Cargo Stowage Planning in RoRo Shipping

Optimisation Based Naval Architecture

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Background
The shipping world has in the later years experienced a boom, with high and persistent rate levels. However, nothing grows without limits into the sky, and with the financial crises emerging mid-2008, questions were raised whether all shipping prospects and new-building activity would see robust and viable commercial life. One of the key issues in ship-owner/ship-operator planning is the strategic planning of the size and mix of the fleet of vessels, known generically as fleet size and mix problems (FSMP). FSMPs are dominated by uncertainty in several dimensions, given fluctuating and changing market demands, changing opportunities that may become open for different types and sizes of vessels, redesign of transport networks, as well as upcoming or changing physical or regulatory "bottlenecks". Questions like;
- Given transport demand and network, how may our current fleet be utilised in the best possible and/or emission effective way, and how should our fleet be developed to meet future market and network opportunities, as well as emission regulations?
- How may changing network structure or fleet mix best achieve a given improvement in performance measurements?

Are among the important decisions that ship-owners have to make to position their fleet of vessels in commercial market operations, as well as meet the regulatory requirements. From the regulators side, the same questions may be addressed with the focus of what the effect and cost of specific regulations could be, given available fleet applicable measures of technology.

Objective
This thesis shall contribute with knowledge of the applicability and models for use of operations research in cargo stowage planning in the RoRo shipping segment. The focus will be stowage in an operational planning perspective.

Tasks
From a naval architecture perspective, one of the more important aspects of stowage on a vessel is the vessel's intact stability.

- A published article and optimisation model on the matter will be used as a reference.
- This model shall be expanded to include tighter stability constraints and other constraints that mimic reality.
- The expanded model shall be implemented in commercial optimisation software and the stowage plans will be checked with more exact hydrostatic calculations to ensure that the stability is indeed satisfactory.

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
Main supervisor: Prof. Bjørn Egil Asbjørnslett

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Deadline: 10.06.2012

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PREFACE

This master thesis was written as a part of the candidate's two year Master of Science degree in Marine Technology with specialization in Design and Logistics as well as some Operations Research from the department of Industrial Economics and Technology Management, both at the Norwegian University of Science and Technology (NTNU).

I would like to thank my supervisor Prof. Bjørn Egil Asbjørnslett at the department of Marine Technology for his guidance throughout the semester. Special thanks go to my sub- supervisor Jørgen G. Rakke for offering valuable support when needed the most.

Trondheim, 09 June 2012

Eivind Wathne

EXECUTIVE SUMMARY

After the economic crisis in the end of the last decade, the market experienced a catastrophic fall in worldwide trade. The shipping market was no exception, and as a result of increasingly meagre profit margins in the years to follow, ship owners have opened up for, in the shipping industry, untraditional planning systems.

Operations research has proven itself to be advantageous in several areas of the industry for many years, but is operations research a good approach to operational maritime planning? Expressions used to calculate the initial stability of a vessel are often non-linear. Optimisation models demand linearity, and approximated linearisations of the proven stability formulas needed to be developed. This was arguably found to be the biggest challenge when modelling the cargo stowage optimisation model.

The characteristics of the RoRo shipping industry have been examined to gain a better understand of the segment. Further, some methods for calculating the initial stability of floating bodies have been presented for the readers that are not already familiar with this area of science.

The thesis has used a published optimisation model as a foundation for further expansions. The model is a mathematical formulation of a cargo stowage problem in the RoRo shipping segment, where a predetermined vessel ships mandatory and optional cargoes from fixed loading ports to unloading ports. The reference model controls the vertical and transverse stability of the vessel by imposing constraints that are linear approximations of stability formulas. The model was expanded to ensure the longitudinal stability of the vessel as well. Additionally, the definitions of the existing vertical and transverse stability constraints were altered to provide more accurate co-ordinates for the expanded optimisation model.

The computational study showed that the original model was able to find the optimal solution faster than the expanded model. The stowage flexibility was also better than for the expanded model, and the revenue generated was equal or higher in the original model for all scenarios. This was because the expanded model is of a greater size than the original, and is much more constrained in terms of stowage on the various decks. The expanded model divides the decks on the vessel not only into lanes, as the original model does, but also into slots. It can therefore ensure the longitudinal stability of the vessel as well. In addition to this, the lanes and slots in the expanded model are subject to lower and upper bounds for width and length, respectively. The original model allows the width of a lane to take values from zero up to the total width of the deck. In the original model, the size of the set of lanes therefore does not dictate the division of decks into lanes. This was found good for stowage flexibility, but is problematic to defend from a stability and safety perspective.

It was decided that the most beneficial addition would be to let the model handle a different number of lanes per deck. Typically, the lower decks would be divided into a low amount of lanes, say 5-6, while the upper decks intended for lighter and narrower cargo would be divided into some 12-15 lanes, depending on deck width. However, this would require great restructuring to the model as the majority of the decision variables and constraints are dependent on the set of lanes to be a fixed number.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Nomenclature

LP	Linear Programming
IP	Integer Programming
MIP	Mixed Integer Programming
FSMP	Fleet Size and Mix Problem
RSSP	RoRo Ship Stowage Problem
CEU and RT43	Car Equivalent Unit $\Leftrightarrow$ RT43
HH	High and Heavy cargo
NCC	Non-Containerised Cargo
RoRo	Roll-on/Roll-off ship
RO-RO	RoRo ship designed for
PCC	Pure Car Carrier
PCTC/LCTC	Pure Car Truck Carrier/Long Car Truck Carrier
VCB	Vertical Centre of Buoyancy
VCG, LCG, TCG	Vertical, Longitudinal and Transverse Centre of Gravity
BM	Metacentric radius
GM	Metacentric height
GZ	Righting moment
I_x	Second moment of area about the x-axis
Δ and ∇	Weight and volume displacement of a floating vessel
CoG	Centre of Gravity
LWT	Lightweight of a ship
DWT	Deadweight of a ship
MT	Metric Tonne
DNV	Det Norske Veritas
FEU	Forty foot Equivalent Container

1 INTRODUCTION

The first decade of the 21st century ended with a worldwide economic crisis. Several countries experienced a decrease in their gross domestic product, and in 2009 the world trade fell by 22.9 per cent compared to the year before. This was the steepest fall in 70 years [1]. According to the same source, this downturn led to a 4.5 per cent reduction in seaborne trade volumes. The shipping market is still struggling to recover, and in 2010 the idle RoRo fleet accounted for 3.21 per cent of the world's total RoRo fleet due to over-tonnage. This was the highest share recorded for any shipping segment and vessel type in 2010 [2].

Operations research has been a popular area of study within many industries. Airline and railway-transportation are some of the more active industries within this field. The shipping industry, with its often conservative players, has in the author's opinion traditionally not realised the potential of operations research in strategic, tactical and operational planning. Seemingly, this trend is starting to turn. As profit margins decrease, the traditional way of planning does not seem to cut it; the risk of losing money is becoming apparent.

With the constant development in computer technology, complex mathematical problems one could only hope to solve just a decade ago are now possible to crack using commercial optimisation software. However, computational capacity will always have its limitations, and even the most powerful computers may spend years crunching numbers before coming up with a solution, if the problem is complex enough. To cope with this, optimisation problems must be modelled in the simplest way possible, while ensuring that the solution also meets the desired level of quality.

An operational planning perspective of a RoRo cargo stowage problem has been considered in this thesis, and a published optimisation model has been used as a foundation. The model has then been expanded to handle aspects the original model did not consider; mostly from a naval architecture perspective. This thesis will shed some light on some of the challenges operations research may be faced with in a maritime transportation problem.

The next chapter will give the reader a brief insight into literature regarding operations research in maritime transportation, where the main focus will be on stowage. Chapter 3 will serve as an introduction to those who are not already familiar with the RoRo shipping segment. Further, chapter 4 will describe the problem this thesis addresses, followed by chapter 5 where the new model will be presented in its entirety, along with the process of developing the expanded model. Chapter 6 will consist of a computational study where the original and the expanded model are compared to each other. And lastly, chapters 7 and 8 will provide conclusive remarks by the author, and suggestions for further work, respectively

2   LITERATURE REVIEW

In this section literature regarding stowage optimisation in both maritime transportation and the industry in general, is given. Further, publications regarding deployment and general operations research in maritime shipping are presented. The papers mentioned here are results of the author's choosing, and the intention has not been to present a complete survey of available literature.

2.1   STOWAGE

In RoRo- shipping, contracts between cargo owner and shipper are often determined by the percentage of the cargo unit production quantity. For this reason stowage problems should be considered in an operational time window, i.e. a short and case-specific planning period. Supporting this statement, some RoRo vessel types are designed to carry NCC (Non-Containerised Cargo), which often means various project cargoes on a short term basis.

While stowage optimisation has been studied extensively in land-based transportation problems, the topic has not been given as much attention within maritime shipping. In the payload sensitive air cargo industry, papers discussing problems regarding weight and volume are available in great numbers. Kasilingam et al., 1996 [3] presented two models for assessing payload sensitive cargo planes: A stochastic programming model in which the capacity follows a discrete probability function, and a Linear Programming (LP) model with Lagrangian relaxation. In container liner shipping, the issue of finding optimal plans for stowing containers onto ships, has been studied to some extent. Ambrosino et al., 2003 [4] published a paper about their research on such a problem, called the Master Bay Plan Problem. The problem was solved with an LP model as well as a heuristic approach for relaxation purposes. Not much attention has been given to operations research and optimisation based planning in RoRo-shipping. However, Øvstebø et al., 2011 [5] considered the problem of optimisation of stowage plans for RoRo ships. The paper proposed both a Mixed Integer Programming (MIP) model, as well as a heuristic model for fast execution time purposes. MIP may suggest impractical solutions, and the heuristic was therefore also developed to create stowage plans that are easily implemented in practice. Another paper, Øvstebø et al., 2011 [6] also included routing and scheduling of RoRo ships in a problem with stowage constraints. This paper considered several variations with optional cargoes as well as flexible cargo quantities. The problem was modelled as an MIP, as well as a heuristic with a squeaky wheel optimisation and tabu search metaheuristic.

2.2   DEPLOYMENT

Perakis and Powell, 1997 [7] investigated a fleet deployment optimisation problem in liner shipping. The objective was to minimise the operating and lay-up costs for a fleet of

liner ships operating on various routes. The problem was modelled as an Integer Programming (IP) model, but as a precaution to expose rounding errors in the IP model, the solution was also compared to an LP model of the problem. Álvarez, 2009 [8] discusses the problem in determining the optimal routing and deployment of a fleet of container vessels. A Mixed IP (MIP) model that minimises costs is proposed. A paper discussing research on a pickup and delivery problem with time windows (m-PDPTW) is carried out by Fagerholt and Christiansen, 2011 [9]. The team considers a bulk ship scheduling case with multi-allocation possibilities. The problem was modelled as an IP problem with a set partitioning approach.

2.3 GENERAL LITERATURE

As a part of this literature review, published works themselves being extensive literature reviews regarding maritime operations research, have been studied. The notion was that this would be beneficial in order to attain a more thorough understanding of operations research in this particular area.

Hoff et al., 2010 [10] presents the current state of research regarding fleet composition and routing in the form of an extensive literature review. Also noteworthy is the literature survey by Pantuso et al., 2011 [1]. This paper gives a thorough overview of published works on the Fleet Size and Mix Problem (FSMP) in maritime transportation. On a more general note, Christiansen et al., 2011 [11] presents a chapter on maritime transportation in the book *Handbook in Operations Research and Management Science*. In addition to presenting small example cases on various optimisation problems, the chapter also serves as an introduction to those who are not already familiar with maritime transportation.

3 INTRODUCTION TO RORO SHIPPING

This chapter will serve as an introduction to RoRo shipping for those who are not familiar with this segment, but may also be of interest to those who are more experienced in the area. Readers who want to learn more about RoRo design, cargo handling and -types, should read Levander, 2009 [12].

Wheeled cargo such as automobiles, trucks, trailers or railroad cars offer the advantage of rolling on and off its transportation carrier. Roll-on/Roll-off vessels (RoRo) are specifically designed to carry these types of cargo, as opposed to lo-lo (lift-on/lift-off) vessels, which use either built-in cranes or dock cranes to load and unload cargo. RoRo vessels have strong built-in ramps, often at their stern, which allows for efficient on- and offloading by rolling the cargo on and off the vessel. A ramp located amidships to ease the flow of cargo, is also common for some types of these vessels [13].

RoRo cargo is typically measured in units of lane meters. According to [14], a lane meter is: *"a unit of deck area for "roll on/roll off" ships: (…) A lane is a strip of deck 2 meters wide. A lane meter is an area of deck one lane wide and one meter long, that is, 2 square meters (…)".* This is ultimately a measure to determine the total effective deck area and lane length a carrier offers.

3.1 TYPES OF RORO CARGO

There are many definitions of the various types of cargo, but the three most common groupings are:

- Automobiles or cars
- High and Heavy (HH) cargo
- Non-Containerized Cargo (NCC).

Figure 3.1: Truck with trailer being offloaded off a short-sea RoRo-ship [15].

Automobiles are defined in Car Equivalent Units (CEU) or RT43, where one CEU typically represents the size of a 1966 Toyota Corona RT43 [13]. HH cargo could be heavy construction equipment such as bulldozers, quarry trucks or excavator machines, but also tractors for agriculture, semi-trailer trucks with or without trailers, railway wagons (trains), containerised cargo etc. NCC cargo, on the other hand, could for instance be project cargo such as a large generator for a power plant, but it could just as well be a yacht stowed on the top deck of the vessel.

3.2 RoRo Terminal Equipment

The advantage of most RoRo cargo is that it is not very dependent on the infrastructure at ports. Disregarding the obvious need for suitable docking facilities for the ship, most RoRo cargo is possible to load and discharge without large harbour equipment, such as cranes and trucks.

However, RoRo cargo is not limited to cargo that is able to "roll" by itself. As mentioned in the previous section, types of RoRo cargo include railway wagons, containerised cargo, boats and project cargo. For these types of equipment it is necessary to use roll trailers (cassettes) or jack-up trailers (heavy) to store the cargo on. These trailers are stowed and pushed into position by dedicated terminal tractors, see Figure 3.2. See [12, 16] for descriptions of a selection of RoRo terminal equipment.

Figure 3.2: Terminal tractor discharging a container on a cassette [17].

3.3 RoRo Vessel Types

As the types of cargo differ, so do the types of vessels designed to carry them. The three most common design types are:

- PCC – Pure Car Carriers
- PCTC – Pure Car Truck Carriers
    - LCTC – Long Car Truck Carriers
- RO-RO

Pure Car Carriers are specifically designed to transport automobiles and similar light cargo as efficiently as possible. A PCC may have up to 13 car decks, where 2 of these (at most) are liftable. These types of vessels are usually the smallest of the RoRo designs, and typically have a length of around or less than 200 meters. Cargo capacity for a PCC design ranges from 1 000 – 6 500 RT43 or CEU. [18].

Pure Car Truck Carriers are optimised for transporting a mix of both cars and trucks, and are typically outfitted with more liftable car decks than a PCC. The capacity of a PCTC typically ranges from 5 000 - 7 000 CEU. [18].

Introduced by WWL's 8 000 CEU carrier MV Faust, a new class of RoRo vessels emerged called the Large/Long Car Truck Carriers, or LCTC. These carriers have a capacity to ship more than 7 000 CEU and are more than 200 meters long [13, 18].

RO-RO vessels are designed to carry mostly HH and NCC cargo, with cars as supplementary cargo. A typical RO-RO vessel has a length between 240 to 300 meters. A deep-sea RO-RO vessel is usually fitted with 7-9 decks, where the bottom decks are fixed decks, intended for stowing heavy cargo. Some of the upper decks are often hoistable to ensure cargo stowage flexibility. RO-RO vessels typically have a more full body hull than PCCs and PCTCs, which allows for heavier cargo. [18]. See Figure 3.3 below for an example of the flexibility in deck height for the various RoRo design types.
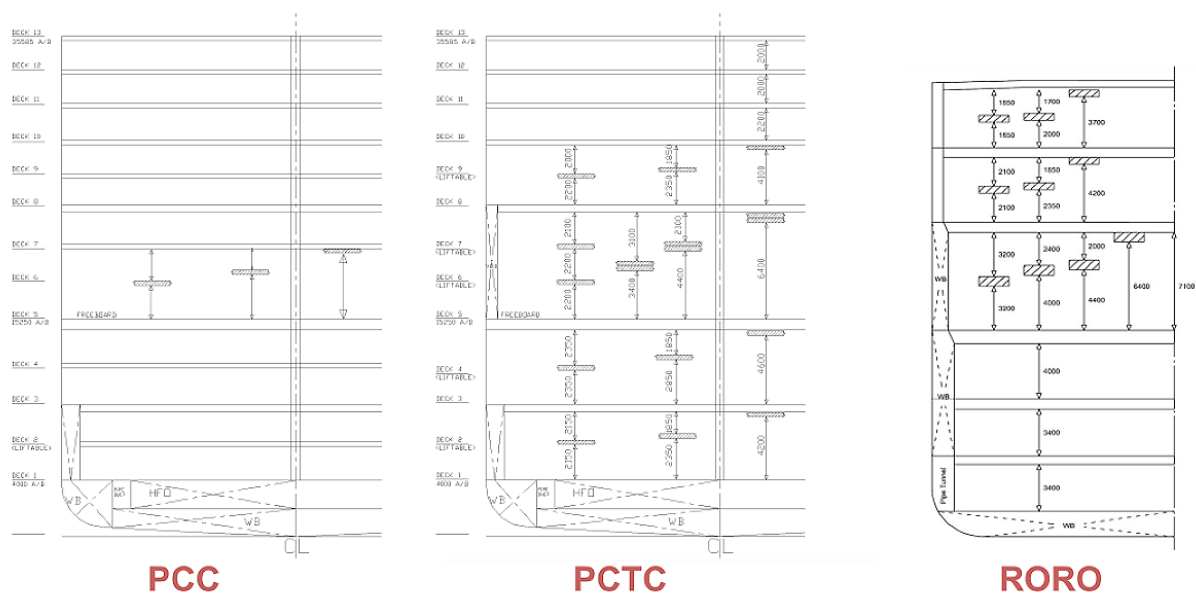
Figure 3.3: RoRo ship type deck height configuration [18].

3.4 RoRo Shipping Business

For companies engaged in RoRo cargo shipping, it is often in their best interest to secure long term contracts with car-, truck and rolling equipment manufacturers. However, the customers could also be construction companies or yacht builders. In the case of the smaller assembly line manufactured cargo unit contracts, it is customary that the contracts give the ship owners the right to transport a percentage of the cargo owner's production quantity, and not a given number. The RoRo shipping industry is part of the liner shipping segment. The shipments are therefore normally scheduled, where the majority of the itineraries are predetermined and regulated by contract.

Examples of some of the dominating companies operating in the RoRo segment are the Tokyo based shipping companies NYK Line and Mitsui O.S.K Lines (MOL), EUKOR Car Carriers, Höegh Autoliners, and the joint venture company WWL between the shipping companies Wallenius Lines and Wilh. Wilhelmsen.

Figure 3.4: Wilh. Wilhelmsen owned RO-RO vessel MV Talisman [19].

A description of the problem discussed in this thesis will be given in the next chapter.

4   PROBLEM DESCRIPTION

The scope of this thesis is to provide decision support for stowage planning on RoRo ships. While commercial stowage planning software (SPS) dedicated to RoRo ships already exists (Autoload [20]), this type of software serves mainly as a visual aid for cargo planners. An advantage of the SPS Autoload module is that the software lets you export the stowage plan to the hydrostatic module in Autoship and automatically check the stability of the laden ship. With both 3D overview and hydrostatic calculations it is most certainly of great help to the planner; however it does not provide any decision support in terms of calculating an optimised stowage plan. Profits are likely to be missed out on due to manual stowage planning, and a mathematical approach to the stowage problem may yield significant increased profits.

While operations research has proven itself applicable in numerous sectors of the industry, it has severe limitations when faced with complex non-linear problems. Cargo stowage problems in maritime transportation depend on a number of factors that are negligible or non-existent in land based transportation, such as buoyancy and ship stability. Especially LP, IP and MIP show weaknesses when faced with these problems. This is largely because common practice for calculating a ship's stability is by using proven non-linear expressions. Arguably, this weakness can be overcome by developing simplified linear expressions. However, the proven non-linear expressions for ship stability should always be used to ensure that a ship in fact has satisfactory stability when it sails.

The next section will be dedicated to explaining the basic concepts of ship stability for readers who are not intimate with this. Be advised that it is assumed the reader is familiar with Archimedes' principle of buoyancy, as it will not be explained here. Readers who are already familiar with the concept of ship stability should skip this part.

4.1   SHIP STABILITY

From a naval architect's perspective, perhaps the most important aspect of a sailing vessel is its stability. With insufficient stability a vessel may not be able to return to its upright position after rolling (heeling to the side), and the result could be that the vessel capsizes. Stability can therefore be explained as a vessel's ability to upright itself after heeling.

In any state, a floating vessel's weight component is working vertically downwards through its global vertical centre of gravity (VCG). The VCG of the vessel depends on the vessel's weight distribution. In the opposite direction and with equal force, the buoyancy force from the water is acting through the vessel's vertical centre of buoyancy (VCB). The VCB is located at the centre of the submerged volume of the vessel. Figure 4.1 shows the location of the VCG and VCB for a simple hull.
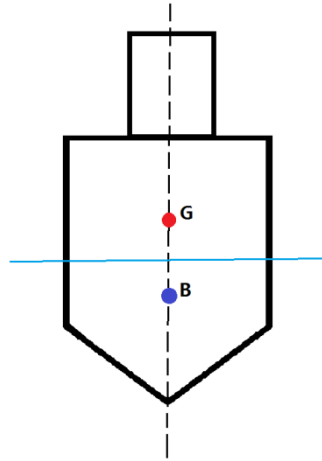
Figure 4.1: Vertical Centre of Gravity and Vertical Centre of Buoyancy.

When a vessel heels, the VCB will shift as a result of a change in the submerged volume. Through this new centre of buoyancy, B', a vertical line crosses the line of the initial VCB. See Figure 4.2. This intersection is called the metacentre, M. The distance GZ is the horizontal distance from the VCG to the new centre of buoyancy, B'. This distance is an indicator of the counteracting forces providing the righting moment that attempts to bring the vessel back to equilibrium. At small angles of heel, the distance between the metacentre and the VCG makes up the initial height of the metacentre. The Metacentric height, GM is a measure of how much and how fast a vessel will heel, or how "stiff" it is. A low GM value indicates a vessel which easily heels, however slowly. A high value represents the opposite and the vessel will heel to each side more rapidly. A negative metacentric height value must be avoided at all costs, as this implies a negative righting moment (GZ). However, a GM value that is too high is also undesirable, especially for cargo ships such as RoRo ships, as the cargo may actually be damaged underway from the high accelerations in roll. Not to mention, it will not be very comfortable for the crew either.
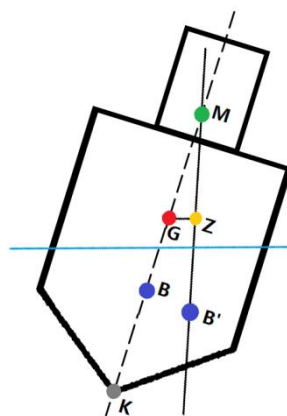
Figure 4.2: Metacentric Height.

For small angles of heel, the transverse GM value of a floating vessel is calculated from the relationship in equation (4.1):

$$GM_T = KB + BM_T - KG \qquad (4.1)$$

KB and KG represent the distance from the keel, K, of the vessel to the VCB and the VCB, respectively. See Figure 4.2. The distance BM_T is the height of the transverse metacentre above the VCB, or the metacentric radius, and can be derived to the expression in equation (4.2) below.

$$BM_T = \frac{I_x}{\nabla} \qquad (4.2)$$

Here, I_x is the second moment (or moment of inertia) of the water-plane area about the centre line. ∇ is the displaced volume of the vessel, i.e. the volume of the submerged part of the hull. For a rectangular water-plane area the second moment about the centre line can be found using equation (4.3):

$$I_x = \frac{LB^3}{12} \qquad (4.3)$$

where,

L = the length of the water-plane, i.e. the length of the vessel

B = the breadth of the water-plane, which incidentally is the beam of the vessel

By inserting (4.3) into (4.2) the expression for BM for a box-shaped vessel now becomes:

$$BM_T = \frac{LB^3}{12\nabla} = \frac{LB^3}{12LBT} = \frac{B^2}{12T} \qquad (4.4)$$

where,

T = the draught of the vessel, i.e. the distance from the keel, K, to the waterline (see Figure 4.2).

More about this in Barrass and Derrett, 2006 [21].

4.2   AN OPERATIONS RESEARCH APPROACH TO THE STOWAGE PROBLEM

Øvstebø et al., 2011 [5] discuss the problem of optimisation of stowage plans on RoRo ships. Their model, which they call the *RoRo ship stowage problem* (RSSP), assumes a predefined route with several port calls for a chosen ship. At each port the ship may pick up one or several cargoes to be shipped to a later port on the route. Some cargoes are mandatory for the route, while some cargoes are optional. The optional cargoes generate additional revenue for the shipper. Typically cargoes are loaded in a supply region and

discharged and delivered to a demand region in the RSSP. Cargoes are defined as packages with a fixed number of units. These can be stowed on separate decks or lanes, but the whole cargo package must be delivered if it is to be shipped to its demand port. The cargo is loaded and discharged by a ramp at the far aft of the vessel. The First In-First Out principle applies for loading and discharging of cargo. If a vehicle from a cargo is to be discharged before another cargo that is located further back in the lane, the latter cargo must be moved in order to discharge the cargo in the front. The model penalizes such undesired behaviour by assigning a fictitious cost for this type of incident.

In their RSSP, Øvstebø et al., 2011 [5] have also included stability constraints. However, as pointed out in the introduction of this chapter, they had to implement these constraints as linear approximations and consequently they did not mirror exact stability calculations. If the exact non-linear calculations were to be implemented in the optimisation model, the model tractability would be reduced significantly. In fact, commercial optimisation software would likely be rendered useless to solve the problem within acceptable time.

The linear approximations that were implemented in the RSSP constrained the ship's transverse (roll) stability, represented by two constraint sets. One constraint set stated that the moment (or torque) from the cargo about the centre line should not exceed a predetermined maximum value, set by the authors. The other constraint set dealt with the VCG of the ship. Similarly, they decided upon a maximum global VCG to ensure the stability of the ship. The moment from the cargo about the centre line was approximated by first dividing the ship's decks into a fixed number of lanes, and then estimating the transverse distance from each lane to the ship's centre line. Longitudinal stability (trim, see Figure 4.3.) constraints were not included in the original RSSP optimisation model. See [5] for the complete model.
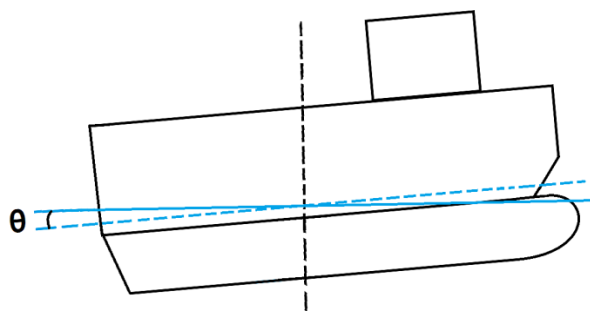
Figure 4.3: Illustration of a vessel trimming by the stern.

It was decided that the most favourable way to discuss optimisation based stowage in RoRo shipping, would be to use the model in Øvstebø et al., 2011 [5] as a foundation. Their article states that constraints for longitudinal stability were not included, but that it could be controlled by a constraint similar to the constraint that ensures the transverse stability in the RSSP. It is, however, of the author's opinion that one cannot control the longitudinal stability simply by adding a constraint, as the model in [5] does

not differentiate between where in the lanes the cargo is stored. Based on this, it is interpreted that the model assumes balanced stowage on both sides of the midship[1] area, regardless of the specific weight of the various cargoes.

The purpose of this thesis will therefore be to expand the model in [5] primarily in terms of controlling longitudinal stability, but aspects such as tighter stability constraints and deck strength capacity will also be explored. Sample data sets will be generated for the expanded RSSP model, and the optimised stowage plans will then be checked with hydrostatic calculations to ensure that the stowage allows the vessel to be stable.

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[1] The transverse division at the middle of the ship

5   MATHEMATICAL FORMULATION

The following chapter will first describe the process of expanding the mathematical model in Øvstebø et al., 2011 [5]. Subsequently, the expanded RSSP model will be presented. The original RSSP model is not included in this thesis. Readers are encouraged to examine the original to better see the changes made in the expanded RSSP model. The last section will discuss the data input used for the optimisation model.

5.1   ADDITIONS TO ØVSTEBØ ET AL., (2011) OPTIMISATION MODEL

In this section the additions that the model in Øvstebø et al., 2011 [5] will be expanded with are explained in detail. First the major modification of controlling longitudinal stability will be discussed. Subsequently, tightening of the existing stability constraints and some variables will be studied, in order to control the stability of the vessel in other areas than transverse moment from the cargo too. Lastly, constraints ensuring sufficient deck strength capacity will be implemented, to prevent heavy cargo being loaded on the weaker decks.

5.1.1   TRIM CONTROL

It was decided at an early stage that it would be beneficial if the model in [5] had trim controlling stability constraints. In their article, Øvstebø et al. state:

> "*Trim can be controlled by a similar constraint, although this was not considered necessary for the model as presented.*"

Here referring to the roll-controlling constraint set in their model. Contrary to this, it is of the author of this thesis' opinion that in order to control the trimming of the vessel, the model needs to be expanded so that each lane is divided into smaller slots. The model would need to distinguish between where the cargo is stowed in the longitudinal direction, and how this affects the longitudinal stability of the vessel. Similar to the parameter set that contains approximated transverse distances of each lane on each deck from the ship's centre line ($\overline{X}_{dl}$ in [5]), a set containing estimated distances of each slot in each lane on each deck from the ship's midship is needed. See Figure 5.1 for a comparison of the deck arrangement of the original with the expanded model.
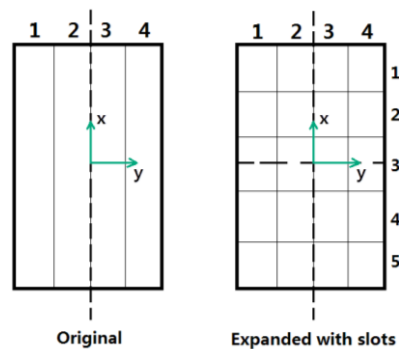
Figure 5.1: Deck arrangements, original versus expanded model.

The illustration shows an example of a deck division of four lanes in the original model, and four lanes with five slots in each lane in the expanded model. The co-ordinate system has its origin at the ship's midship for both the x and y-component in the direction shown in Figure 5.1. The vertical component, z, goes from the ship's bottom deck and upwards. As in the original model, the lanes are numbered from port to starboard side in increasing order. Slots are numbered from the fore part to the aft, in increasing order. The longitudinal distance, $\overline{X}_{ds}$ from the centre of each slot to the ship's midship, is estimated with the expression in equation (5.1). Negative values of $\overline{X}_{ds}$ indicate slots aft of the midship.

$$\overline{X}_{ds} = \frac{L_d}{2} - \left(s - \frac{1}{2} \right) \cdot \frac{L_d}{|\mathcal{S}|} \tag{5.1}$$

Where,

L_d =   the length of deck, d

s =   number of the slot in question

$|\mathcal{S}|$ =   the size of the set of slots

As a comparison, the formula used to calculate the pre-estimated transverse centre of gravity (CoG), $\overline{Y}_{dl}$, in the expanded model, is given in expression (5.2). This formula differs slightly from the one used in [5] as the author of this thesis preferred the co-ordinate system to assign negative values to the CoG of the lanes to the port of the centre line, and positive values to the CoG of the lanes on the starboard side of the vessel.

$$\overline{Y}_{dl} = \left(l - \frac{1}{2} \right) \cdot \frac{W_d}{|\mathcal{L}|} - \frac{W_d}{2} \tag{5.2}$$

Where,

W_d =   the width of deck, d

l =   number of the lane in question

$|\mathcal{L}|$ =   the size of the set of lanes

The number of slots in a set is fixed and equal for all decks. A new variable l_{dls} that can take any positive real[2] value will represent the length of a given slot in a given lane on a given deck. To limit the length of each slot, an upper and lower bound is decided for each deck by the author, and the bounds can be seen in the inequality expression in (5.3).

$$\frac{L_d}{|\mathcal{S}|+1} \leq l_{lds} \leq \frac{L_d}{|\mathcal{S}|-1} \tag{5.3}$$

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[2] Rational number

Now that the slot variable has been defined, cargo can be linked to separate slots. For each lane in the model in [5] two variable sets were defined:

x_{dlpc} = 1   if a cargo c has been loaded in lane l on deck d when the ship sails from port p to p+1, 0 otherwise.

y_{dlpc} integer variable stating how many units from cargo c that is stowed in lane l on deck d when the ship leaves port p.

It was decided to keep these original variables, and create two similar additional variable types for the slots in the expanded model:

u_{dlspc} = 1   if a cargo c has been loaded in slot s in lane l on deck d when the ship sails from port p to p+1, 0 otherwise.

s_{dlspc} integer variable stating how many units from cargo c that is stowed in slot s in lane l on deck d when the ship leaves port p.

The trim constraints are quite similar to the roll constraint in [5], but modified to control trim using the new slot variables. See the full model in the next section for both the trim and roll constraints. In addition to these, some new constraints have been added to ensure the right relationship between the new variables and the original. Where necessary, some of the original constraints have also been expanded to include slots in the constraint sets.

5.1.2 STRICTER STABILITY CONSTRAINTS

The model in [5] limits the distance from the VCG to the laden ship's bottom deck by setting a maximum limit for this distance. However, as mentioned in section 4.1, the VCG of a ship should not be too low either. If the ship's VCG is too low the ship could have a very high metacentric height (GM) and it will be overly stiff, meaning it will roll from side to side very quickly. This could potentially be harmful to both cargo and crew. It was therefore decided that the model should have a limit for the minimum allowable VCG for the laden ship. More on this and the parameter Z^{MIN} in the section about data generation for the optimisation model, later in this chapter.

As previously mentioned, a disadvantage of such an optimisation model is that it demands linearity. This is the reason why the CoG for each lane on each deck needed to be pre-estimated in the original model. Much in the same way as in equation (5.1) the distance was determined on the basis of the average expected lane width, i.e. the width of the deck divided by the number of lanes. However, the model in [5] did not include any lower or upper bounds on the width of each lane (as done for the slot lengths in the expanded model). The result of this is that the width of a lane can take values from 0 to the maximum width of the entire deck. Keeping in mind that the CoG for each lane is

estimated based on an average lane width, the CoG used by the model for each lane can be very shifted compared with the actual stowage plan proposed by the model. In worst case it could mean that the ship is highly unstable, even though all stability constraints in the model are met. Thus, to keep within an acceptable range for the pre-estimated CoG of each lane, it was decided that also the lane width variables, v_{dl} needed lower and upper bounds. This was enforced by the following constraint shown in the inequality expression in (5.4):

$$L_d^L \leq v_{dl} \leq L_d^U \tag{5.4}$$

Where L_d^L and L_d^U represent the lower and upper limit for the allowable lane width for each deck, respectively. Moreover, all slots in a given lane are the same width as the lane they belong to.

The constraint in expression (5.4) tightens the placement of the lanes and reduces the difference between pre-estimated CoG and real CoG after stowage. However, the formula used to calculate these locations (expression (5.2)) assumes that half of the lanes are on each side of the centre line. For the lane division proposed by the model to comply with this, a new constraint is necessary. The equation in (5.5) forces half of the lanes to be located on the port side, and consequently, the other half to the starboard side of the vessel.

$$\sum_{l \in |\mathcal{L}|/2} v_{dl} = W_d / 2 \tag{5.5}$$

Note that this constraint demands that the size of the set of lanes is an even number. The constraint will reduce the stowage flexibility, but will make the calculations of the transverse stability of the laden vessel far less intricate.

Øvstebø et al., 2011 [5] considered hoistable decks in their model. In order to pre-estimate the vertical CoG of the cargo when stowed on a given deck, they used an expression similar to equation (5.6) below:

$$\overline{Z}_d = \frac{D_d^L + D_d^U}{2} \tag{5.6}$$

Where,

$\overline{Z}_d$	=	the approximated vertical distance of deck d from the ship's bottom deck
D_d^L and D_d^U	=	the lower and upper bound for where deck d could be placed, respectively

This equation calculates the average placement of deck d using the lower and upper bounds for deck d, but is in fact used to calculate the CoG of the cargo stowed *on* the deck

in the original RSSP. Consequently it seems that, in the original model, the vertical CoG of the cargo is assumed to lie on the same height as the deck itself. Considering that a RoRo cargo of a certain height would have a local CoG of about half its height (or a little less, considering engine placement), it is likely that the approximation of the parameter set , $\overline{Z}_d$, will be inaccurate. It was therefore the author of this thesis' opinion that it would be beneficial to modify the definition of this parameter set.

As several types of cargoes with varying heights can be stowed on the same deck in the model, a very precise pre-estimate of the vertical CoG on each deck is difficult to define. However, it was decided as a compromise that the available cargo space between the deck in question and the deck above, could serve as an estimate for the vertical CoG of the cargoes stowed there. As all decks in the model by definition are adjustable, the parameter set, $\overline{Z}_d$, was defined as can be seen in equation (5.7):

$$\overline{Z}_d = \frac{D_d^L + D_d^U}{2} + \frac{\left(D_{d+1}^L + D_{d+1}^U\right)/2 - \left(D_d^L + D_d^U\right)/2}{2} \tag{5.7}$$

Where in the new model, $\overline{Z}_d$ is now defined as the approximated centre of gravity of cargo stowed on deck d, measured from the ship's bottom deck.

5.1.3 DECK STRENGTH CAPACITY

An aspect that was not taken into consideration in the model in [5], is the strength characteristics of the various decks on a RoRo ship. In fact, in the original model, all decks seem to have identical qualities in regards to strengths. One might argue that the model in [5] was intended for PCCs, where cargo types usually are quite similar in terms of size and weight. Then the model would not need to differentiate between the strength capacities for the various decks. It was decided that it would be desirable if the expanded model was able to suit all types of RoRo ships, and that the input could be fitted for the vessel type. A parameter set, D_d^C, dictating deck strength capacity for each deck was therefore created, along with a constraint set in the expanded RSSP model, seen in the inequality expression in (5.8) below:

$$x_{dlpc} \cdot \frac{C_c^V}{C_c^L \cdot C_c^W} \leq D_d^C \tag{5.8}$$

Where,

x_{dlpc}	= 1	if a cargo c has been loaded in lane l on deck d when the ship sails from port p to p+1, 0 otherwise.
D_d^C	=	Deck strength capacity of deck d, in $tons / m^2$
C_c^L, C_c^W and C_c^V	=	the length, width and weight of cargo c, respectively

In the next section the expanded RSSP optimisation model will be presented.

5.2   EXPANDED ØVSTEBØ ET AL., 2011 OPTIMISATION MODEL

By now the reader should have a fair idea of which additions have been made to the original model. Nevertheless, the reader is encouraged to cross reference the expanded optimisation model with the original, in order to see the differences between the two. This should, however not be a necessary for understanding the expanded RSSP optimisation model on its own.

Below the expanded RSSP is presented. First sets, parameters and variables are given, followed by the mathematical optimisation model. Lastly, a short description of each constraint set is given.

Indices

d	deck
l	lane
s	slot
c	cargo
p	port

Sets

$\mathcal{C}$	set of all cargoes
$\mathcal{C}_M$	set of all mandatory cargoes
$\mathcal{C}_O$	set of all mandatory cargoes
$\mathcal{D}$	set of all decks. Decks are numbered from the bottom in increasing order
$\mathcal{D}_R$	set of all decks plus the roof of the top deck
$\mathcal{L}$	set of all lanes on each deck. Lanes are numbered from port side to starboard side in increasing order
$\mathcal{S}$	set of all slots in each lane. Slots are numbered in increasing order from the fore to the aft section of the deck in each lane on each deck of the ship
$\mathcal{P}$	set of all ports, except the last port on the route

$\mathcal{P}_c$ set of ports from loading port of cargo c to the port before the unloading port of cargo c, $P_c = \left\{ P_c^L, \ldots, P_c^U - 1 \right\}$

$\mathcal{C}_c$ set of cargoes c' such that $P_{c'}^L < P_c^L < P_{c'}^U < P_c^U$

Parameters

W_d width of deck d

L_d width of deck d

C_c^L length of one vehicle in cargo c

C_c^W width of one vehicle in cargo c

C_c^H height of one vehicle in cargo c

P_c^L loading port of cargo c

P_c^U unloading port of cargo c, $P_c^U > P_c^L$

D_d^L lower bound for where deck d can be placed

D_d^U upper bound for where deck d can be placed

D_d^C Deck strength capacity for deck d, in $tons/m^2$

L_d^L lower bound for the width of a lane on deck d

L_d^U upper bound for the width of a lane on deck d

R_c^F revenue for transporting optional cargo c

N_c number of vehicles in cargo c

C_c^M cost incurred if cargo c needs to be moved

M_r^{MAX} maximum allowable roll moment on the ship from the cargo

M_t^{MAX} maximum allowable trim moment on the ship from the cargo

Z^{MAX} highest allowable centre of gravity of the laden ship, from the bottom deck

Z^{MIN} lowest allowable centre of gravity of the laden ship, from the bottom deck

C_c^V weight of one vehicle from cargo c

W^S lightweight of the ship

Z^S vertical distance from the ship's bottom deck to its centre of gravity when empty

$\overline{Y}_{dl}$ approximated transverse distance of lane l on deck d from the ship's centre of gravity, $\overline{Y}_{dl} = \left(l - \dfrac{1}{2} \right) \cdot \dfrac{W_d}{|\mathcal{L}|} - \dfrac{W_d}{2}$

$\overline{X}_{ds}$ approximated longitudinal distance of slot s in lane l on deck d from the ship's centre of gravity, $\overline{X}_{ds} = \dfrac{L_d}{2} - \left(s - \dfrac{1}{2} \right) \cdot \dfrac{L_d}{|\mathcal{S}|}$

$\overline{Z}_d$ approximated centre of gravity of cargo stowed on deck d measured from

the ships's bottom deck, $\overline{Z}_d = \dfrac{D_d^L + D_d^U}{2} + \dfrac{\left(D_{d+1}^L + D_{d+1}^U\right)/2 - \left(D_d^L + D_d^U\right)/2}{2}$

M_d Big-M for deck d, equal to the upper bound for l_{dls} for each deck

Decision variables

h_d height of deck d from the bottom deck

v_{dl} width of lane l on deck d

l_{dls} length of slot s in lane l on deck d

$w_{dlcc'}$ $\begin{cases} 1 & \text{if cargo } c' \text{ is loaded in front of cargo } c \text{ in lane } l \text{ on deck } d \text{ in port } P_{c'}^L \\ 0 & \text{otherwise} \end{cases}$

x_{dlpc} $\begin{cases} 1 & \text{if lane } l \text{ on deck } d \text{ is used from port } p \text{ to } p+1 \text{ by cargo } c \\ 0 & 0 \text{ otherwise} \end{cases}$

u_{dlspc} $\begin{cases} 1 & \text{if slot } s \text{ in lane } l \text{ on deck } d \text{ is used from port } p \text{ to } p+1 \text{ by cargo } c \\ 0 & \text{otherwise} \end{cases}$

y_{dlpc} number of vehicles from cargo c in lane l on deck d

when the ship leaves port p

s_{dlspc} number of vehicles from cargo c in slot s in lane l on deck d

when the ship leaves port p

z_c $\begin{cases} 1 & \text{if optional cargo } c \text{ is taken} \\ 0 & \text{otherwise} \end{cases}$

Objective function

$$\max \sum_{c \in \mathcal{C}_O} R_c^F z_c - \sum_{c \in \mathcal{C}} \sum_{c' \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^M w_{dlcc'} \tag{5.9}$$

Constraints

$$C_c^L \cdot y_{dlpc} - L_d \cdot x_{dlpc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.10}$$

$$C_c^L \cdot s_{dlspc} - M_d \cdot u_{dlpc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.11}$$

$$u_{dlspc} - x_{dlpc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.12}$$

$$x_{dlpc} - y_{dlpc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.13}$$

$$u_{dlspc} - s_{dlspc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.14}$$

$$C_c^H \cdot u_{dlspc} - \left(h_{d+1} - h_d\right) \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \tag{5.15}$$

$$C_c^W \cdot u_{dlspc} - v_{dl} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad (5.16)$$

$$y_{dl,p+1,c} - y_{dlpc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \setminus \{P_c^U - 1\}, |\mathcal{P}_c| \geq 2 \qquad (5.17)$$

$$s_{dls,p+1,c} - s_{dlspc} \leq 0, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \setminus \{P_c^U - 1\}, |\mathcal{P}_c| \geq 2 \qquad (5.18)$$

$$\sum_{l \in \mathcal{L}} v_{dl} = W_d, \qquad\qquad d \in \mathcal{D} \qquad (5.19)$$

$$\sum_{s \in \mathcal{S}} l_{dls} = L_d, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L} \qquad (5.20)$$

$$\sum_{s \in \mathcal{S}} s_{dlspc} = y_{dlspc}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad (5.21)$$

$$\sum_{l \in \mathcal{L}} \sum_{d \in \mathcal{D}} y_{dlpc} = N_c, \qquad\qquad c \in \mathcal{C}_M, p \in \mathcal{P}_c \qquad (5.22)$$

$$\sum_{l \in \mathcal{L}} \sum_{d \in \mathcal{D}} y_{dlpc} = N_c z_c, \qquad\qquad c \in \mathcal{C}_O, p \in \mathcal{P}_c \qquad (5.23)$$

$$\sum_{l \in |\mathcal{L}|/2} v_{dl} = W_d \Big/ 2, \qquad\qquad d \in \mathcal{D} \qquad (5.24)$$

$$\sum_{c \in \mathcal{C}} C_c^L \cdot y_{dlpc} \leq L_d, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, p \in \mathcal{P} \qquad (5.25)$$

$$\sum_{c \in \mathcal{C}} C_c^L \cdot s_{dlspc} \leq l_{dls}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, p \in \mathcal{P} \qquad (5.26)$$

$$x_{dlpc} \cdot \frac{C_c^V}{C_c^L \cdot C_c^W} \leq D_d^C, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P} \qquad (5.27)$$

$$-M_r^{MAX} \leq \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^V \cdot y_{dlpc} \cdot \overline{Y}_{dl} \leq M_r^{MAX}, \qquad\qquad p \in \mathcal{P} \qquad (5.28)$$

$$-M_t^{MAX} \leq \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} \sum_{s \in \mathcal{S}} C_c^V \cdot s_{dlspc} \cdot \overline{X}_{ds} \leq M_t^{MAX}, \qquad\qquad p \in \mathcal{P} \qquad (5.29)$$

$$W^S Z^S + \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^V \cdot y_{dlpc} \cdot \overline{Z}_d \leq \left(W^S + \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^V \cdot y_{dlpc} \right) Z^{MAX}, \qquad\qquad p \in \mathcal{P} \qquad (5.30)$$

$$W^S Z^S + \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^V \cdot y_{dlpc} \cdot \overline{Z}_d \geq \left(W^S + \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} C_c^V \cdot y_{dlpc} \right) Z^{MIN}, \qquad\qquad p \in \mathcal{P} \qquad (5.31)$$

$$x_{dl,P_c^L,c} + x_{dl,P_c^L,c'} \leq 1 + w_{dlcc'}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, c' \in \mathcal{C}_c \qquad (5.32)$$

$$D_d^L \leq h_d \leq D_d^U, \qquad\qquad d \in \mathcal{D}^R \qquad (5.33)$$

$$L_d^L \leq v_{dl} \leq L_d^U, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L} \qquad (5.34)$$

$$\frac{L_d}{|\mathcal{S}| + 1} \leq l_{lds} \leq \frac{L_d}{|\mathcal{S}| - 1}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S} \qquad (5.35)$$

$$w_{dlcc'} \in \{0,1\}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, c \in \mathcal{C}_c \qquad (5.36)$$

$$x_{dlpc} \in \{0,1\}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad (5.37)$$

$$u_{dlspc} \in \{0,1\}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad (5.38)$$

$$z_c \in \{0,1\}, \qquad\qquad c \in \mathcal{C}_O \qquad (5.39)$$

$$y_{dlpc} \geq 0 \text{ and integer}, \qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad (5.40)$$

$s_{dlspc} \geq 0$ and integer, $\qquad\qquad\qquad d \in \mathcal{D}, l \in \mathcal{L}, s \in \mathcal{S}, c \in \mathcal{C}, p \in \mathcal{P}_c \qquad$ (5.41)

As some of the constraints are quite similar to the constraints of the original model in [5], the original definition of some of these constraints have been used, where applicable.

The model's objective function (5.9) maximises the profit from the optional cargoes by maximising the revenue from the optional cargoes subtracted the penalty cost caused by having to move cargoes. Constraints (5.10) and (5.11) link the binary indicator variables x_{dlpc} and u_{dlspc} to the integer variables y_{dlpc} and s_{dlspc}. The constraints also provide a bound for the number of vehicles of a given cargo that is possible to carry in a lane (5.10) and a slot (5.11). Constraints (5.12) link the binary lane variables x_{dlpc} to the binary slot variables u_{dlspc}, i.e. if $u_{dlspc} = 1$ because slot s in lane l on deck d is used by cargo c from port p to $p+1$, then x_{dlpc} must be 1 for the same lane l on deck d by cargo c from port p to port $p+1$. Constraints (5.13) and (5.14) ensure that the binary variables x_{dlpc} and u_{dlspc} do not take any value if the integer variables y_{dlpc} and s_{dlspc} are 0, respectively. Constraints (5.15) ensure that there is sufficient vertical deck space where the cargoes are stowed. Adequate width of a slot is enforced by constraints (5.16). The model does not allow stowage of several cargoes side-by side in the same slot and lane. Constraints (5.18) and (5.17) make sure that once a cargo has been stowed, it remains unmoved until it is discharged. If the cargo must be moved due to discharging of other cargoes, this does not affect the integer variables in the model. The partitioning of lanes and slots are constrained by (5.19) and (5.20), respectively. Constraints (5.21) govern that the number of cargoes, s_{dlspc}, from cargo c summed over all slots in lane l is exactly the same as the value of y_{dlpc} in lane l, for all decks and ports in the set $\mathcal{P}_c$. Constraints (5.22) make sure that all mandatory cargoes in cargo c are stowed on the ship from port p to $p+1$. Similarly, constraints (5.23) ensure that *if* an optional cargo c is carried, then all cargoes from this cargo are carried. As the pre-estimated CoGs for the lanes assume that half of the lanes are located on the vessel's port side, and half of the lanes are located on the starboard side, it seems sensible to make sure that the lanes proposed by the RSSP will lie in the proximity of these estimates. Constraints (5.24) make sure of this for all decks. Constraints (5.25) and (5.26) ensure that the length of a lane or a slot is not violated by the cargoes stowed in that lane or slot, respectively. Constraints (5.27) secures that the weight per square meter of cargo c stowed on deck d does not exceed the deck capacity of deck d. Constraints (5.28) impose that the moment (torque) from the cargo on the ship is kept within the allowable limit, to avoid roll. The parameter set $\overline{Y}_{dl}$ represents approximated transverse distances of a lane to the centre of the ship, as mentioned in section 5.1.1. Here negative values indicate a lane on the port side of the vessel, and starboard side for positive values. To achieve sufficient stability, constraints (5.28) ensure that the sum of all moments is kept within the range of $\left\{ -M_r^{MAX}, M_r^{MAX} \right\}$.

Similarly, trim is controlled by constraints (5.29), where the parameter set $\overline{X}_{ds}$ represents approximated longitudinal distances of a slot to the midship. Negative values for slots located at the aft of the midship, positive for slots ahead of midship. The effect of the moment from cargo must at all times keep within the range of $\left\{-M_t^{MAX}, M_t^{MAX}\right\}$.

Constraints (5.30) make sure that the maximum allowable vertical distance Z^{MAX} from the ship's bottom deck to the ship's centre of gravity when loaded, is not exceeded. Constraints (5.31) work in a similar way, but as a limit to the *minimum* distance from the ship's bottom deck to the laden centre of gravity. The limits M_r^{MAX}, M_t^{MAX}, and Z^{MAX} and Z^{MIN}, will all be discussed in the next section.

When cargoes from cargo *c* are loaded in front of cargoes from cargo *c'*, and cargo *c'* is discharged before cargo *c*, there is an inconvenience as cargoes from cargo *c* must be moved out of the way. Constraints (5.32) make sure that a corresponding penalty is accounted for in the objective function. Upper and lower bounds on deck height, lane width and slot lengths are enforced by constraints (5.33), (5.34) and (5.35), respectively. These bounds will be discussed in the next section. Constraints (5.36), (5.37), (5.38) and (5.39) impose binary values for the variables $w_{dlcc'}$, x_{dlpc}, u_{dlspc} and z_c, respectively. Lastly, constraints (5.40) and (5.41) impose non-negativity and integrality on the number of vehicles stowed in each lane and slot, respectively.

5.3 DATA INPUT GENERATION

It was decided at an early stage that the RoRo ship to be used in the computational study, should be a RO-RO ship. The reason for this was to have the model demonstrate its flexibility with regards to handling various cargo types and deck arrangements. Wilh. Wilhelmsen owned RO-RO ship MV Talisman was chosen as the reference ship. A picture of the vessel can be seen in Figure 3.4. MV Talisman and its sister ships MV Tamesis, MV Talisman and MV Tarago, together constitute the Mark IV generation of Wilh. Wilhelmsen's RO-RO carriers. The first ship of the Mark IV set sail in the year 2000. While a new generation of Mark V RO-RO carriers was launched in 2011, a Mark IV vessel was chosen as reference ship for the model. This was mostly because the information available on the Mk. IV design on the company's website was more relevant for the model than that of the Mk. V.

5.3.1 SHIP CHARACTERISTICS

A fair share of the characteristics of the RO-RO vessel MV Talisman have been found on the web page of the shipping company Wilh. Wilhelmsen [22], while other data are estimated. Additionally, some data have been determined by comparing drawings and ship characteristics of another Pure Car Carrier (PCC) reference ship. The data were then scaled to fit the MV Talisman. The drawings are confidential and were given to the author of this thesis as a part of a course taken at Delft University of Technology, spring 2011. The drawings have been edited to make the ship untraceable and may be found in

the Digital Appendix and a low resolution version in Appendix A. The data in Table 5.1 was collected from [22].

Length Over All [m]:	240.6
Beam [m]:	32.26
Depth to Upperdeck [m]:	32.45
Draught, Design/Max [m]:	11.00/11.75
Deadweight at Maximum Draught [MT3]:	38,486
Stern Ramp Width [23] [m]:	12
Stern Ramp Capacity [MT]:	320
Number of Decks:	8 (of which 4 are hoistable)
Capacity Deck Area [m²]:	46,350

Table 5.1: MV Talisman Ship Data

The MV Talisman's deadweight capacity is only given for its maximum draught in Table 5.1. Therefore, the max draught of 11.75 [m] has been used in the calculations that follow.

5.3.1.1 Lightweight and Hydrostatics

The ship's lightweight, *LWT,* can be calculated by the expression in equation (5.42):

$$LWT = \Delta - DWT \tag{5.42}$$

Here, Δ is the ship's displacement in MT, i.e. the weight of the water it displaces. *DWT* is the ship's deadweight capacity, as given in Table 5.1. The ship's deadweight and its components will be discussed at a later stage in this section.

To calculate the displacement of the vessel, a few parameters are needed, namely the ship's block coefficient, C_b and the density of sea water, ρ. The block coefficient was estimated by the author of this thesis by evaluating the block coefficient of the reference PCC (see Digital Appendix) and adding a small margin as the MV Talisman is a RO-RO vessel with a more full bodied hull. The new parameters can be seen in Table 5.2:

Block Coefficient, C_b [-]	0.65
Density of Sea Water, ρ [MT/m³]	1.025

Table 5.2: Block Coefficient and Density of Sea Water

Now the displacement of the vessel can be calculated using the expression in equation (5.43):

$$\Delta = L_{WL}BT \cdot C_b \cdot \rho \tag{5.43}$$

Where L_{WL} is the length of the vessel in the waterline, estimated to a factor of 0.97 of the vessel's length of all (LOA) (see Table 5.1). When inserting (5.43) into (5.42), the

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[3] Metric Tonne

estimated lightweight of the vessel if found. The calculations can be found in the Digital Appendix.

The deadweight of a ship can be divided into three main parts: payload, ballast water, and lastly, bunker and crew. The payload is the weight of the cargo on the ship. Ballast water is sea water stored in dedicated tanks in the hull, usually near the bottom of the vessel. These tanks are used to lower the VCG of the vessel, increase the draught, and to achieve an angle of zero heel and pitch[4]. Bunker represent the weight of fuel, lube oil, fresh water, stores, bilge tanks for sewage, while crew is simply the weight of the crew on board the vessel. The bunker and crew loads were estimated to account for a factor of 0.2 of the total deadweight.

In the input file, the parameter W^S consists of the vessel's lightweight, and the bunker and crew loads. The vessel's VCG without any payload was estimated by the author to be 17 [m] from the keel.

The parameters M_r^{MAX} and M_t^{MAX} in the optimisation model are dependent on the ballast water capacity of the vessel. The capacity was estimated using drawings of the tank arrangement on the reference PCC(see Appendix A). By summing up the ballast tank capacities on either side of this vessel, the ballast capacities available to reduce roll for the reference PCC were found. The same was done for the tanks aft of the midship and fore of the midship, which are used to reduce trim. The reference PCC is a smaller vessel than the MV Talisman; however, by scaling these tank capacities up with the relationship in equation (5.44), an estimate for the tank capacities of the MV Talisman could be found. The total capacity of the tanks also tells us how much the vessel can reduce its draught and VCG by utilising the maximum capacity of its ballast water tanks.

$$\eta = \frac{L_{Tamerlane}}{L_{Hyundai\ 105}} \tag{5.44}$$

It is assumed that a full utilisation of, for instance, all port side ballast tanks implies a horizontal CoG for the ballast of half the length of the vessel's port side. The same assumption applies for starboard, aft and fore ballast tanks. By multiplying the horizontal CoG with the maximum capacity of the belonging ballast tanks, i.e. on the same side or end of the vessel, an estimate for the maximum moment the ballast tanks on each side and end of the vessel can counteract is generated. The optimisation model demands symmetry on both sides and ends of the vessel. Therefore, the side and end that has the smallest ballast capacity dictate the value of the parameters M_r^{MAX} and M_t^{MAX}, respectively. The limits were then significantly lowered, to prevent the vessel from being dependent on full ballast utilisation. The values for M_r^{MAX} and M_t^{MAX} were set to 10 000 [MT*m] and 100 000 [MT*m], respectively. See the Digital Appendix for the spreadsheet calculations.

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[4] The trim angle of a vessel

A RO-RO vessel needs to avoid too high accelerations on the cargo when sailing, and the accelerations are dependent on the natural period of roll for the vessel. The natural roll period can be defined as the time it takes for a vessel to roll through a complete cycle from its equilibrium position, to its port side, then over to its starboard side and finally, back to equilibrium. A low transverse GM value means that the vessel will heel slowly, with low accelerations. This in turn means a long natural roll period. A rolling period of over 10 seconds can be considered a long rolling period. Papanikolaou et al., 1997 [24] use a formula for the natural period of roll, T_R, and the expression can be seen in equation(5.45).

$$T_R = 2\pi \sqrt{\frac{I_x}{\Delta \cdot g \cdot GM_T}} \tag{5.45}$$

Where g is the gravitational constant with a value of 9.81 m/s^2.

Note that this formula merely gives a theoretical estimate for the natural roll period. The exact value is best determined through simulations or preferably observations of the actual event during e.g. sea trials.

DNV (Det Norske Veritas) classification rules [25] state that the initial transverse GM of all commercial cargo ships must be higher than 0.15 [m]. This was used to determine Z^{MAX} by solving equation (4.1) for KG (the VCG) as can be seen in equation (5.46).

$$KG = KB + BM_T - GM_T \tag{5.46}$$

KB, or the VCB, was estimated with a factor of 0.6 of the ship's draught, T. The results can be seen in Table 5.3. For the full calculations, see the Digital Appendix.

KB [m]	BM [m]	KG [m]	GM [m]	T_R [s]
7.05	11.38	18.28	0.15	17.3

Table 5.3: Calculations for Maximum KG

As the Z^{MAX} parameter is defined as the height of the VCG measured from bottom deck, the height of the bottom deck from the keel of the vessel must be subtracted before it is implemented in the model. The location of the bottom deck was estimated to be a distance of 3 [m] from the keel and up.

As mentioned earlier, the model would benefit from also being limited by a minimum VCG, the parameter Z^{MIN}. This prevents the optimisation model from making the laden vessel *too* stable. An expression in the maritime segment is "too much stability". This may sound a bit off, but as mentioned earlier, a vessel with a too high GM value will be overly stiff and may cause damage to the cargo and, in worst case, crew.

By calculating the GM and T_R for a range of values for the vessel's VCG, the ideal minimum VCG for the model could be found. It was decided by the author of the thesis

that T_R should not be shorter than 7.5 seconds. By following this limit, the maximum allowable transverse GM of the vessel could be found by solving equation (5.45) for GM_T. The modified expression can be seen in equation (5.47).

$$GM_T = \frac{4\pi^2 I_x}{T_R^2 \Delta g}$$

(5.47)

Consequently the corresponding VCG (KG) could be found easily with equation (5.46). The results can be seen in Table 5.4. The full calculations are found in the spreadsheet in the Digital Appendix.

KB [m]	BM [m]	KG [m]	GM [m]	T_R [s]
7.05	11.38	17.64	0.79	7.5

Table 5.4: Calculations for Minimum KG

As for the Z^{MAX} parameter, the value for Z^{MIN} is defined from the ship's bottom deck, and thus the height from the keel to the bottom deck was subtracted when used in the model input.

5.3.1.2 Deck Arrangement

The deck arrangement has been defined largely based on the findings in [22]. Here the deck area for decks 1, 2, 3, 4, 5 and 7 are given. From Table 5.1 we can see that the MV Talisman has eight decks, of these are four hoistable. The total deck area capacity is also found in the same table. As the model does not allow stowage on the weather deck of the ship, some deck area must be discarded. Deciding upon the deck area dimensions has been an iterative process, where the objective was to obtain a deck area capacity of about 40,000 [m²].

Each deck is divided into a fixed number of lanes, which in turn is divided into a fixed number of slots (see Figure 5.1). The number of lanes on a deck, and slots in a lane, is the same for all decks. In order for the optimisation model to be able to approximate the total VCG of the stowage plan, the CoG of these lanes and slots needed to be pre-estimated. The formulae used to find these co-ordinates were listed earlier in the full expanded optimisation model, but for the sake of the reader, the expression for lane CoG will be listed here as well. The expression used to pre-estimate the transverse CoG, $\overline{Y}_{dl}$, of each lane on each deck can be seen in equation (5.48).

$$\overline{Y}_{dl} = \left(l - \frac{1}{2}\right) \cdot \frac{W_d}{|\mathcal{L}|} - \frac{W_d}{2}$$

(5.48)

Where,

W_d =   the width of deck, d

l = number of the lane in question

$|\mathcal{L}|$ = the size of the set of lanes

Lanes are numbered from port side to starboard side, with positive co-ordinates for lanes located on the starboard side of the midship. For the computational study the decks were divided into a set of 8 lanes each. Again, note that constraints (5.24) dictate the division of lanes on a deck to be an even number.

The CoG of the slots was determined in a similar way, and the formula was described in equation (5.1), earlier in this chapter. Five slots make up a lane in the computational study.

A spreadsheet was developed to calculate the horizontal CoG for all lanes and slots on each deck and is found in the <u>Digital Appendix</u>. The number of decks, slots per lane, or lanes per deck can be altered with ease in the input, but usually requires some updates to the parameters that are dependent on these sets.

In the expanded model, lower and upper bounds for slot, and correspondingly, lane width has been defined. These bounds were decided on the principle that the lower decks were intended for the heavy cargoes, which are often quite wide.

As previously mentioned, four of the decks on the MV Talisman are hoistable. Øvstebø et al., 2011 [5] accounted for this by implementing the deck height variable, and by providing lower and upper bounds on the vertical placement of the decks. For this thesis, these bounds were determined by iteration; the principle being the same as for the definition of bounds for width of slots and lanes: that the lower decks are intended for heavier cargo, which is often higher. From Table 5.1 we see that that the depth to the upper deck is nearly 32.5 [m]. The thickness of the upper deck structure is further assumed to be roughly 1 [m]. Taking into account that the bottom deck is located 3 [m] from the bottom, we have the vertical extremities of the entire cargo space for the vessel in the model.

For the deck bounds a margin of 0.25 [m] was added to represent deck thickness of each deck, i.e. the distance from the bottom of the deck structure to the top, where cargo is stowed. Another margin of 0.25 [m] was added to represent a height clearance requirement between the roof and the cargo stowed on deck. This extra margin of totally 0.5 [m] was then added for the height of each specific cargo in the input. This will be discussed further later in this sub-section.

It was also desirable to assign varying deck strength capacities to the decks, depending on the type of deck. From [22], the capacities for decks 1, 2, 3, 4, 5 and 7 were found. For decks 6 and 8, the maximum uniform loads in MT/m^2 have been estimated on the assumption that they are meant for lighter cargo types, such as cars. The deck dimensions and deck strength capacities used for the various decks in the optimisation model can be seen in Table 5.5.

	Length [m]	Width [m]	Deck Area [m²]	Capacity [MT/m²]
Deck 1	140	22	3080	10
Deck 2	180	22	3960	3
Deck 3	200	22	4400	3
Deck 4	200	25	5000	4
Deck 5	200	28	5600	3
Deck 6	220	28	6160	0.25
Deck 7	225	30	6750	1
Deck 8	180	30	5400	0.25

Table 5.5: Deck Dimensions and Capacities

Summing up the available area of each deck gives a total of 40550 [m²]. It is assumed that while the decks may have different capacities, the ramps from deck to deck always have sufficient capacity to move the cargo to the preferred deck.

5.3.2 *CARGO SPECIFICATIONS*

A RO-RO vessel can ship a vast assortment of cargoes. In this subsection a handful of cargo types have been chosen for the input data. However, the dimension parameters of these can be changed easily in the input file without necessarily having to alter other parameters.

5.3.2.1 Cargo Types

5 cargo types will be listed here, but the model is not limited to these specific cargoes, or this number of different cargoes. A clearance margin of 0.10 [m] on each side, front and back of the cargo unit has been added to the width and length for all cargoes in the input. This totals to an extra 0.2 [m] to the width and length of the cargoes, unless otherwise stated. Some dimensions and weights of the various cargo types have been rounded up or down. Naturally, cargoes can be switched from being mandatory to optional and vice versa, but the set of mandatory cargoes *must* be listed *first* in the input data matrix for this modification. The quantity of all cargo types can be changed easily in the model input file.

Cargo 1

This is a contract to ship a number of FEU[5] containers, of the type 1 AA, which according to Levander, 2009 [12], is the most common type. These containers need to be stowed on cassettes when shipped with the vessel. Figure 5.2 shows a Rolux Cassette that can be used to stow containers on RO-RO ships. The cassettes will be loaded onto the vessel using terminal tractors (see Figure 3.2). Cassettes are larger than the FEU containers, and thus the length and width of the cassettes are used in the input of the optimisation model. The height of the cassettes has been added to the height of the FEU, and after adding the clearance height requirement as well as deck thickness, the input height is defined. The dimensions and weight of FEU containers and cassettes have been

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[5] Forty foot Equivalent Unit

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extracted from [12] and the final input values can be seen in Table 5.6. The load of the cargo inside the containers has been chosen as the average net cargo capacity given in [12].
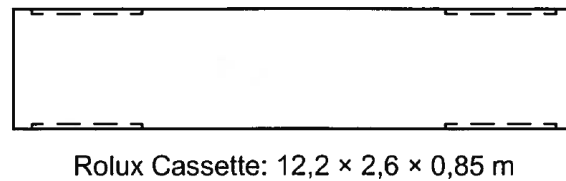
Figure 5.2: Cassette Dimensions [12]

Cargo 2

The contents of this cargo are semi-trailers *without* trucks. These will be loaded onto the vessel, and discharged, using terminal tractors. The trailers' dimensions have been found in [12], and the dimensions and weight used for the input can be seen in Table 5.6. See Figure 5.3 for a sketch of the semi-trailer unit.
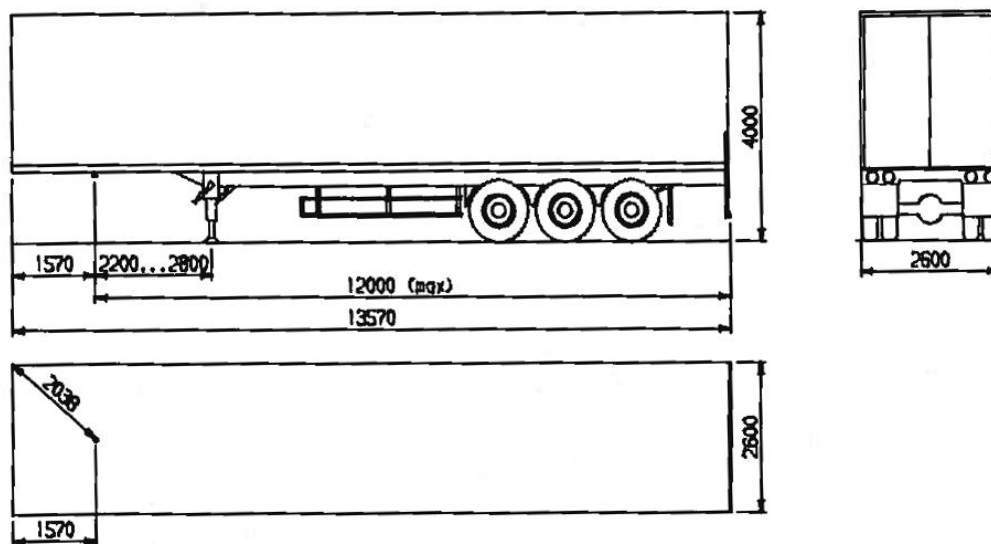
Figure 5.3: Semi-Trailer Dimensions [12]

Cargo 3

This cargo will consist of automobiles. All vehicles in this cargo are of the type Toyota Avensis 2007 [26] (see Figure 5.4), and the dimensions and kerb weight[6] of these are given in Table 5.6

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[6] Weight of the vehicle including fuel and oil, excluding driver and expected payload.
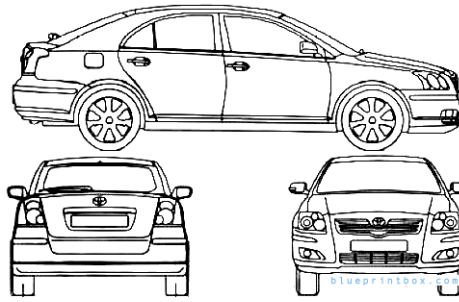
Figure 5.4: Toyota Avensis 2007 [27]

Cargo 4

This is a contract for shipping heavy Caterpillar off-highway Trucks. The dimensions and weights are taken from [28] and the truck can be seen in Figure 5.5. See Table 5.6 for dimensions used in the input.
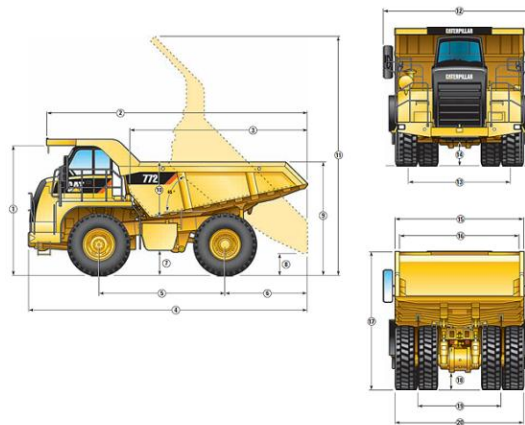
Figure 5.5: Cat Off-Highway Truck [28]

Cargo 5

The fifth cargo consists of a number of MAN marine diesel engines (see Figure 5.6) for new ships. The dimensions and weight were found in [29]. The engines are stored on roll trailers [16], which add about 0.85 [m] to the stowage height. The roll trailers are about 2.5 [m] wide and 20 [m] long. An extra 0.2 [m] was added to the safety margin on the sides of the cargo. Table 5.6 shows the final input values for the engine used in the optimisation model.
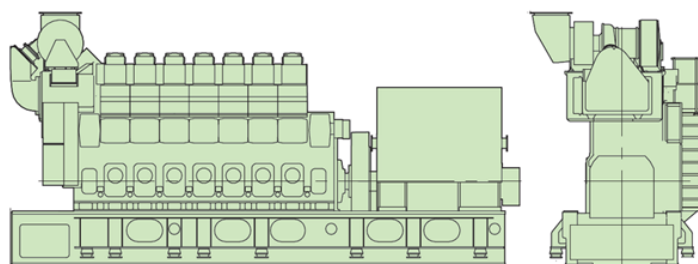
Figure 5.6: MAN Marine Diesel Engine [29]

	Type	Length [m]	Width [m]	Height [m]	Weight [MT]	Spec. Weight
Cargo 1	Container	12.40	2.8	3.95	23.00	0.66
Cargo 2	Semi-trailer	13.75	2.8	4.50	15.00	0.39
Cargo 3	Toyota	4.85	2.0	2.00	1.35	0.14
Cargo 4	Cat Truck	9.00	4.2	4.50	35.00	0.93
Cargo 5	Engine	20.40	3.0	6.00	78.00	1.27

Table 5.6: Input for Cargo Dimensions and Weights

5.3.2.2 Cargo Itinerary

The respective ports of loading and unloading have been chosen largely at random, while following the rule that the route consists of a set of supply ports and a set of demand ports. The first ports act as supply ports where the ship loads cargo, while the last ports are demand ports where the cargo is discharged. The port of loading and unloading for each cargo can be varied in the input data, and before the running the analysis, a crude estimate of the feasibility of the combined contracts is performed using a spreadsheet (See the Digital Appendix) for the capacity of the vessel in terms of lane length, deck area and payload. A penalty is added to cargoes that must be moved because they are stowed in such a way that they block the path of another cargo that is being discharged. For realistic purposes, this penalty is considerably higher for cargo that is not wheeled than it is for rolling cargo. The penalties have been chosen by the author of the thesis and do not represent realistic labour- or time costs, as the model does not allow progressive penalty values, in terms of how many units in a cargo that must be moved.

In the computational study, a set of 6 ports are chosen for the analyses, but the model is not limited to this number of ports.

5.3.2.3 Type of Cargo Contract

The contracts are of two types: Mandatory and optional. The mandatory cargoes bring no extra revenue to the shipper in the optimisation model, as these are considered long-term contracts. The optional cargoes are naturally optional to carry, but generates extra revenue to the shipper. The values for the revenue of the various optional cargoes have been decided by the author of the thesis, and do not represent real market values. The number of mandatory and optional cargoes in the computational study has been chosen to be two and three, respectively, where cargo 1 and cargo 2 are mandatory cargoes.

5.3.2.4 Vertical Centre of Gravity for Cargo Stowed on Decks

While the height of the cargoes varies, the model needs an approximated CoG for the cargo that is stowed on each deck. The procedure for estimating these locations, $\overline{Z}_d$ has been explained earlier in this chapter (see equation (5.7)), and the full calculations can be seen in the spreadsheet in the Digital Appendix.

6 COMPUTATIONAL STUDY

This chapter consists of two parts. Section 6.1 will inform the reader about which software and hardware has been used to perform the computational study. Lastly, section 6.2 will present the results of a selection of the computational study. Following in this section is a discussion of the results from the analyses.

The scope has been to compare the original RSSP model by Øvstebø et al., 2011 [5] with the expanded RSSP model from chapter 5. The comparison will be based on solution quality of the stowage proposed by the models. The main focus of the stowage assessment has been on capacity utilisation and the stability of the laden vessel with the proposed stowage plan.

6.1 COMPUTATIONAL IMPLEMENTATION

To perform the computational study, the mathematical model was implemented in the programming language *Mosel* using Xpress IVE by FICO™ and solved with the optimisation software Xpress Optimizer. For the data sets, spreadsheets in Microsoft Excel were developed for most of the calculations. The Mosel code can be found in Appendix B and the Digital Appendix. In the latter, the spreadsheet calculations and resulting data sets are also found. Explanatory notes are added in the Mosel code to aid the reader when interpreting the code.

Both the original RSSP model in [5] and the expanded RSSP model were implemented in Xpress Mosel Version 3.2.3, using Xpress-IVE Version 1.22.04 64 bit with Xpress Optimizer Version 22.01.09. The models were run on a Windows 64 bit laptop computer with an Intel® Core™ i5 CPU M 460 @ 2.53GHz processor and installed memory of 4 GB RAM.

6.2 COMPUTATIONAL STUDY

While all parameters and sets can be altered, the computational study uses a predetermined vessel configuration, with a fixed number of mandatory and optional cargoes, with predefined ports for loading and discharging of the various cargoes. The size of the expanded model can be seen in Table 6.1.

Mandatory Cargoes	Optional Cargoes	Ports	Decks	Lanes	Slots
2	3	6	9	8	5

Table 6.1: Size of Model in Computational Study

For the original RSSP model analyses, the values in Table 6.2 will be identical, except the set of slots which is not defined. The number of decks in Table 6.1 includes the top weather deck. Stowage on this deck is not allowed in the models, but is necessary for their upper deck bound, D_d^U, which determines the height between the deck and the floor of the upper internal deck, in this case deck 8.

The ports of loading and unloading for the various cargo contracts have been predetermined and can be seen in Table 6.2. Additionally, the revenue for optional cargoes and the penalty for moving cargoes can be seen in the same table.

	Cargo 1	Cargo 2	Cargo 3	Cargo 4	Cargo 5
Loading Port	1	2	1	3	1
Unloading Port	6	4	5	6	6
Revenue [-]	-	-	1500	1000	2000
Penalty [-]	50	25	10	15	100

Table 6.2: Revenue Values, and Load and Unload Ports

The amount of units in each cargo contract can be altered easily in both models.

6.2.1 SCENARIOS 1-5

To compare the expanded to the original RSSP, scenarios of varying contract sizes have been run for both models. The first scenarios all represent fairly low cargo quantities. The scope of these analyses was to quickly determine the difference in the flexibility between the original and the expanded RSSP. The cargo quantities for the first scenario can be seen in Table 6.3.

	Cargo 1	Cargo 2	Cargo 3	Cargo 4	Cargo 5
Scenario 1	50	50	50	50	25

Table 6.3: Cargo Quantity Scenario 1

The results for both the original and expanded RSSP model can be seen in Table 6.4.

	Solution time [s]	Best Bound [-]	Gap [%]	Best Integer Solution [-]
Original RSSP	0.1	4 500	Opt.	4 500
Expanded RSSP	0.4	-	-	Infeasible

Table 6.4: Results from Cargo Quantity Scenario 1

The results show that the scenario is infeasible for the expanded RSSP. This is certainly not due to insufficient capacity on the vessel, but more likely a result of the new maximum stability constraint (5.31) in the expanded RSSP. The initial VCG of the ship without payload is set to 14 [m] in the input file, and the range $\left[Z^{MIN}, Z^{MAX} \right]$ is equal to $\left[14.64, 15.28 \right]$. The heavy cargoes 4 and 5, which must be stowed in the lower decks due to their height, comparatively lowers the global VCG of the vessel considerably more than the lighter cargoes do. Especially cargo 3, which has a unit weight of only 1.35 [MT] has little contribution to raise the VCG when the quantity is so low. Thus the vessel's laden VCG will never be able to exceed the minimum limit, Z^{MIN}. The limit for minimum VCG in the expanded RSSP has been implemented as an attempt to provide a long natural roll period for the vessel, but it seems that for this cargo contract configuration with such small cargo quantities, this limits the stowage so severely that the problem becomes infeasible. A new analysis was executed for the expanded RSSP, This time without constraints (5.31). The results can be seen in Table 6.5.

	Solution time [s]	Best Bound [-]	Gap [%]	Best Integer Solution [-]
Expanded RSSP	2.1	4 500	Opt.	4 500

Table 6.5: Results Scenario 1, Expanded RSSP (w/o Maximum Stability Constraint)

After disabling the maximum stability constraints in the Mosel model, the expanded model found a feasible solution to Scenario 1. Both solutions are optimal, but the relative time used to find the optimal solution was significantly longer for the expanded RSSP. With a considerable increase in constraints, binary and integer variables in the expanded RSSP, this is not unexpected.

To see the difference in solution time between the original and the expanded RSSP, more scenarios with steadily increasing cargo contract volumes were generated. As a main rule, the cargo quantities were increased with 10 units each, except cargo 5, which the ship has a far lower unit capacity for. Cargo 5 was increased with 5 units. The scenarios can be seen in Table 6.6. All results from the expanded model are to this point without the maximum stability constraints (5.31). The results can be seen in Table 6.7

	Cargo 1	Cargo 2	Cargo 3	Cargo 4	Cargo 5
Scenario 1	50	50	50	50	25
Scenario 2	60	60	60	60	30
Scenario 3	70	70	70	70	35
Scenario 4	80	80	80	80	40
Scenario 5	90	90	90	90	45

Table 6.6: Cargo Quantity Scenarios 1-5

	Solution time [s]	Best Bound [-]	Gap [%]	Best Integer Solution [-]
-Scenario 1-				
Original RSSP	0.1	4 500	Opt.	4 500
Expanded RSSP	2.1	4 500	Opt.	4 500
-Scenario 2-				
Original RSSP	0.3	4 500	Opt.	4 500
Expanded RSSP	2.2	4 500	Opt.	4 500
-Scenario 3-				
Original RSSP	0.5	3 500	Opt.	3 500
Expanded RSSP	1.7	2 500	Opt.	2 500
-Scenario 4-				
Original RSSP	13.9	3 500	Opt.	3 500
Expanded RSSP	4.3	2 500	Opt.	2 500
-Scenario 5-				
Original RSSP	0.1	3 500	Opt.	3 500
Expanded RSSP	-	2 500	-	N/A

Table 6.7: Results from Scenarios 1-5

From Table 6.7 we see that the expanded RSSP is unable to ship cargo 5 already in scenario 3 (see Table 6.2 for the cargo revenues). Cargo 5 is a very long cargo, and it is so high that only deck 1 can accommodate it. The original RSSP allows empty lanes to have a value of zero, and the model can therefore utilise the deck width, and thus length more effectively. For transverse stability reasons the expanded RSSP has restricted the lane width with lower and upper bounds, so that the pre-estimated CoG of each lane is as accurate as possible. Deck 1 is 22 [m] wide and demands a minimum width of 1.5 [m] of each lane. This means that for a cargo as wide as cargo 5, all lanes cannot be used to stow this cargo. In fact, it means that only 6 lanes can be used for cargo 5, whereas in the original RSSP, 7 lanes can be used. Incidentally, it seems that in scenario 3, deck 1 is used to accommodate cargo 4 as well. At first glance, deck 1 should have the capacity for cargo 5 in both models, but due to slot length constraints (5.35) some lane length is expected to be lost. Constraints (5.24) would also normally represent a limiting factor, but in this specific scenario, these constraints do not keep the vessel from shipping cargo 5.

In scenario 4 the original RSSP prioritises cargo 5 over cargo 4 as it generates more revenue. In scenario 5, the expanded RSSP is unable to find a solution within a maximum set runtime of 300 seconds.

6.2.1.1 Stability Results

So far, the stability of the stowage plans has not been commented. In general it is safe to say that the maximum GM limit, and thus the minimum VCG limit, Z^{MIN}, are both violated. This is due to the fact that the bulk of the cargo weight shipped in scenarios 1-5 are from the heavier cargoes, cargo 4 and 5, which require stowage on either deck 1 or on the main deck, deck 4.

The vertical stability can easily be calculated directly in Mosel for the stowage plan proposed by both the original and the expanded RSSP. The principle used to calculate the CoG of the cargo is as described in equation(6.1). See Appendix B for the Mosel code.

$$\overline{Z} = \frac{\sum_i m_i \cdot z_i}{\sum_i m_i}$$
(6.1)

Where,

$\overline{Z}$ =   the total centre of gravity for the system

m_i =   The mass of element, i

z_i =   the centre of gravity of element, i

The vessel's TCG for the original model, on the other hand, is a rather complicated task to calculate. In fact, the author of this thesis has not been able to develop a satisfying algorithm to calculate the real transverse CoG of the proposed stowage plan of the

original RSSP, directly in Mosel. Lane widths are allowed to take values from zero up to the total width of the deck in the original model. The lane configurations proposed by the model can therefore be quite unbalanced. An extreme example comparing the lane division on deck 5 in the original with the expanded RSSP in scenario 2, is given in Figure 6.1. Note that the length and width of the decks are not in proportion.
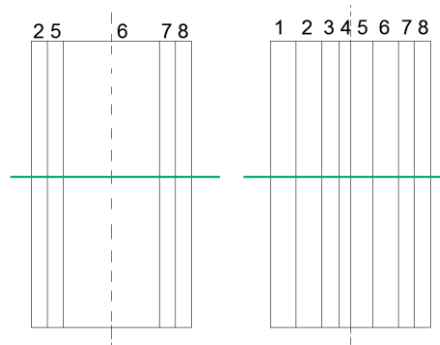
Figure 6.1: Lane Division Example – Original vs. Expanded RSSP

From this we understand that lane 1, 3 and 4 all have a width of zero, and can be neglected. We also see that only two full lanes out of 8 are on the port side of the centre line. Instinctively, the lanes look very balanced, however, the real CoG of, for instance, lane 5, will be severely shifted compared to the pre-estimated CoG that the model uses to balance the moment from the cargo about the centre line. This is largely due to the fact that the lane locations are given pre-estimated co-ordinates on the assumption that half of the lanes are on the port side of the centre line, and the other half on the starboard side. The input file tells the model that the transverse location of lane 5 is expected to be around 1.75 [m] towards the starboard side of the vessel from the centre line. Calculating the location from the stowage plan proposed by original RSSP, the lane's co-ordinate is -9.8, i.e. 9.8 [m] towards the port side of the vessel from the centre line. This represents a total shift of 11.55 [m]. Arguably, this would not matter if the lane was empty, but for this particular scenario, cargoes from cargo 1 are indeed stowed in lane 5 on deck 5. The moment balance calculated to satisfy constraints (5.28) in the original RSSP is therefore likely to use faulty co-ordinates. Figure 6.2 shows the shift of lane 5's real transverse CoG from the pre-estimated CoG in the input for the original RSSP.

Figure 6.2: Transverse CoG Shift in Original RSSP

Comparing the expanded RSSP to this, we see that on this deck in this scenario, the lane that will represent the largest shift in real CoG in the expanded RSSP compared to the pre-estimated CoG, is lane 4. The shift in lane 4's CoG will on deck 5 in this particular scenario be 0.75 [m] from the pre-estimated transverse CoG.
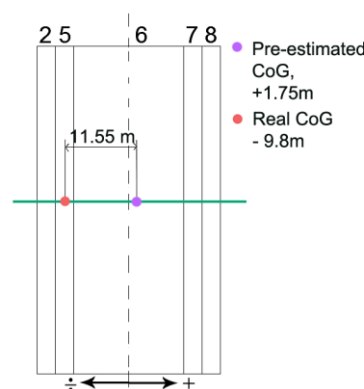
As the number of lanes on each side of the centre line will always be balanced in the expanded RSSP, the real transverse CoG will be far less complicated to calculate. The fact that none of the lanes will have zero width in the stowage proposal also helps the development of an algorithm. With these constraints the real CoG of each lane, and the momentum from the cargo about the centre line can be calculated by adding the widths of all lanes from the centre line up to the lane in question. The transverse CoG was calculated using the principle in equation (6.1) directly in Mosel. The transverse CoG of the stowage plan proposed by the original RSSP cannot be calculated using an automatic algorithm directly in Mosel, as developing such an expression requires knowledge about the lane division on each deck. The longitudinal CoG for the expanded RSSP was found in a similar way, but as the number of slots in these scenarios is an odd number, the cargoes stowed in the slot in the middle of each lane was not considered to contribute to the longitudinal momentum about the midship of all the cargoes on each deck.

The vertical stability of the laden vessel was calculated using expression (4.1) in chapter 4, for both the original and the expanded RSSP. The definition of the vertical cargo CoG parameter, $\overline{Z}_d$, varies slightly for the models (compare expression (5.6) developed for the original RSSP with expression (5.7) for the expanded model). But in any case, both definitions are merely estimates for the final deck placement. The first is not necessarily more accurate than the other in all cases, but the author of this thesis has chosen to use the last definition, (5.7), for the expanded RSSP. In Table 6.8 an example of the calculated stability in scenario 2 for both models is given. The values are from when the vessel sails from port 3 to port 4. Transverse and longitudinal stability of the stowage plans is only included for the expanded RSSP. This is because longitudinal stability is not defined in the original model. Further, the expression to calculate the real transverse stability proposed by the original model may first be defined after the stowage plan is known based on how many lanes the original RSSP divides each deck in. Therefore, the transverse CoG of the stowage plan was not calculated directly in Mosel for the original RSSP. See Appendix B for the calculations in the Mosel code.

	TCG [m]	LCG [m]	VCG [m]	GM [m]
Original RSSP	N/A	N/A	16.24	2.19
Expanded RSSP	0.38	2.26	16.43	2.00

Table 6.8: Stability of Vessel from port 3 to port 4 in Scenario 2

We see that the TCG and LCG of the vessel are quite acceptable for the expanded RSSP, with a slight heel to starboard, and trim to the fore. This is easily counteracted with some ballast on the port side, and at the aft, respectively. The VCG is lower than the minimum limit suggested in sub-section 5.3.1, and consequently, the GM will take a high value. However, the GM value is calculated on the assumption that the vessel is sailing

with its maximum draught. With so little payload from the cargoes, the vessel is not able to achieve this draught. In fact, using equation (5.43), the draught with the payload in scenario 2 and maximum ballast is found to be around 9.2 [m]. This means that the vessel will have an even higher GM value, and be even stiffer than the initial calculations. A solution to mitigate this faulty draught problem from the models could be to add decision variables to the optimisation model, representing the tank filling of the available ballast water capacity. That way, the weight of the vessel without cargo, which is how the parameter W^S is defined in the model, would be more accurate for the expanded RSSP.

6.2.2 SCENARIOS 6-18

The cargo contract quantities in scenarios 1-5 were rather crudely generated. By using the spreadsheet in the Digital Appendix, the utilisation of lane meters, deck area and weight is given instantaneously. This means that more sensible contracts were generated for scenarios 6-18. Note that the spreadsheet does not consider deck height or the division of lanes and slots. Regardless, the original model has already been established to offer more flexible stowage, whereas the expanded model can guarantee that both the transverse and longitudinal stability of the laden vessel is kept within reasonable values. The cargo quantities in scenario 6-18 can be seen in Table 6.9.

	Cargo 1	Cargo 2	Cargo 3	Cargo 4	Cargo 5
Scenario 6	100	100	1500	50	10
Scenario 7	100	100	1500	60	10
Scenario 8	100	100	1500	70	10
Scenario 9	100	100	1500	80	10
Scenario 10	100	100	1500	90	10
Scenario 11	100	100	1500	50	20
Scenario 12	100	100	1500	60	20
Scenario 13	100	100	1500	70	20
Scenario 14	100	100	1500	80	20
Scenario 15	100	100	1750	30	10
Scenario 16	100	100	1750	30	20
Scenario 17	100	100	1750	40	20
Scenario 18	100	100	1750	50	20

Table 6.9: Cargo Quantities Scenarios 6-18

The scenarios were analysed for both the original and the expanded RSSP. The maximum run time was set to 600 [s] for the smaller problems and 1 800 [s] for the bigger problems. The results can be seen in Table 6.10, and the detailed results from all analyses can be found in the Digital Appendix.

	RSSP Version	Solution time [s]	Best Bound [-]	Gap [%]	Best Integer Solution [-]
-Scenario 6-	*Original*	0.1	4 500	Opt.	4 500
	Expanded	8.1	4 500	Opt.	4 500

	RSSP Version	Solution time [s]	Best Bound [-]	Gap [%]	Best Integer Solution [-]
-Scenario 7-	*Original*	0.1	4 500	Opt.	4 500
	Expanded	5.75	4 500	Opt.	4 500
-Scenario 8-	*Original*	0.6	4 500	Opt.	4 500
	Expanded	1 800	4 500	80	2 500
-Scenario 9-	*Original*	0.1	4 500	Opt.	4 500
	Expanded	1 800	4 500	28.57	3 500
-Scenario 10-	*Original*	1 800	4 500	28.57	3 500
	Expanded	1 800	4 500	28.57	3 500
-Scenario 11-	*Original*	0.5	4 500	Opt.	4 500
	Expanded	1 800	4 500	80	2 500
-Scenario 12-	*Original*	0.6	4 500	Opt.	4 500
	Expanded	1 800	4 500	28.57	3 500
-Scenario 13-	*Original*	1 800	4 500	28.57	3 500
	Expanded	1 800	4 500	28.57	3 500
-Scenario 14-	*Original*	1 167	3 500	Opt.	3 500
	Expanded	1 800	4 500	28.57	3 500
-Scenario 15-	*Original*	0.1	4 500	Opt.	4 500
	Expanded	2.0	4 500	Opt.	4 500
-Scenario 16-	*Original*	0.3	4 500	Opt.	4 500
	Expanded	5.8	4 500	Opt.	4 500
-Scenario 17-	*Original*	0.1	4 500	Opt.	4 500
	Expanded	155.5	4 500	Opt.	4 500
-Scenario 18-	*Original*	0.9	4 500	Opt.	4 500
	Expanded	1800	4 500	-	N/A

Table 6.10: Results from Scenarios 6-18

We see that for all scenarios, the expanded model uses more time than the original RSSP, and for several of the scenarios, the maximum run time was not enough to finish the iterations for the expanded RSSP. A peculiar observation is the results from the expanded RSSP in scenario 11 and 12. In scenario 11 the highest revenue generating cargo 5, has been left out, and cargo 3 and 4 are shipped. Then in scenario 12, where only the lower revenue generating cargo 4's quantity has been increased, the model proposes to stow cargo 5 instead of cargo 4. However, this is naturally because the expanded RSSP did not reach optimum in scenario 11 and 12. With a longer run time, it is plausible that the best integer solution in scenario 11 would return as good as the

solution in scenario 12, and possibly better. A similar event seems to have occurred for the original RSSP in scenario 13 and 14. Here, the optimal solution has been found for the larger problem in scenario 14 and not for the smaller scenario 13, within the maximum run time. In scenario 18, the expanded RSSP was unable to find an integer solution within the maximum run time.

A quick assessment of Table 6.10 tells us that the original RSSP reaches optimality quicker and far more often than the expanded RSSP. The original model has, as mentioned in the previous sub-section, considerably more decision variables and constraints. A possible solution to reduce the size of the expanded RSSP, could be to remove both the binary and integer lane variables, x_{dlpc} and y_{dlpc}, as the slot variables can be summed to represent a lane instead. The decision was, however, made early on to keep the lane variables. The main motive for this was that the penalty constraints (5.32) were entirely dependent on these lane variables, and the solution to restructuring the constraint set to use slot variables, was not at all apparent.

Summaries of the search development for both models in scenario 17 are presented in Figure 6.3 and Figure 6.4.
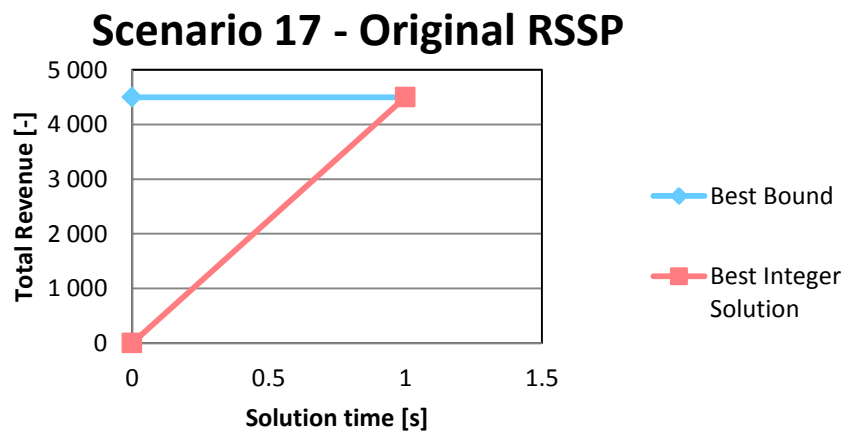
Figure 6.3: Solution Development, Scenario 17 – Original RSSP
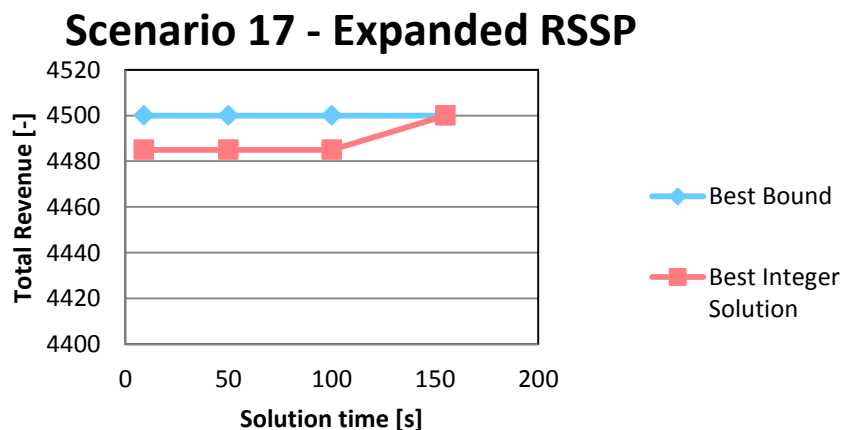
Figure 6.4: Solution Development, Scenario 17 – Expanded RSSP

From Figure 6.3 we see that the original RSSP finds the optimal solution almost instantly for scenario 17. While Figure 6.4 shows that the expanded RSSP first found an integer solution that involved penalties for moving cargoes in port, but ultimately was able to avoid these penalties after further iterations.

The utilisation of the deck area on the vessel from port 2 to port 3 in scenario 17 is given in Table 6.11 along with the initial stability calculations for maximum draught.

	Deck Area Utilisation [%]	TCG [m]	LCG [m]	VCG [m]	GM [m]
Original RSSP	62.9	N/A	N/A	16.84	1.59
Expanded RSSP	62.9	0.61	12.94	17.02	1.41

Table 6.11: Deck Utilisation and Stability from port 2 to port 3 in Scenario 17

The VCG of the vessel is still considerably higher than the desired limit of Z^{MIN}. Correspondingly, the GM value represents a value that theoretically would involve a fairly short natural rolling period with the cargo being subjected to high accelerations. Running the expanded RSSP for scenario 17 with maximum stability constraints (5.31) enabled, results in an infeasible problem.

The search development from scenario 14 is also depicted in Figure 6.5 and Figure 6.6 for the original and the expanded RSSP, respectively.

In scenario 14 the original RSSP finds an integer solution quite fast, but is not able to determine if this is indeed the optimal solution before further iteration have been performed (see Figure 6.5). The expanded RSSP does not finish its search within the maximum set run time. However, as the original RSSP is less constrained and has found the optimal solution, it is reasonable to assume that the best integer solution found for the expanded RSSP (Figure 6.6) is in fact the optimal solution for the expanded RSSP as well.
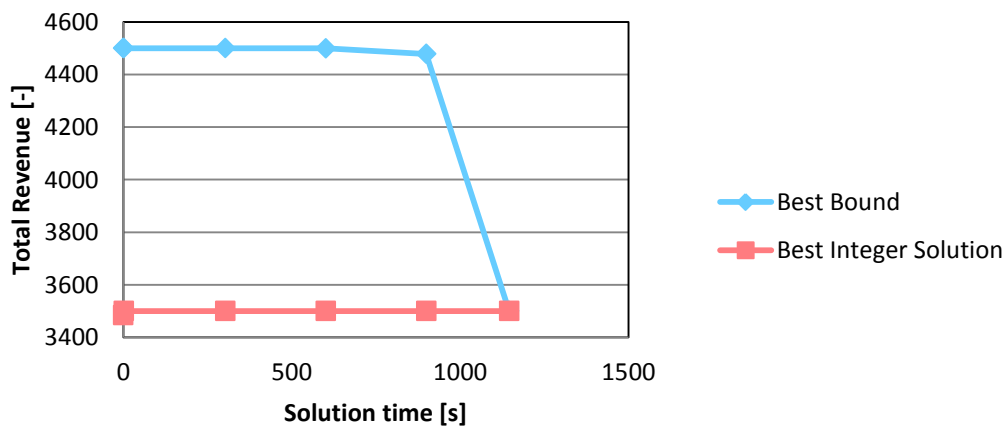
Figure 6.5: Solution Development, Scenario 14 – Original RSSP

Scenario 14 - Expanded RSSP
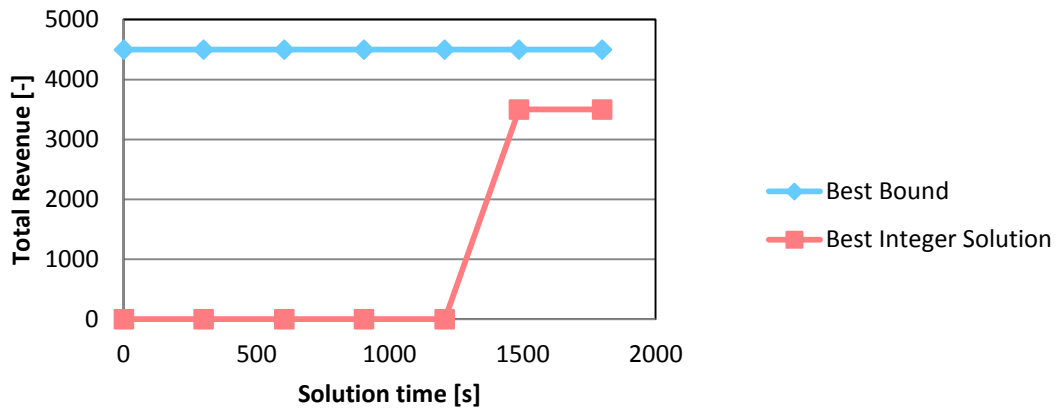
Figure 6.6: Solution Development, Scenario 14 – Expanded RSSP

See Table 6.12 for the utilisation of the deck area and initial stability properties when the vessel sails from port 2 to port 3 in scenario 14.

	Deck Area Utilisation [%]	TCG [m]	LCG [m]	VCG [m]	GM [m]
Original RSSP	56.9	N/A	N/A	17.00	1.45
Expanded RSSP	56.9	-0.90	9.67	16.83	1.60

Table 6.12: Deck Utilisation and Stability form Port 2 to Port 3 in Scenario 14

The deck utilisation is naturally lower than for scenario 17 as only two out of three optional cargoes are transported. The expanded RSSP returns stability properties of tendencies to a list to the port side of the vessel, and trim towards the fore. The LCG of both scenarios 14 and 17 may seem substantial, but the MV Talisman is 240 [m] long, and these trim values can easily be balanced with ballast in the aft part of the vessel. The VCG of the original RSSP is higher, and thus better, than for the expanded RSSP when the vessel sails from port 2 to port 3 in scenario 14.

7 CONCLUDING REMARKS

The original RSSP model has been expanded, mainly to ensure the total stability of the laden vessel. This was accomplished using the same principle as Øvstebø et al., 2011 [5] ,which divided the width of each deck into longitudinal lanes to control transverse stability. By dividing the length of the lanes into separate slots, the location of the stowed cargo could be used to also control the longitudinal stability of the vessel. New variables for slots were added, similar to the existing lane variables from the original model.

Additionally, the lane width variables, v_{dl}, and the new slot length variable set l_{dls} were constrained by lower and upper bounds to reduce the shift between the real centre of gravity from the proposed stowage plan, and the pre-estimated centre of gravity of each lane or slot in the input data. The objective with these limits was to secure the transverse stability of the vessel to a greater extent than the original RSSP did. The maximum vertical stability of the vessel was attempted limited by introducing the parameter Z^{MIN}, for the minimum allowable VCG in order to ensure long natural rolling periods in the expanded RSSP. This is vital for RoRo vessels in order to reduce the accelerations on the cargo on board, but made the scenario problems in the computational study infeasible. Some input that involve this aspect have been estimated by the author, and altering certain data, such as the ship's lightweight VCG, Z^{S}, could improve the model's ability to run while being constrained by this limit.

It has been established that the expanded RSSP suffers in terms of stowage flexibility as a result of the additions made to the original RSSP. Largely this is because of the lane width restrictions, which secure the transverse stability of the vessel. For cargoes of various widths it is not ideal that all decks are divided into an equal number of lanes. The lane division of 8 lanes per deck in the computational study was in fact a compromise to accommodate both the narrow vehicles in cargo 1, as well as the wide Caterpillar trucks in cargo 4. The original RSSP does not suffer from this lane division, as it allows the lane width to take values from zero up to the entire width of the deck. However, the way the transverse stability is upheld in the original RSSP has raised some questions as to the validity of the pre-estimated CoGs used by the optimisation models. For the cargoes in cargo 1 a deck division of 15 lanes per deck would be optimal for a deck of 30 [m], while for the Caterpillar trucks in cargo 4, a total of 6 will be preferable. One could argue that if the model is to stow a selection of cargoes with varying length, width and also height, the lane division needs to correspond to the type of deck, and the type of cargoes the deck is designed to accommodate. Lower decks, intended for larger and heavier cargoes, typically would need to be modelled with fewer lanes per deck in the optimisation model. Implementing this into the RSSP would, however, require great restructuring of the model, as the lane set dictates the majority of the parameters, decision variables and constraints in the RSSP models.

The introduction of the new variables and constraints in the expanded RSSP has made the model very large and constrained. For all scenario analyses, the original RSSP found the solution faster than the expanded RSSP. It is based on this, of the author's opinion that the introduction of slot variables and a tighter lane division has made the model more dependable from a stability and safety perspective, but made worse from an operations research and business point of view.

In the next chapter and final chapter, some recommendations for further work to improve the overall solution quality of the expanded RSSP will be discussed.

8 SUGGESTIONS FOR FURTHER WORK

After the computational study it has become apparent that some aspects of the expanded RSSP would benefit from improvements. As mentioned in the previous chapter, the most beneficial improvement would involve making the model able to handle a varying number of lanes per deck. Typically a few lanes per deck for the lower decks, and from 10 to 15 lanes per deck for the upper decks, would be appropriate. This would naturally depend on the width of each deck, but in any case, the lanes should have bounds for their final width.

Even though the expanded RSSP has taken stability of the laden vessel to a far greater extent than the original RSSP, the maximum stability limit of the vessel must be met before the model's stowage plans can be considered for realisation. A too stiff ship cannot transport RoRo cargo without risking damage to the cargo en route. A long roll period must be achieved to keep crew and cargo safe.

Another desirable improvement would be to implement decision variables for the filling of the ballast tanks in the vessel. A suggestion would be to have one decision variable for each area of the ship, i.e. one for each side and end of the vessel. This would make the RSSP even larger, but could help produce quite accurate approximations of the draught, and thus the stability properties of the laden vessel. However, non-linearity could pose a challenge for this improvement

The deck height is determined for the entire itinerary in the RSSP. If the deck height of a deck could be adjusted from port to port (provided said deck is empty), then the stowage flexibility would improve vastly.

Lastly, both models assign penalties if there are cargoes, B, in the same lane of a cargo, A, that is located in front of the other cargoes, B, and cargo A is being discharged. However, in a real setting, the stevedores[7] will try to avoid this if the lanes on the sides are not full and the cargo can be discharged through a different lane. For the RSSP this seems a tricky challenge, but is a potential improvement that would add to the realism of the optimisation model.

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[7] Dock worker

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APPENDICES

- ## APPENDIX A

    General Arrangement of reference PCC vessel

- ## APPENDIX B

    Mosel Code Expanded RSSP

- ## APPENDIX C

    ### DIGITAL APPENDIX

    General Arrangement reference PCC vessel

    Excel Spreadsheet with calculations for data input and misc.

    Mosel Code Original and Expanded RSSP

    Input files Original and Expanded RSSP

    Results from scenario analyses 1-18

APPENDIX A – GENERAL ARRANGEMENT OF REFERENCE PCC
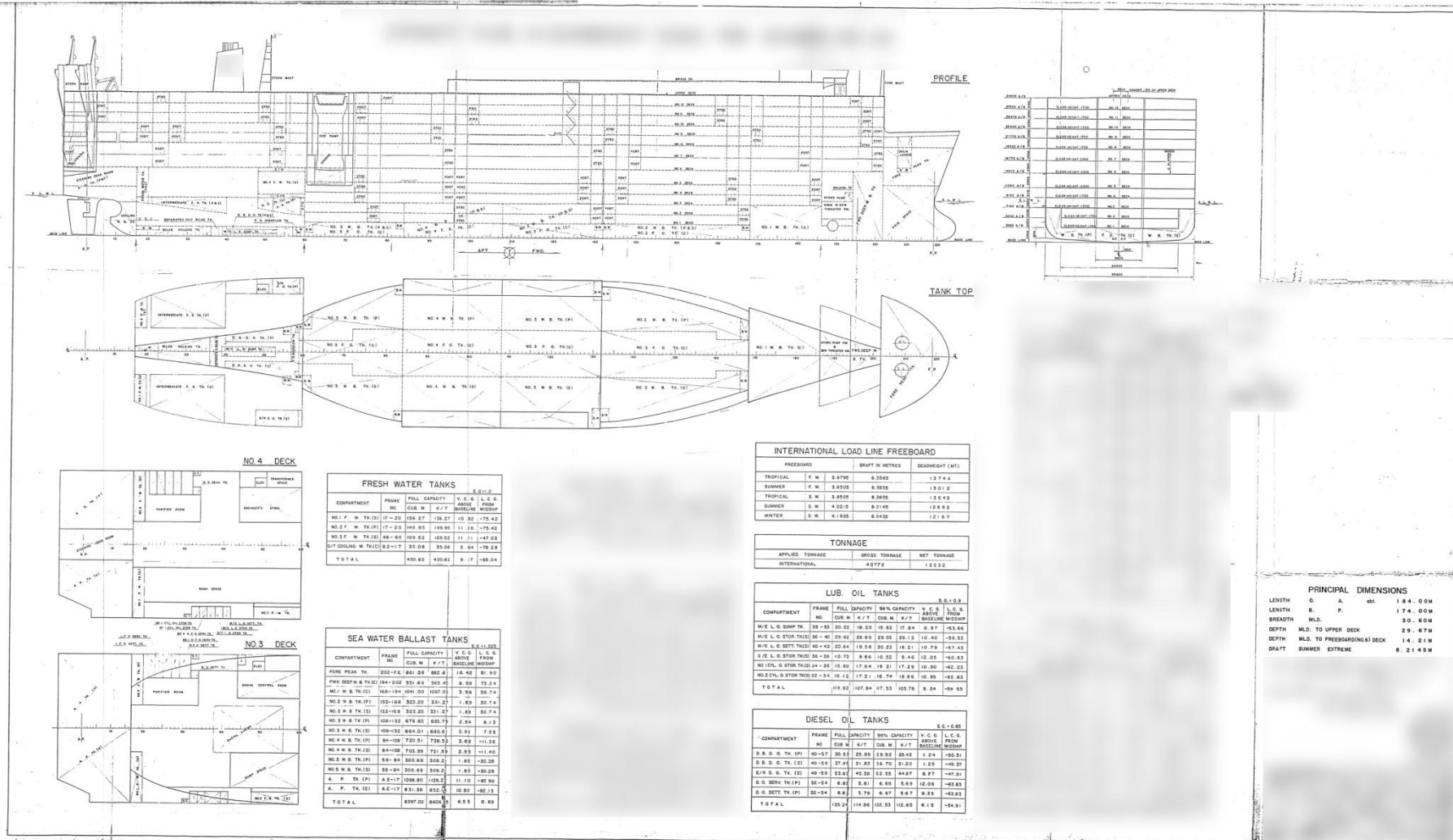
Appendix B - Mosel Code

```
!Expanded RSSP Mosel Code
!Eivind Wathne, Spring 2012
!NTNU

model OvsteboRSSPplus

options explterm
options noimplicit

uses "mmxprs"; !Xpress Optimizer
uses "mmsystem"; !enables gettime attributes

parameters
    DataFile = 'RSSPdata_expanded.txt'; !Name of input file

    Presolve = true;
    Heuristic = true;
    Branching = 'Depth';
    Cutting = 'Yes';
    Print = true;
end-parameters

!---------------Sets--------------------!

declarations
    nManCargoes:    integer;
    nOptCargoes:    integer;
    nPorts:         integer;
    nDecks:         integer;
    nLanes:         integer;
    nSlots:         integer;
end-declarations

!from the input file
initializations from DataFile
    nManCargoes;
    nOptCargoes;
    nPorts;
    nDecks;
    nLanes;
    nSlots;
end-initializations

declarations
    OptCargo:   set of integer;
    ManCargo:   set of integer;
    cargo:      set of integer;
    port:       set of integer;
    deck:       set of integer;
    lane:       set of integer;
    slot:       set of integer;
end-declarations


ManCargo       := 1 .. nManCargoes;
OptCargo       := nManCargoes+1 .. nOptCargoes+nManCargoes;
cargo          := 1 .. (nManCargoes + nOptCargoes);
port           := 1 .. nPorts;
deck           := 1 .. nDecks;
lane           := 1 .. nLanes;
slot           := 1 .. nSlots;

finalize(ManCargo);
finalize(OptCargo);
finalize(cargo);
finalize(port);
finalize(deck);
finalize(lane);
finalize(slot);
```

```
!-----------------Parameters--------------!

declarations
    W_d:    array(deck)          of integer;
        ! width of deck d
    L_d:    array(deck)          of integer;
        ! Length of deck d
    C_L_c:  array(cargo)         of real;
        ! Length required for one vehicle in cargo c
    C_W_c:  array(cargo)         of real;
        ! Width required for one vehicle in cargo c
    C_H_c:  array(cargo)         of real;
        ! height required for one vehicle in cargo c
    P_L_c:  array(cargo)         of integer;
        ! loading port of cargo c
    P_U_c:  array(cargo)         of integer;
        ! unloading port of cargo c, P_U_c > P_L_c
    L_L_d:  array(deck)          of real;
        ! lower bound for the width of a lane on deck d
    L_U_d:  array(deck)          of real;
        ! upper bound for the width of a lane on deck d
    D_L_d:  array(deck)          of real;
        ! lower bound for where deck d can be placed
    D_U_d:  array(deck)          of real;
        ! upper bound for where deck d can be placed
    D_C_d:  array(deck)          of real;
        ! Capacity for deck d in MT/m2
    R_F_c:  array(OptCargo)      of integer;
        ! revenue for transporting optional cargo c
    N_c:    array(cargo)         of integer;
        ! number of vehicles in cargo c
    C_M_c:  array(cargo)         of real;
        ! cost incurred if cargo c need to be moved
    M_MAX_r:                     integer;
        ! Maximum allowable transverse moment on the
        ! ship from the cargo, i.e. roll
    M_MAX_t:                     integer;
        ! max allowable longitudinal moment on the
        ! ship from the cargo, i.e. trim
    Z_MAX:                       real;
        ! Highest allowable centre of gravity of the laden ship,
        ! measured from the bottom deck
    Z_MIN:                       real;
        ! Lowest allowable centre of gravity of the laden ship,
        ! measured from the bottom deck
    C_V_c:  array(cargo)         of real;
        ! weight of one vehicle from cargo c, in MT
    W_S:                         integer;
        ! lightweight of the ship, in MT
    Z_S:                         integer;
        ! vertical distance from the ship's bottom deck
        ! to its centre of gravity when empty
    Y_dl:   array(deck,lane)     of real;
        ! approx. vertical distance of cargo stowed on
        ! deck d from the ship's CoG.
        ! Y_dl= (l-1/2)*(W_d)/(|L|)-(W_d)/2
    X_ds:   array(deck,slot)     of real;
        ! Approx. longitudinal distance of slot s
        ! from the CoG of the ship
        ! !X_ds = L_d/2-(s-1/2)*(L_d)/(|S|)
    Z_d:    array(deck)          of real;
        ! approx. vertical distance of deck d from the ship's CoG.
        ! Z_d= (D_U_d+D_L_d)/2+((D_L_d+1+D_U_d+1)/2-(D_L_d+D_U_d)/2)/2
    C_c:    dynamic array(cargo)of set of integer;
        ! set of cargoes c' such that P_L_c' < P_L_c < P_U_c' < P_U_c.
        ! That is, if first loading vehicles from c' and later from c
        ! using the same lane, then the vehicles from c must be moved
        ! when unloading c'.
    BigM:   dynamic array(deck) of real;
        ! Big M for constraint BigMSlotCon (5.9), BigM = L_d/(|S|-1)
    HalfLanes:                   integer;
        !number of lanes on one side of the centre line

end-declarations
```

```
initializations from DataFile
        W_d;
        L_d;
        C_L_c;
        C_W_c;
        C_H_c;
        P_L_c;
        P_U_c;
        L_L_d;
        L_U_d;
        D_L_d;
        D_U_d;
        D_C_d;
        R_F_c;
        N_c;
        C_M_c;
        M_MAX_r;
        M_MAX_t;
        Z_MAX;
        Z_MIN;
        C_V_c;
        W_S;
        Z_S;
        Y_dl;
        X_ds;
        Z_d;
end-initializations

HalfLanes := 4;

forall(c in cargo, c2 in cargo )do
        if(P_U_c(c2)<P_U_c(c) and P_L_c(c2)<P_L_c(c)
            and P_L_c(c)<P_U_c(c2) )then
                C_c(c)+={c2};
        end-if
end-do

forall(d in deck | d < nDecks) do
    BigM(d)+=(L_d(d)/(nSlots-1));
end-do

!-----------Decision Variables----------------!

declarations
    h_d:        dynamic array(deck)                 of mpvar;
        ! height of deck d from the bottom deck
    v_dl:       dynamic array(deck,lane)            of mpvar;
        ! width of lane l on deck d
    l_dls:      dynamic array(deck,lane,slot)       of mpvar;
        ! length of slot s in lane l on deck d
    w_dlcc2:    dynamic array(deck,lane,cargo,cargo)    of mpvar;
        ! = 1 if cargo c´ is loaded in front of cargo c in lane l
        ! on deck d in port P_L_c, /=0 otherwise
    x_dlpc:     dynamic array(deck,lane,port,cargo)     of mpvar;
        ! = 1 if lane l on deck d is used from port p to p+1
        ! by cargo c, /=0 otherwise
    u_dlspc:    dynamic array(deck,lane,slot,port,cargo)of mpvar;
        ! = 1 if slot s in lane l on deck d is used from
        ! port p to p+1 by cargo c, /=0 otherwise
    y_dlpc:     dynamic array(deck,lane,port,cargo)     of mpvar;
        ! number of vehicles from cargo c in lane l on deck d
        ! when the ship leaves port p
    s_dlspc:    dynamic array(deck,lane,slot,port,cargo)of mpvar;
        ! Number of vehicles from cargo c in slot s in lane l
        ! on deck d when the ship leaves port p
    z_c:        dynamic array(cargo)                 of mpvar;
        ! if optional cargo c is taken, /=0 otherwise
end-declarations
```

```
forall(d in deck ) do
    create(h_d(d));
    D_L_d(d) <= h_d(d);
    h_d(d) <= D_U_d(d);
end-do

forall(d in deck, l in lane | d < nDecks) do
    create(v_dl(d,l));
    v_dl(d,l) <= L_U_d(d);
    v_dl(d,l) >= L_L_d(d);
end-do

forall(d in deck, s in slot, l in lane | d < nDecks) do
    create(l_dls(d,l,s));
    l_dls(d,l,s) <= L_d(d)/(nSlots-1);
    l_dls(d,l,s) >= L_d(d)/(nSlots+1);
end-do

forall(d in deck, l in lane, c in cargo, c2 in C_c(c)
    | exists(C_c(c)) and  d < nDecks ) do
        create(w_dlcc2(d,l,c,c2));
        w_dlcc2(d,l,c,c2) is_binary;
end-do

forall(d in deck, l in lane, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        create(x_dlpc(d,l,p,c));
        x_dlpc(d,l,p,c) is_binary;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        create(u_dlspc(d,l,s,p,c));
        u_dlspc(d,l,s,p,c) is_binary;
end-do

forall(d in deck, l in lane, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        create(y_dlpc(d,l,p,c));
        y_dlpc(d,l,p,c) is_integer;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        create(s_dlspc(d,l,s,p,c));
        s_dlspc(d,l,s,p,c) is_integer;
end-do

forall(c in OptCargo) do
    create(z_c(c));
    z_c(c) is_binary;
end-do
```

```
!-------------------Objective Function and Constraints----------------!
!Notations in the form of (x) indicate the constraints' original numbering
!in Øvstebø et al., 2011 RSSP
!Notation (x.xx) behind indicate the numbering from the belonging thesis

!Notations in the form (x+) indicate expanded constraints from the original RSSP
!Notations (New x.xx) represent the new constraints.
!Numbering from the belonging thesis

!Explanation of constraints are found in thesis

declarations
    ObjectiveFunction:                                      linctr;
        !(1) (5.9)
    LaneCapCon1:        dynamic array(deck,lane,port,cargo)      of linctr;
        !(2) (5.10)
    BigMSlotCon:        dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(new 5.11)
    BinaryLaneCon:      dynamic array(deck,lane,port,cargo)      of linctr;
        !(new 5.12)
    BinarySlotCon:      dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(new 5.13)
    SlotLaneUse:        dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(new 5.14)
    DeckHeightCon:      dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(3+)(5.15)
    LaneWidthCon:       dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(4+)(5.16)
    CargoCon1:          dynamic array(deck,lane,port,cargo)      of linctr;
        !(5) (5.17)
    CargoCon2:          dynamic array(deck,lane,slot,port,cargo)  of linctr;
        !(new 5.18)
    LanePartition:      dynamic array(deck)                      of linctr;
        !(6) (5.19)
    SlotPartition:      dynamic array(deck,lane)                 of linctr;
        !(new 5.20)
    SlotCapCon1:        dynamic array(deck,lane,port,cargo)      of linctr;
        !(new 5.21)
    ManCargoCon:        dynamic array(port,ManCargo)             of linctr;
        !(7) (5.22)
    OptCargoCon:        dynamic array(port,cargo)                of linctr;
        !(8) (5.23)
    LaneLocCon:         dynamic array(deck)                      of linctr;
        !(new 5.24)
    LaneCapCon2:        dynamic array(deck,lane,port)            of linctr;
        !(9) (5.25)
    SlotCapCon2:        dynamic array(deck,lane,slot,port)       of linctr;
        !(new 5.26)
    DeckCapCon:         dynamic array(deck,lane,port,cargo)      of linctr;
        !(new 5.27)
    TransStabCon:       dynamic array(port)                      of linctr;
        !(10+)(5.28)
    LongStabCon:        dynamic array(port)                      of linctr;
        !(new 5.29-30)
    VertStabCon1:       dynamic array(port)                      of linctr;
        !(11)(5.29-30)
    VertStabCon2:       dynamic array(port)                      of linctr;
        !(new 5.31)
    CargoMovePen:       dynamic array(deck,lane,cargo,cargo)     of linctr;
        !(12)(5.32)
end-declarations
```

```
!-------------------Mathematical Model------------------!

ObjectiveFunction :=
    sum(c in OptCargo ) R_F_c(c)*z_c(c) -
    sum(d in deck, l in lane, c in cargo, c2 in C_c(c)
        | exists(C_c(c)) and d < nDecks )
            C_M_c(c)*w_dlcc2(d,l,c,c2);

forall(d in deck, l in lane, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        LaneCapCon1(d,l,p,c) :=
            C_L_c(c)*y_dlpc(d,l,p,c) - L_d(d)*x_dlpc(d,l,p,c) <= 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        BigMSlotCon(d,l,s,p,c) :=
            C_L_c(c)*s_dlspc(d,l,s,p,c) - BigM(d)*u_dlspc(d,l,s,p,c) <= 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        SlotLaneUse(d,l,s,p,c) :=
            u_dlspc(d,l,s,p,c) - x_dlpc(d,l,p,c) <= 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        BinaryLaneCon(d,l,p,c) :=
            x_dlpc(d,l,p,c) - y_dlpc(d,l,p,c) <= 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        BinarySlotCon(d,l,s,p,c) :=
            u_dlspc(d,l,s,p,c) - s_dlspc(d,l,s,p,c) <= 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        DeckHeightCon(d,l,s,p,c) :=
            C_H_c(c)*u_dlspc(d,l,s,p,c) - (h_d(d+1) - h_d(d)) <= 0;
end-do

forall(d in deck, l in lane, s in slot,c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks )  do
        LaneWidthCon(d,l,s,p,c) :=
            C_W_c(c)*u_dlspc(d,l,s,p,c) - v_dl(d,l) <= 0;
end-do

forall(d in deck, l in lane, c in cargo, p in P_L_c(c)..P_U_c(c)-2
    | d < nDecks ) do
        CargoCon1(d,l,p,c) :=
            y_dlpc(d,l,p+1,c) - y_dlpc(d,l,p,c) = 0;
end-do

forall(d in deck, l in lane, s in slot, c in cargo, p in P_L_c(c)..P_U_c(c)-2
    | d < nDecks ) do
        CargoCon2(d,l,s,p,c) :=
            s_dlspc(d,l,s,p+1,c) - s_dlspc(d,l,s,p,c) = 0;
end-do

forall(d in deck | d < nDecks) do
    LanePartition(d) :=
        sum(l in lane) v_dl(d,l) = W_d(d);
end-do

forall(d in deck, l in lane | d < nDecks) do
    SlotPartition(d,l) :=
        sum(s in slot) l_dls(d,l,s) = L_d(d);
end-do
```

```
forall(d in deck, l in lane, c in cargo, p in P_L_c(c)..P_U_c(c)-1
    | d < nDecks ) do
        SlotCapCon1(d,l,p,c) :=
            sum(s in slot) s_dlspc(d,l,s,p,c) = y_dlpc(d,l,p,c);
end-do

forall(c in ManCargo, p in P_L_c(c)..P_U_c(c)-1 ) do
    ManCargoCon(p,c) :=
        sum(d in deck, l in lane | d < nDecks) y_dlpc(d,l,p,c) = N_c(c);
end-do

forall(c in OptCargo, p in P_L_c(c)..P_U_c(c)-1) do
    OptCargoCon(p,c) :=
        sum(d in deck, l in lane | d < nDecks) y_dlpc(d,l,p,c) =
            N_c(c)*z_c(c);
end-do

forall(d in deck | d < nDecks ) do
    LaneLocCon(d) :=
    sum(l in 1..HalfLanes) v_dl(d,l) = W_d(d)/2;
end-do

forall(d in deck, l in lane, p in port | d < nDecks and p < nPorts) do
    LaneCapCon2(d,l,p) :=
        sum(c in cargo)C_L_c(c)*y_dlpc(d,l,p,c) <= L_d(d);
end-do

forall(d in deck, l in lane, s in slot, p in port
    | d < nDecks and p < nPorts)do
        SlotCapCon2(d,l,s,p) :=
            sum(c in cargo) C_L_c(c)*s_dlspc(d,l,s,p,c) <= l_dls(d,l,s);
end-do

forall(d in deck, l in lane, c in cargo, p in port
    | d < nDecks and p < nPorts)do
        DeckCapCon(d,l,c,p) :=
            C_V_c(c)/(C_L_c(c)*C_W_c(c))*x_dlpc(d,l,p,c) <= D_C_d(d);
end-do

forall(p in port | p < nPorts) do
    TransStabCon(p) :=
        -M_MAX_r <=
        sum(d in deck, l in lane, c in cargo)
            C_V_c(c)*y_dlpc(d,l,p,c)*Y_dl(d,l);
        sum(d in deck, l in lane, c in cargo)
            C_V_c(c)*y_dlpc(d,l,p,c)*Y_dl(d,l) <=
        M_MAX_r;
end-do

forall(p in port | p < nPorts) do
    LongStabCon(p) :=
        -M_MAX_t <= sum(d in deck, l in lane, s in slot, c in cargo)
            C_V_c(c)*s_dlspc(d,l,s,p,c)*X_ds(d,s);
        sum(d in deck, l in lane, s in slot, c in cargo)
            C_V_c(c)*s_dlspc(d,l,s,p,c)*X_ds(d,s) <= M_MAX_t;
end-do


forall(p in port | p < nPorts) do
    VertStabCon1(p) :=
        W_S*Z_S +
        sum(d in deck, l in lane, c in cargo) C_V_c(c)*y_dlpc(d,l,p,c)*Z_d(d)
        <=  ( W_S + sum(d in deck, l in lane, c in cargo)
                C_V_c(c)*y_dlpc(d,l,p,c) )* Z_MAX;
end-do
(!
forall(p in port | p < nPorts) do
    VertStabCon2(p) :=
        W_S*Z_S +
        sum(d in deck, l in lane, s in slot, c in cargo)
            C_V_c(c)*s_dlspc(d,l,s,p,c)*Z_d(d) >=
        ( W_S + sum(d in deck, l in lane, s in slot, c in cargo)
            C_V_c(c)*s_dlspc(d,l,s,p,c) )* Z_MIN;
end-do
!)
```

```
forall(d in deck, l in lane, c in cargo, c2 in C_c(c)
    | exists(C_c(c))  and d < nDecks )do
        CargoMovePen(d,l,c,c2) :=
            x_dlpc(d,l,P_L_c(c),c) + x_dlpc(d,l,P_L_c(c),c2) <=
                l + w_dlcc2(d,l,c,c2);
end-do

!get solution time
declarations
    start:      real;
    stop:       real;
    time_used:  real;
end-declarations



! Maximum runtime
setparam('xprs_maxtime',-1800);

setparam('xprs_verbose',true);

!------------------Optimisation---------------------!
start := gettime; ! start time

maximize(ObjectiveFunction);

stop := gettime; !stop time
time_used := stop - start; !time elapsed

!------------Parameters for Stability Check-----------!

declarations
    L:                          real;!Length of the vessel in the waterline
    B:                          real;!beam of the vessel
    T:                          real;
        !Draught of the vessel with maximum deadweight
    Cb:                         real;!Block coefficient of the vessel
    rho:                        real;!Density of sea water
    CoB_f:                      real;
        !Location of the centre of buoyancy as a factor of draught
    W_WB:                       real;!weight of ballast at max capacity
    GM_MIN:                     real;!minimum GM value
    GM_MAX:                     real;!maximum GM value
    MomT:   dynamic array(port) of real;
        !Transverse moment from cargo about the centre line
    MomL:   dynamic array(port) of real;
        !Longitudinal moment from cargo about the midship
    CoGt:   dynamic array(port) of real;
        !Transverse centre of gravity of the laden vessel
    CoGl:   dynamic array(port) of real;
        !Longitudinal centre of gravity of the laden vessel
    KG:     dynamic array(port) of real;
        !Vertical centre of gravity of the laden vessel,
        !measured from the bottom deck
    KB:     dynamic array(port) of real;
        !Location of the centre of buoyancy at max draught
    T_real: dynamic array(port) of real;!real draught
    KB_real:dynamic array(port) of real;
        !Location of the centre of buoyancy at real draught
    BM:     dynamic array(port) of real;
        !Height of the transverse metacentre above the
        !centre of buoyancy at maximum draught
    BM_real:dynamic array(port) of real;
        !Height of the transverse metacentre above the
        !centre of buoyancy at real draught
    GM:     dynamic array(port) of real;
        !Metacentric height at maximum draught
    GM_real:dynamic array(port) of real;
        !Metacentric height at real draught
end-declarations
```

```
L :=         232.8;
B :=          32.3;
T :=          11.75;
Cb :=          0.65;
rho:=          1.025;
CoB_f :=        0.6;
W_WB  :=       11220;
GM_MIN:=        0.15;
GM_MAX:=        0.79;

forall(p in port | p<nPorts) do
    MomT(p) +=
    -sum(d in deck, c in cargo | d < nDecks) C_V_c(c)*(
        getsol(y_dlpc(d,1,p,c))*(W_d(d)/2 - getsol(v_dl(d,1))/2)+ ! lane 1
        getsol(y_dlpc(d,2,p,c))*( W_d(d)/2 - ( getsol(v_dl(d,1)) +
        getsol(v_dl(d,2))/2)) + !lane 2
        getsol(y_dlpc(d,3,p,c))*( getsol(v_dl(d,4))+
        getsol(v_dl(d,3))/2) + ! lane 3
        getsol(y_dlpc(d,4,p,c))*(getsol(v_dl(d,4))/2) ) + ! lane 4
    sum(d in deck, c in cargo | d < nDecks) C_V_c(c)*(
        getsol(y_dlpc(d,5,p,c))*(getsol(v_dl(d,5))/2) +! lane 5
        getsol(y_dlpc(d,6,p,c))*( getsol(v_dl(d,5))+
        getsol(v_dl(d,6))/2) + ! lane 6
        getsol(y_dlpc(d,7,p,c))*( W_d(d)/2 - ( getsol(v_dl(d,8)) +
        getsol(v_dl(d,7))/2)) + ! lane 7
        getsol(y_dlpc(d,8,p,c))*(W_d(d)/2 - getsol(v_dl(d,8))/2) ); ! lane 8
end-do

forall(p in port | p<nPorts) do
    CoGt(p) +=
    (-sum(d in deck, c in cargo | d < nDecks) C_V_c(c)*(
        getsol(y_dlpc(d,1,p,c))*(W_d(d)/2 - getsol(v_dl(d,1))/2)+ ! lane 1
        getsol(y_dlpc(d,2,p,c))*( W_d(d)/2 - ( getsol(v_dl(d,1)) +
        getsol(v_dl(d,2))/2)) + !lane 2
        getsol(y_dlpc(d,3,p,c))*( getsol(v_dl(d,4))+
        getsol(v_dl(d,3))/2) + ! lane 3
        getsol(y_dlpc(d,4,p,c))*(getsol(v_dl(d,4))/2) ) + ! lane 4
    sum(d in deck, c in cargo | d < nDecks) C_V_c(c)*(
        getsol(y_dlpc(d,5,p,c))*(getsol(v_dl(d,5))/2) +! lane 5
        getsol(y_dlpc(d,6,p,c))*( getsol(v_dl(d,5))+
        getsol(v_dl(d,6))/2) + ! lane 6
        getsol(y_dlpc(d,7,p,c))*( W_d(d)/2 - ( getsol(v_dl(d,8)) +
        getsol(v_dl(d,7))/2)) + ! lane 7
        getsol(y_dlpc(d,8,p,c))*(W_d(d)/2 - getsol(v_dl(d,8))/2) )) / !lane 8
    (sum(d in deck, l in lane, c in cargo)getsol(y_dlpc(d,l,p,c))*C_V_c(c));
end-do

forall(p in port | p < nPorts) do
    MomL(p) +=
    sum(d in deck, l in lane, c in cargo | d < nDecks) C_V_c(c)* (
        getsol(s_dlspc(d,l,1,p,c))*(L_d(d)/2 - getsol(l_dls(d,l,1)/2) + !slot 1
        getsol(s_dlspc(d,l,2,p,c))* getsol(l_dls(d,l,2))/2) ) + !slot 2
    -sum(d in deck, l in lane, c in cargo | d < nDecks) C_V_c(c)* (
        getsol(s_dlspc(d,l,4,p,c))* getsol(l_dls(d,l,4))/2 + !slot 4
        getsol(s_dlspc(d,l,5,p,c))*(L_d(d)/2 - getsol(l_dls(d,l,5))/2) );!slot 5
end-do

forall(p in port | p < nPorts) do
    CoGl(p) +=
    (sum(d in deck, l in lane, c in cargo | d < nDecks) C_V_c(c)* (
        getsol(s_dlspc(d,l,1,p,c))*(L_d(d)/2 - getsol(l_dls(d,l,1)/2) + !slot 1
        getsol(s_dlspc(d,l,2,p,c))* getsol(l_dls(d,l,2))/2) ) + !slot 2
    -sum(d in deck, l in lane, c in cargo | d < nDecks) C_V_c(c)* (
        getsol(s_dlspc(d,l,4,p,c))* getsol(l_dls(d,l,4))/2 + !slot 4
        getsol(s_dlspc(d,l,5,p,c))*(L_d(d)/2 - getsol(l_dls(d,l,5))/2) ))/
    (sum(d in deck, l in lane, c in cargo)
        getsol(y_dlpc(d,l,p,c))*C_V_c(c)); !slot 5
end-do
```

```
forall(p in port | p < nPorts) do
    KG(p) +=
    (W_S*(Z_S)+
        sum(d in deck, l in lane, c in cargo | d <nDecks)
            ( C_V_c(c)*getsol(y_dlpc(d,l,p,c))*(getsol(h_d(d)) +
                C_H_c(c)*0.4))) /!approx CoG of each cargo
    (W_S+
        sum(d in deck, l in lane, c in cargo| d <nDecks)
            getsol(y_dlpc(d,l,p,c))*C_V_c(c));
end-do

forall(p in port | p < nPorts) do
    KB(p) += T*CoB_f;
end-do

forall(p in port | p < nPorts) do
    T_real(p) += (W_S + W_WB +
        sum(d in deck, l in lane, c in cargo| d <nDecks)
            getsol(y_dlpc(d,l,p,c))*C_V_c(c)) /
    (L*B*Cb*rho);
end-do

forall(p in port | p < nPorts) do
    KB_real(p)  +=  T_real(p)*CoB_f;
end-do

forall(p in port | p < nPorts) do
    BM(p) += ((L*B^3)/12)/(L*B*T*Cb);
end-do

forall(p in port | p < nPorts) do
    BM_real(p) += ((L*B^3)/12)/(L*B*T_real(p)*Cb);
end-do

forall(p in port | p < nPorts) do
    GM(p) += T*CoB_f + BM(p) - (KG(p) + 3);
end-do

forall(p in port | p < nPorts) do
    GM_real(p) +=   T_real(p)*CoB_f + BM_real(p) - (KG(p) + 3);
end-do


!The code directly below is to only to separate the models when run in batches.
!The following code is NOT a new model, merely results written to a .txt file
writeln('---------------------------next model---------------------------');
writeln;


!writes results to txt file
fopen('RSSPexpanded-Output.txt',F_OUTPUT);

writeln('Expanded RSSP:');

declarations
    status: string;
end-declarations

case getprobstat of
    XPRS_OPT: status:="Optimum found";
    XPRS_UNF: status:="Unfinished";
    XPRS_INF: status:="Infeasible";
    XPRS_UNB: status:="Unbounded";
    XPRS_OTH: status:="Failed";
    else status:="???";
end-case

writeln("Problem status: ", status);
writeln;
```

```
writeln('-------------------Solution----------------');
writeln;

writeln('Maximum profit: ',getobjval);
writeln;

writeln('Time used: ',time_used,' s');
writeln;

forall( c in OptCargo) do
    if getsol(z_c(c))=1 then
        writeln('Optional cargo ',c,' is carried - Profit earned: ',R_F_c(c));
            else
                writeln('Optional cargo ',c,' is not carried');
    end-if
end-do
writeln;

writeln('Penalties paid due to relocating cargo on board: ',
    sum(d in deck, l in lane, c in cargo, c2 in C_c(c)
        | exists(C_c(c)) and d < nDecks )
            getsol(w_dlcc2(d,l,c,c2))*C_M_c(c));
writeln;

writeln('-----------------------Stowage-------------------------');
writeln;

forall(p in port | p < nPorts)
writeln('Deck area utilisation from port ',p,' to port ',p+1,': ',
    ((sum(d in deck, l in lane, c in cargo | d < nDecks)
        C_L_c(c)*C_W_c(c)*getsol(y_dlpc(d,l,p,c)))/
    sum(d in deck| d<nDecks) W_d(d)*L_d(d))*100,' %');
writeln;

forall(c in cargo) do
writeln('deck area needed for cargo ',c,': ',C_L_c(c)*C_W_c(c)*N_c(c),' m2');
end-do
writeln;

writeln('Total deck area needed for all cargoes combined: ',
    sum(c in cargo)C_L_c(c)*C_W_c(c)*N_c(c),' m2');
writeln;

writeln('available deck area on ship in total: ',
    sum(d in deck| d<nDecks) W_d(d)*L_d(d),' m2');
writeln;

forall(p in port | p<nPorts) do
    writeln('Lane length used from port ',p,' to port ',p+1,': ',
        sum(d in deck, l in lane, c in cargo)
            C_L_c(c)*getsol(y_dlpc(d,l,p,c)),' meters');
end-do
writeln;

forall(c in cargo) do
    writeln('Lane length needed for cargo ',c,': ',C_L_c(c)*N_c(c),' meters');
end-do
writeln;

writeln('Total lane length needed for all cargoes combined: ',
    sum(c in cargo)C_L_c(c)*N_c(c),' m');
writeln;

writeln('Lane length available: ',sum(d in deck | d<nDecks)
        L_d(d)*nLanes,' meters');
writeln;
```

```
forall (p in port | p < nPorts)
writeln('Weight of payload from port ',p,' to port ',p+1,': ',
    sum(d in deck, l in lane, c in cargo) C_V_c(c)*getsol(y_dlpc(d,l,p,c)),' MT');
writeln;

forall(c in cargo)
writeln('Weight of cargo ',c,': ',N_c(c)*C_V_c(c),' MT');
writeln;

writeln('Total weight of available cargo: ',sum(c in cargo)N_c(c)*C_V_c(c),' MT');
writeln;

writeln('-------------Stability Check----------------');
writeln;

forall(p in port | p < nPorts)
writeln('Longitudinal moment from cargo from port ',p,' to port ',p+1,': ',
        MomL(p),' MT*m');
writeln;

forall(p in port | p < nPorts)
writeln('Longitudinal CoG from port ',p,' to port ',p+1,': ',CoGl(p),' m');
writeln('(negative = trim towards aft, positive = trim towards fore)');
writeln;

forall(p in port | p < nPorts)
writeln('Transverse moment from cargo from port ',p,' to port ',p+1,': ',
        MomT(p),' MT*m');
writeln;

forall(p in port | p < nPorts)
writeln('Transverse CoG from port ',p,' to port ',p+1,': ',CoGt(p),' m');
writeln('(negative = heel to port, positive = heel to SB)');
writeln;

forall(p in port | p < nPorts) do
    if KG(p) > Z_MAX then
        writeln('Vertical CoG from the bottom deck, from port ',p,
                ' to port ',p+1,': ',KG(p),' m <--- Not OK!');
            elif KG(p) < Z_MIN then
                writeln('Vertical CoG from the bottom deck, from port ',p,
                    ' to port ',p+1,': ',KG(p),' m <--- Not OK!');
            else
                writeln('Vertical CoG from the bottom deck, from port ',p,
                    ' to port ',p+1,': ',KG(p),' m <--- OK!');
    end-if
end-do
writeln;

forall(p in port | p < nPorts) do
    if GM(p) < GM_MIN then
        writeln('Initial GM from port ',p,' to port ',p+1,': ',
                GM(p),' m <--- Not OK!');
            elif GM(p) > GM_MAX then
                writeln('Initial GM from port ',p,' to port ',p+1,': ',
                    GM(p),' m <--- Not OK!');
            else
                writeln('Initial GM from port ',p,' to port ',p+1,': ',
                    GM(p),' m <--- OK!');
    end-if
end-do

fclose(F_OUTPUT);

end-model
```

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