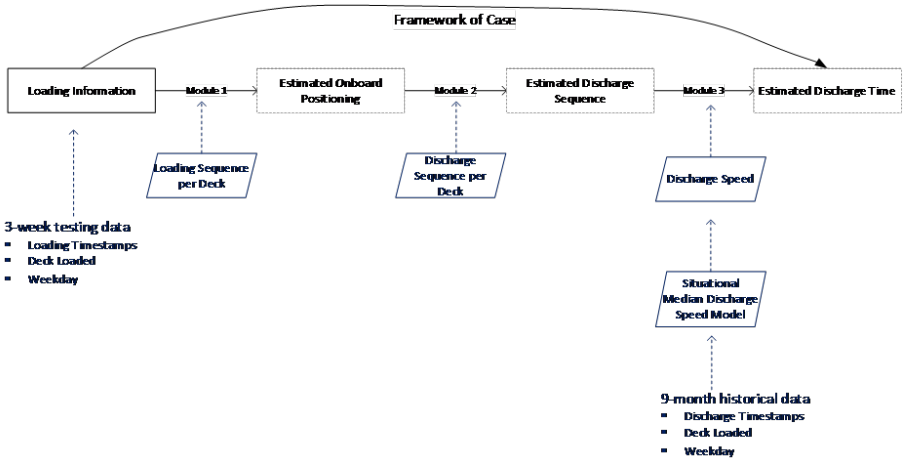

Fig. D.6: Framework Configuration of Case Study

in tug availability, it has been very difficult to determine the number of tugs available per deck at a certain time. Therefore, this information will not be considered and included in the framework for the present, and we assume the constant availability of tugs per deck every day. Unit type, as discussed above in the problem formulation, has an impact on the speed of discharge as well. However, based on analysis, the discharge process appears stable and units are evenly scattered over time, indicating that unit type is not a significant influencing factor, therefore it is not considered in this case. Lastly, vessel arrival conditions and weather are not included in the case study. According to interviews with the company, foremen, managers among others, the study of the discharge speed is delimitated by the focus on loaded deck and day of week. This however also indicates the level of terminal activity and thus indirectly indicating the average number of tugs used. A diagram with data input and output for each module in the case study is illustrated in Fig. D.6. Initial data input to the

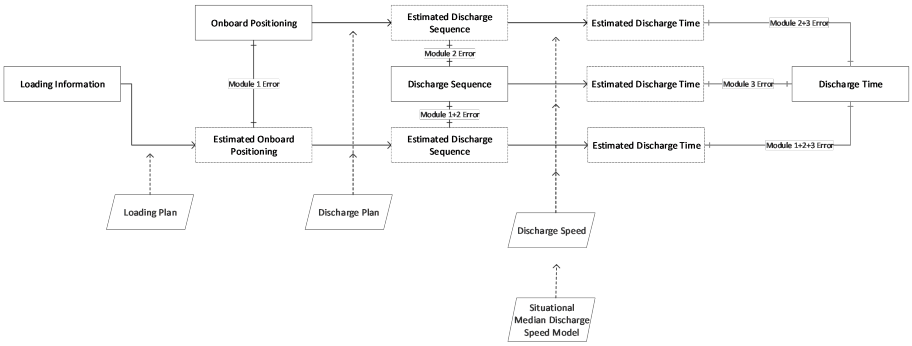

Fig. D.7: Framework Evaluation Map

first module of the framework is the timestamp at which a unit was loaded onto the vessel and the deck the unit was loaded onto. Based on the actual sequence of loading the standardized loading sequence plan, the output of module 1 will be the estimated loaded position for each unit. In the second stage, the output of module 1 is fed into module 2 in order to estimate the discharge sequence based on the standardized discharge sequence plan. Lastly, the overall deliverable of the framework, which is the individual discharge time of a unit is estimated based on the discharge sequence and discharge speed, calculated as in Eq. D.3.

5.2 Framework Evaluation

For a module-based framework, it is important to separate the individual module performance to understand the overall framework accuracy and to improve the performance if possible. Therefore it is important to look at individual module performance as well as combined performance. To achieve this, we have conducted three-week data collection where the company, terminal and crew were actively involved. Among other things, we have collected the onboard positioning of cargoes, actual discharge sequence and the actual discharge timestamp. Individual module performance tells how well a module estimates given the input to the framework is real data instead of estimated. Illustrated in Fig. D.7, the error of module 1 is the difference between estimated position and actual position; if the actual onboard positioning is known, the discharge sequence estimated from module 2 compared with actual discharge sequence is the individual performance of module 2, and the same logic applies to individual performance of module 3. Combined module performance is the result of a combination of two or more modules. A combined performance of all three modules makes the accuracy of the overall framework. By comparing combined performance to individual performance, we are able to tell how well modules can be integrated into one framework and what the accuracy loss is by predicting in a modular way. It also makes it possible for the company to see where with actual data would improve the discharge time estimations most.

<table>
<tr><th></th><th colspan="3">% units <15 min late</th><th colspan="3">% units <30 min late</th><th colspan="3">% units <60 min late</th></tr>
<tr><th></th><th>Individual performance</th><th>Module 1+2</th><th>Overall performance</th><th>Individual performance</th><th>Module 1+2</th><th>Overall performance</th><th>Individual performance</th><th>Module 1+2</th><th>Overall performance</th></tr>
<tr><td>Module 1</td><td>93.0%</td><td rowspan="2">90.3%</td><td rowspan="3">32.5%</td><td>95.0%</td><td rowspan="2">94.8%</td><td rowspan="3">43.2%</td><td>96.8%</td><td rowspan="2">98.3%</td><td rowspan="3">65.8%</td></tr>
<tr><td>Module 2</td><td>91.8%</td><td>95.0%</td><td>98.8%</td></tr>
<tr><td>Module 3</td><td>32.4%</td><td>-</td><td>95.0%</td><td>-</td><td>67.2%</td><td>-</td></tr>
</table>

Table D.1: Results of Framework Performance Evaluation

5.3 Computational Results

The discharge speed was calculated in MySQL and fed into the overall framework, which was coded in excel. Table D.1 presents the results for individual modules, combined modules and the overall framework, with a 15-minute, 30-minute and 60-minute time window. As mentioned in the previous section, individual performance for module 1 represents how well the module estimates loading positions from loading timestamps of units; for module 2 and 3, it is based on actual unit position on board and actual unit discharge sequence respectively. Actual data was gathered during the three-week data collection. Because of the nature of the data input and output in module 1 and 2, the errors are measured by the differences in the sequences. In order for the results to be comparable, we converted it into to a time estimate in minutes by multiplying errors in position by discharge speed. Combined performance of module 1 and 2 presents an integrated result when the input of module 2 is not actual data but predicted data from the output of module 1. Table D.1 shows the computational results of each individual module of the framework and two different combinations of the modules. The overall result appears an undesirable accuracy of 32.5% with a 15-minute window late, 43.2% and 65.8% for 30-minute and 60-minute time window late respectively. When we compare the combined and overall results of modules to individual module performance, the difference in accuracy is relatively small. This means that the three modules they have little influence among each other and proves the robustness of the modular EDT framework.

From loading information to loading sequence (module 1), and from loading sequence to discharge sequence (module 2), we could predict the loading and discharge sequence with an accuracy of more than 90%. Furthermore, the combined result of module 1 and 2 does not show a significant drop in the accuracy. The robustness of the modules relies on the standardization of the loading and discharge procedures. From experience and practices, there already exist patterns of loading and discharge Ro-Ro vessels. Standardization of patterns is a challenge however, as the result shows, it is not impossible to overcome and acquire robust outcome out of it.

Module 3 has the lowest the accuracy – 32.4%, 45.1% and 67.2% predicted within 15, 30 and 60 minutes late respectively. This is the bottleneck of the framework since the overall accuracy follows closely the accuracy of module 3 with little difference. However this result is expected without pulling in tug availability and other factors discussed in section 3. From a business perspective, almost 70% of the units can be estimated its discharge time with an hour time window. This means 70% of the customers get correct available pick-up time for their trailers, instead of hours after the ship's arrival and they can therefore avoid traffic jams around the terminal and time waste in general.

6 Concluding Remarks

This paper describes a currently unsolved problem for the Ro-Ro shipping industry – the estimation of discharge time for individual cargo units before vessel arrival and proposes a data-driven module based approach for the problem. The motivation behind predicting cargo unit discharge times was that it enable ship and terminal operators to deliver a more efficient cargo supply chain for customers, a better utilization of the Ro-Ro terminal as well as a better service product from the shipping company.

The main idea of the proposed solution method is to approach the discharge time from loading information step by step, on a modular basis. With the input of instructed loading sequence plan, by ranking the timestamps when units are loaded, their positions on board are estimated. Based on the discharge sequence plan and position on board, a discharge sequence of all units is estimated. Then the discharge time of the individual unit can be estimated by incorporating the dis-charge speed, which was solved as a sub-problem where we introduced a situational median approach to find the discharge speed suitable for each unit.

The weak part of the framework is module 3, which was expected due to framework simplifications and limited data availability for tug usage, unit types, vessel arrival conditions and weather for the case study. Nevertheless, the overall results achieved with data obtained from real Ro-Ro cargo operations seem to verify the relevance and robustness of a modular and quantitative based approach. Compared to individual performance, combined and overall performance of modules deteriorate only to a trivial degree. The framework is widely applicable and customizable to different routes, ships and companies by tuning individual modules and adjusting the set of situations based on various influencing factors in Ro-Ro shipping. As for container terminals, it provides the framework and inspiration to potential research on discharge time of containers as input to TAS.

Further work could be focused on improving current solutions to calculating discharge speed or modelling discharge time against discharge sequence to improve the accuracy in module 3. Machine learning could also be an interesting investigation compared to the modular framework method, provided sufficient historical data. Another focus could be the problems related to cargo operations, for example, Ro-Ro stowage automation and optimization problems to be incorporated in module 1; dual cycling of loading and discharge operations, tugs planning and scheduling, and etc. which have a significant impact on discharge speed.

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