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Analysis and modelling of the inland container ship stowage process: A case study

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Abstract

The rapidly growing containerization, related volumes and increased complexity has triggered terminal operators and shipping companies to invest in new technologies to improve the container handlings and operational efficiency. For example, in inland shipping, several operations and related challenges exist, which need the development of decision support tools. Among those the stowage process, defined as the exact positioning of containers on board to reach stability, is a complex problem which, to our knowledge, is still performed manually and driven by the experience of the decision makers. Also, literature partially addresses this challenging problem. Hence, in this paper we first study the stowage process for inland shipping barges in depth and thereafter identify and mathematically model all the possible constraints during the stowage process of a barge. This work is supported by a case study of a real-world barge. The barges features are available to us and it typically sails from the port of Rotterdam to an inland terminal located in Veghel. By means of an experimental framework based on real world instances, we test the mathematical model and its complexity. The mathematical model lays a foundation for the replacement of the current trial and error methods, used by skippers of barges, for a computer program creating the optimal stowage plan.

Keywords: Inland Shipping, Container Stowage Problem, Barge, Case Study, Mixed Integer Programming

Contents

1 Introduction

Nowadays, over 80% of the world trade is transported via containers (Zhang and Lee, 2016). In 1956 Malcolm Purcell McLean introduced the first intermodal container (Singh et al., 2012), which was the first step in the containerization. El Yaagoubi et al. (2016) defined the containerization as: "a system that involves the transportation of freight using intermodal containers". During the 1960s, the container shipping industry appeared quickly and its performances advanced rapidly over the years (Roso et al., 2009). Since the early 1990s, world container traffic has been growing at almost three times world GDP growth (UN ESCAP, 2005). In the Netherlands, the Dutch government expects the container flow to keep growing over the next 20 years (Ministry of infrastructure and environment, 2017). They are anticipating on this by expanding the port of Rotterdam by 20%, creating an extra transshipment capacity of 17 million containers per year (Projectorganisatie Maasvlakte, 2010).

Notteboom and Rodrigue (2009) stated that: "it is underlined that the future of containerization will dominantly be shaped by inland transport systems". Inland transport is often referred to as the hinterland (the interior region served by the port (Van Klink and Den Berg, 1998)) transport and is of key importance for the overall performance of maritime transport (Almotairi et al., 2011). Bergqvist (2012) showed that the hinterland transport system benefits from the use of high capacity transport modes, such as trains and barges, for advantages in terms of faster throughput in ports, economies of scale, less delay related to road congestion, less accidents and decreased environmental impact. Hence, authorities are supporting the shift of the hinterland transport distribution more towards rail and inland waterway transport instead of road transport. In the Netherlands, for example, the expectation is that the inland shipping will grow from 2 million Twenty-foot Equivalent Units (TEU) to 8 million TEU per year in 2035 and will cover 45% of the total container discharge

(Projectorganisatie Maasvlakte, 2010). The response of the terminal operators and shipping companies, is investments in new technologies to improve the container handling and operational efficiency, which are both largely affected by loading and unloading operations (Imai et al., 2002; Rashidi and Tsang, 2013).

Among these operations is the container stowage planning (CSP) (Steenken et al., 2004), which concerns the exact position of containers on a boat with the goal of maintaining stability during navigation. The general CSP was defined by Ambrosino et al. (2006) as: "given a set C of n containers of different types to load on a ship and a set S of m available locations within the ship, we need to determine the assignment of the containers to the ship locations in order to satisfy the given structural and operational constraints related both to the ship and to the containers". CSP is a difficult operational problem (Gharehgozli et al., 2016) and is even proven to be NP-complete (Avriel et al., 2000). Available literature rather focuses on large container vessels transporting thousands of containers and related developed models contain several assumptions or are oversimplified due to the base complexity of the problem and large number of containers handled. See for example Zhang and Lee (2016), who assume that all containers are the same type, length and height, or Liang et al. (2016), who excluded all the stability constraints and assume that all containers are the same type.

With concern to barges, literature is lacking. However, the specific boat category, which is handling hundreds of containers at the most instead, offers opportunities to develop more accurate models. From a more practical point of view, presently CSP for barges (CSPB) is solved manually by the skippers of the barges, using mainly rules of thumb and their experiences. They are supported by decision support tools that graphically represent the ship, calculate measurements associated with static constraints, and notify them when potential plans do not meet static constraints (Gumus et al., 2008). However, this method is basically trial and error and may result in containers rejection if stability is not reached and consequently harming the economies of scale.

Hence, the aim of this study is to determine and mathematically model the objectives and constraints taken into account during the stowage process on a barge. Since the literature is still very scarce on the CSPB, a case study is conducted to generate a complete analysis of the problem and to gain an understanding of underlying reasons, opinions, and motivations during the decision making process of stowage planning on barges.

This paper is organized as follows. In Section 2, the previous research on CSP and CSPB will be discussed. In Section 3, a general problem description will be given, the case study will be discussed briefly and all the possible constraints during the stowage process of a barge will be clarified. In Section 4, the mathematical model will be formulated. In Section 5, numerical experiments based on real life data obtained from the case study will be presented. Finally, in Section 6 the thesis will be concluded and future research directions will be recommended.

2 Background

2.1 Container stowage problem

Due to the fact that the CSP is a NP-complete problem (Avriel et al., 2000), researchers focused on heuristic methods and approximation algorithms to solve the CSP. Most of them focused on a single best solution and are, according to Cohen et al. (2017), characterized by area of the vessel stowage loading plans, the number of phases of the solution and the optimization method. In 1970, Webster and Van Dyke (1970) performed the first ever research on this problem, although the addressed problem was quite simplistic and their methods were never proven to be robust. Monaco et al. (2014) state that: "the wide variety of settings, assumptions, and objectives considered in the previous studies highlights the lack of a commonly accepted view of the problem".

The majority of the research is dedicated to the CSP for a single port, which is also commonly denoted as the master bay planning problem (MBPP). With regard to this problem, Aslidis (1989) showed that the CSP can be modelled as a combinatorial optimization problem and created an set of heuristic algorithms which solve the CSP efficiently. Avriel et al. (1998) created the suspensory heuristic (SH) procedure, which is a dynamic slot-assignment scheme that terminates with a stowage plan. However, this SH was later questioned by Dubrovsky et al. (2002) because of its inflexibility in dealing with constraints. Imai et al. (2006) were the first that conducted research on the relationship between the loading-related rehandle and the ships stability. They defined the problem as a multi-objective integer programming, solved it with the weighing method and their experiments showed that a set of noninferior solutions could be created within a reasonable time. More recent work from Zhang and Lee (2016), also modelled the CSP as a multi-objective problem and considered three ship stability and three container rehandles objectives. As a solution method, they proposed a local search component combined with a variant of the nondominated sorting genetic algorithm III (NSGA-III).

Several studies have been performed on the CSP for multiple ports, also denoted as Multi-Port MBPP (MP-MBPP). To solve this problem, Ambrosino et al. (2015) presented a new mixed integer programming (MIP) model which was solved with a commercial MIP solver. The performed experiments showed that the model can face real-size instances of the problem and solve them efficiently. In Ambrosino et al. (2017), they extended this study and developed two solution methods using a two-step decomposition approach. Extensive computational experimentation showed that the proposed models and related solution methods are effective. Ding and Chou (2015) developed a heuristic algorithm to generate a stowage plan with a tolerable number of shifts. It was even proven to perform better than the SH algorithm in Avriel et al. (1998), which is, according to Ding and Chou (2015), still one of the leading heuristic algorithms. Fan et al. (2010) created an algorithm that applies an efficient block-based container allocation heuristic method while considering constraints in the real-world operations of commercial shipping lines. In 2015, this study was reviewed by Lee et al. (2015). They changed the sequence of constraints and checked the effect on the execution. Experiments showed that they could achieve the stowage planning algorithm to be twice as fast on average.

In contrary to the studies mentioned above, the following studies divided the problem into two different phases. The master planning phases (MPP), assigning container groups to a bay section, and the slot planning phase (SPP), assigning containers to a specific slot. Pacino et al. (2011) combined mixed integer programming for the MPP and a slot planning algorithm for the SPP which generated a stowage plan within 330 seconds for 80% of the instances used. Ambrosino et al. (2006) created a branching tree for the MPP and used a 0/1 linear programming model for the SPP. They had the aim of minimizing the total loading time of the containers on the ship and satisfying weight, size and stability constraints, related to weight distribution. Several studies only focused on the SPP. In promising research, Monaco et al. (2014) combined this CP algorithm with the local search (LS) heuristic from Pacino and Jensen (2009), to solve the SPP of the CSP. The model included some weight

constraints for stacks, but it lacked stability constraints. Liang et al. (2016) solved the SPP problem for single destination slot planning and for mixed destination slot planning. For the latter, the Social Network-based Swarm Optimization Algorithm (SNSO) was used with the assumption made that all the containers are the same type. Parreño et al. (2016) found a high-quality solution (within 1 s) by the use of a Greedy Randomized Adaptive Search Procedure (GRASP). They included features as odd-sized containers and IMO containers.

Where the previously mentioned studies focused on solving the problem, there is also a group of researchers that conducted studies to specifically create an automated stowage system. Low et al. (2011) stated that: "the automated stowage system consists of three modules: stowage plan generator, stability module and optimization engine". In Low et al. (2010), they presented the architecture of an automated stowage system and the work of the first module, the stowage plan generator. In Aye et al. (2010), they presented a tool for the visualization and simulation of automated stowage plan generation for large containerships. Followed by Low et al. (2011) and Zeng et al. (2010), where they focused on the stability module and created a heuristic algorithm that is able to efficiently generate feasible stowage plans within a reasonable time. A study with the similar goal is performed by Cohen et al. (2017), who developed and designed a novel evolutionary metaheuristic algorithm based software system. The software system provides a complete layout of containers as a planning tool and the planner is allowed to make changes when necessary.

2.2 Container stowage problem on barges

To our knowledge, the literature related to the CSPB is quite scarce (Hu and Cai, 2017; Li et al., 2017; El Yaagoubi et al., 2016). El Yaagoubi et al. (2016) combined the CSP with the Travelling Salesman Problem (TSP), but proposed a very simple version of the problem. They included a single barge with: one container stack, one type of container and each destination port asks for the delivery of only one container. Li et al. (2017)

were inspired by the good results of Parreño et al. (2016), to tackle the MP-MMPP with a GRASP and used a heuristic evolutionary strategy algorithm (HES) to solve the SPP. Computational experiments showed that both the methods generated a good solution in a short CPU time. However, they excluded different types and heights of containers from their study and also their stability tolerance was static instead of variable depended on the total weight of the freight. Hu and Cai (2017) mention the lack of safety considerations in the solution methods for the CSP and selected both, the trim and rolling time, as optimization indexes. They put forward a heuristic algorithm to generate an initial solution, which is subsequently optimized with a genetic algorithm that ensures the safety of the ship. Their model excludes different types of containers, different container heights and the angle of list. Additionally, the stability tolerance is static instead of variable. The overall consensus in these papers is that the CSP and CSPB have some differences. First of all, the stability and trim are more sensitive to the stowage plan, since the barges have much less capacity and hatch covers are absent. Next to that, the skippers of the barges emphasize the capacity utilization more than schedules.

This paper contributes to fill the gap between the existing simplified models mentioned above and the market demand for all-encompassing software, including a computational engine that advises possible stowage plans. Our model will have the most similarities with the MBPP model of Ambrosino et al. (2004). However, our model will relate to barges, resulting in additional limitations. The small capacity, the focus on capacity utilization and the high sensitivity to the stowage plan of a barge offers opportunities for a more accurate model. For example, allowing stacks to include 20ft and 40ft containers at the same time, will improve the capacity utilization. Additionally, the structural works and the dimensions of the waterways leads to minimum and maximum weight constraints. Also, high cube containers are very common nowadays and should be included in the model. Finally, the stability tolerance is variable depending on the total weight of the freight, tiers used and the presence of high cube containers on the barge, instead of a constant.

3 Problem description and case study

3.1 Problem description

Stowage planning is the process of assigning containers to a certain location on the barge. The capacity of a barge is expressed in TEU. The cargo space is divided into a cellular structure existing of slots which are designated by three different coordinates: a *bay*, a *row* and a *tier* (see Figure 1). Slots can hold exactly one TEU (Monaco et al., 2014), i.e. the bottom two boxes of the stack in Figure 3. A *bay* is the longitudinal coordinate and consists of even numbered 40ft bay sections and odd numbered 20 ft bay sections, as can be seen in Figure 2. A 20ft container can be indicated by its 20ft container bay or the stackfore/stackaft of a 40ft container bay (see Figure 3). The transversal and vertical coordinates are given by, respectively, the *row* and the *tier* (see Figure 3).

Figure 1: Slot positions are identified by their row, bay and tier

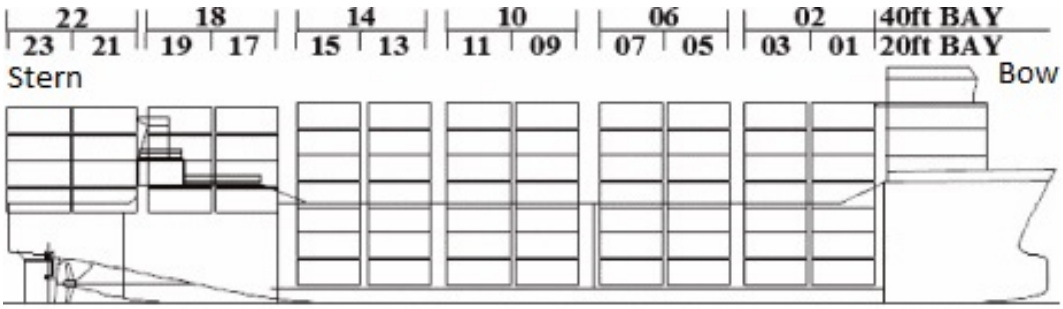

Figure 2: 20ft and 40 ft bays (Hu and Cai, 2017)

The freight on these barges is transported in International Organization for Standardization (ISO) containers. When a *20ft*, *40ft* or *45ft* container is addressed, it is referring to its length and it has the standardized height of 8′6 ft and width of 8ft. Additionally, there are several containers with odd sizes or containers that need special treatments during the stowage process. *High Cube* containers (HC) are 9′6 ft high and pallet wide containers have a width of $8\frac{15}{16}$ft. Refrigerated containers are referred to as *reefers* and will need to be located next to a power plug, as can be seen in the bottom two rows in Fig. 3. Containers filled with dangerous goods are referred to as *IMO* containers, since they have to follow the International Maritime Dangerous Goods Code (IMDG Code) developed by the International Maritime Organization.

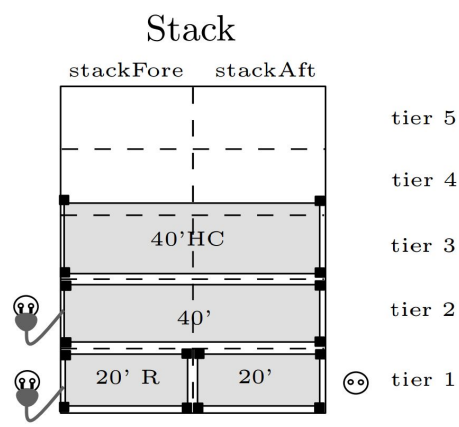

Figure 3: Side view of a single stack of containers, as illustrated, power plugs are often fixed points at the bottom. (Delgado et al., 2009)

Due to the cellular structure, cranes and reach stackers can only access the containers on top of the stacks. This leads to the situation that container x can be stacked on top of container y, while container y has to be unloaded at an earlier port of destination (POD)

than container x. In this case, container x is *overstowing* and leads to a unnecessary handling of container y. This unnecessary handling operation is called a *shift* and is known to be time and money consuming (Ding and Chou, 2015).

The overall goal of the stowage planning process is to create a feasible plan that maximizes the amount of stowed containers. The feasibility is mainly determined by the capacity and safety constraints. All this together, makes the container stowage problem very complex which is presently, still solved by the skippers themselves, using a trial and error method. This resulted in a demand for a software package containing a computational engine that advises possible stowage plans within a reasonable time. This engine should be able to find an optimal or near-optimal stowage plan. In order to create this software package, it is required to have a detailed mathematical model of the stowage process on a barge.

3.2 Case study management

In this subsection we will briefly elaborate on the involved companies, involved barge, existing software package and the data flow during a trip of a barge. It is a single case study based on semi-structured interviews, observations of the author and access to data/software packages of the involved companies below.

3.2.1 Barge 'Victor'

This study focuses on the barge called 'Victor', which operates between the Inland Terminal Veghel (ITV) and the port of Rotterdam. It has a capacity of 108 TEU in total. It can contain 12 20ft containers in the longitudinal, 3 in the transversal and 3 in the vertical direction. This means that it can be divided into 3 rows, 3 tiers, 6 40ft bays or 12 20ft bays. It always contains 4 dummy containers of each 30t in weight. Dummys are 20ft containers filled with sand to lower the ship, which makes it easier to pass bridges. The specifications of this barge can be found Section 6.

3.2.2 Companies and people

The main fieldwork is conducted at the ITV, which is owned by Van Berkel Logistics (VBL). VBL is part of the Van Berkel Groep (VBG), which is a family company established in 1955. Over the years, it has grown into a versatile and flexible organization with over 140 employees, eight locations and an extensive machine park. VBL, was established in 2004, combines storage and transshipment with transport to and from the region. They offer transport between the seaports, Veghel and Cuijk, including pre- and post-transport in the form of trucks. In addition, they distinguish two types of activities: logistics in the field of maritime containers for shippers and freight forwarders on the one hand, and logistics of bulk goods and residual flows for companies on the other. They have three subsidiaries: ITV, 'Inland Terminal Cuijk' and 'Inland Shipping Service Van Berkel Shipping'. Today, Van Berkel Logistics's team consists of 43 employees. Another important company involved in this case study is Autena Marine (AM). AM has delivered ICT and navigation solutions for the inland shipping industry for over 20 years.

3.2.3 Container Planner

AM, has developed the most advanced software package for barge stowage planning that is currently available. The software package is called Container Planner (CP) and it, as stated in the Section 1, graphically represents the barge, calculates measurements associated with static constraints, and notifies the user when potential plans do not meet static constraints. It calculates the depth of the barge, the height of the barge, the weight per tier and the stability of the barge. Subsequently, it compares these variables to the parameters and returns an error when these are exceeded.

The software is not endowed with a computational engine that advises possible stowage plans. Thereby, the user must try to find a feasible stowage plan by hand. If a constraint is violated, the user will have to improve the plan based on his experience and rules of thumb.

3.2.4 Data flow

In Figure 4, the data flow of a barge during a inland trip is shown. If we relate this figure to our case study, the 'barge operator' is a planner from VBL, the 'vessel' is the Victor, the 'terminals' are the terminals in Rotterdam and the 'Fairway authority' is the Dutch fairway authority. The planners of VBL receive all the transportation requests from its clients. They assign the containers to the available barges. However, at this point it is unknown if a feasible stowage plan can be made with the assigned containers, since they only take the capacity of the barge into account. The planner of VBL sent the transportation plan, containing the list of containers, to the specific barges in the form of a standardized IFTMIN (International Forwarding and Transport Message - Instructions). IFTMIN is a popular international UN/EDIFACT (the United Nations rules for Electronic Data Interchange for Administration, Commerce and Transport) message that passes all kinds of information and instructions to the next link in the supply chain. The skipper of the barge uses the transportation plan to create a feasible stowage plan. If this is not possible, the skipper reports back to the planner who, on his turn, makes a new transportation plan. When it is possible to make a feasible stowage plan, the skipper sends a BAPLIE and MOVINS to the terminals of his destination. A BAPLIE provides the current situation in the form of the container's number, exact position on board and general information such as weight and hazardous cargo class. A MOVINS provides the actual stowage plan in the form of instructions regarding

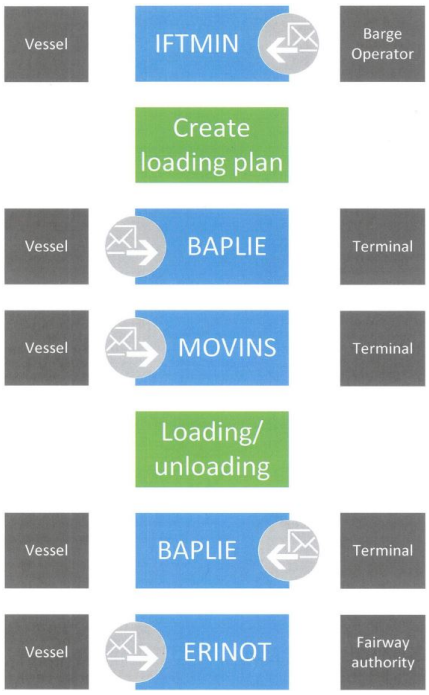

Figure 4: Data flow during inland shipping by barge

the loading, discharging and re-stowage of equipment and/or cargoes and the location on the barge where the operation must take place. With these two documents, the terminal executes the stowage plan and returns the updated BAPLIE to the barge when finished. In the Netherlands, the skipper is also required to send an ERINOT (ERI Notification message) to the fairway authority.

3.3 Constraints of the CSPB

In this subsection, a description of all the possible constraints of the CSPB will be given. Some of the CSP constraints, described in (see Subsection 2.1), will be applicable to the CSPB as well.

3.3.1 Barge Stability

Barge stability is very important for the prevention of a barge tipping over to port or starboard. Every barge that operates in the Netherlands, requires a stability document that is verified by a committee of experts (Ministerie van binnenlandse zaken, 2016). The Netherlands counts two of these committees, which are the 'Inspectie Leefomgeving en Transport' (IL&T) and the 'Nederlands Bureau Keuringen Binnenvaart' (NKBK). Stability documents provide the captain of the barge with comprehensible information on barge stability for each loading condition and it needs to include at least:

a. Information on the permissible stability coefficients, the permissible vertical distance from the keel to the center of gravity or the allowable center of gravity height of the cargo.

b. Data concerning the spaces that can be filled with ballast water

c. Forms for checking stability

d. A sample stability calculation or instructions for the skipper

The stability calculations mainly focus on the interaction between the center of gravity (G), center of buoyancy (B) and the metacenter (M) (see Figure 5 and Appendix 1). The center of gravity is: "an imaginary point in the exact middle of a weight where the entire weight may be considered to act. The force of weight always acts vertically downwards" (Maritime New Zealand, 2006) The center of buoyancy is: "an imaginary point in the exact middle of the volume of displaced water where the entire buoyancy may be considered to act. The force of buoyancy always acts vertically upwards" (Maritime New Zealand, 2006). The metacenter is: "is a point in space where the vertical line upwards through the center of buoyancy of the 'inclined' vessel cuts through the vertical line upwards through the center of buoyancy of the 'upright' vessel" (Maritime New Zealand, 2006).

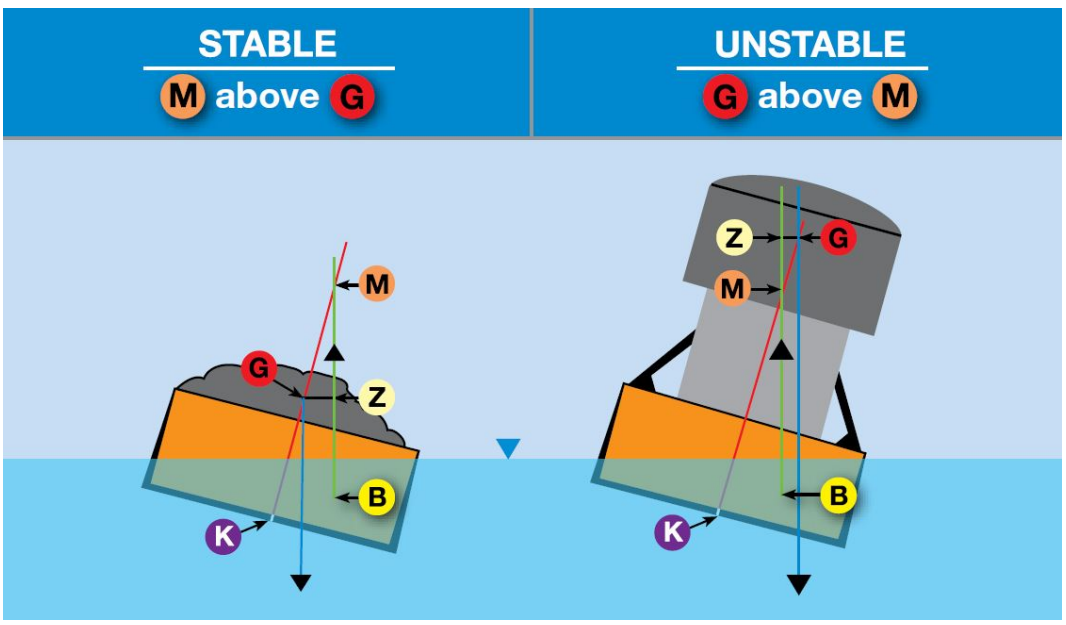

Figure 5: Cross section of a barge in a respectively stable and unstable situation (Maritime New Zealand, 2006)

In a stable situation, the G can never be above the M (see Figure 5). The value of the metacentric height (GM), which is the vertical distance between the metacenter and the center of gravity, should therefore always be positive. The relative position between the four points can be described in the following way (equation (1)) (Maritime New Zealand, 2006):

$$GM = KB + BM - KG \tag{1}$$

Where KB, KM and KG are all vertical distances in meters between the keel (K), B, G and M (see Figure 5). There are different ways to calculate the stability, but in our model we will use the stability calculations provided by the Dutch government. They express the stability requirements in a maximum vertical distance between the keel and the center of gravity (KG^{max}). The Dutch law provides two ways of calculating this by distinguishing between the transportation of non-secured and secured containers in these calculations. However, containers are not secured on most of the barges, including the Victor, and therefore only the calculations for non-secured containers are considered in this study. This calculation can be found below in Equation (2) (Van Pelt & Co B.V., 2014; Ministerie van binnenlandse zaken, 2016). Most of the symbols used can also be found in Appendix 1.

$$KG^{max} = \frac{KM + \frac{X_{wl}}{2F}(\frac{Z*T}{2} - h_{lwp} - h_{fls})}{\frac{X_{wl}}{2F}Z + 1} \tag{2}$$

Where KM is the distance between the metacenter and the keel out of its 'static stability curves' (if not available, it can be calculated with Equation (4)), X_{wl} is the width of the ship at the waterline, F is the available freeboard in the middle of the ship, Z is the coefficient for centrifugal force $(0,04[\frac{v^2}{L}])$, T is the draft (the distance between the waterline and the bottom of the hull (Christensen et al., 2016)), h_{lwp} is the arm of the moment caused by

lateral wind pressure and h_{fls} is the arm of the moment caused by free liquid surfaces.

KG^{max} depends on the weight and locations of the stowed freight on the barge. To show this, we will further decompose the KM and h_{lwp} component out of Equation (2) (Ministerie van binnenlandse zaken, 2016).

$$h_{lwp} = c_{lwp}\frac{A}{D}(l_w + \frac{T}{2})[m] \tag{3}$$

Where c_{lwp} is a coefficient ($c_{lwp} = 0.04[\frac{s^2}{m}]$), A is the lateral surface area above the waterline in $[m^2]$, D is the displacement in tons $[t]$, l_{wl} is the distance from the center of gravity of the lateral surface area until the waterline in $[m]$ and T is the draft in $[m]$.

$$KM = \frac{X_{wl}^2}{(12,7 - 1,2 * \frac{T}{H}) * T} + \frac{T}{2}[m] \tag{4}$$

Where X_{wl} is the width of the ship at the waterline, T is the draft and H is the moulded depth.

Equation (3) and (4) show that the lateral surface area above the waterline and draft are influencing the value of KG^{max}. To relax our model, we will use pre-calculated values of KG^{max} and KM (Van Pelt & Co B.V., 2014), which can partly be found in Appendix 2. We will refer to these pre-calculated values as $KG^{max}(\delta_{xyzi})$ and $KM(\delta_{xyzi})$. δ_{xyzi} will later be introduced (see Subsection 4.1) as the decision variable that specifies the location of the ith container stowed in the xth bay, the yth row and the zth tier.

The ensure the barges stability: $KG \leq KG^{max}$. KG can be calculated with the following equation:

$$KG = KG_0 + \frac{\sum_i w_i z_i}{W_h^b + \sum_i w_i} \tag{5}$$

Where KG_0 is the light weighted distance from the keel to the center of gravity (including half of the maximum water, oil and fuel supply (Ministerie van binnenlandse zaken, 2016)), z_i is the height coordinate of the ith container, z_0 is the height of the initial center of gravity, W_h^b is the lightship weight + half of the maximum water, oil and fuel supply, w_i is the weight of the ith container.

The general rule of thumb, currently used by the skippers, is to stack containers by non-decreasing weight from the bottom. This should guarantee a good chance that the $KG < KG^{max}(\delta_{xyzi})$. However, when the set of containers is large, the rule of thumb is not feasible or very difficult to satisfy. For these reasons, this rule of thumb is not taken into account in our model, but we include $KG \leq KG^{max}(\delta_{xyzi})$ as a constraints.

3.3.2 Angle of list

The angle of list (θ) is the angle in which a ship is heeling over to port or starboard. The goal is always to minimize the angle of list and it can be calculated as follows (Zhang and Lee, 2016):

$$\tan(\theta) = \frac{\sum_i w_i (y_i - y_0)}{(W_0^b + \sum_i w_i) * GM} \tag{6}$$

Where w_i is the weight of the ith container, y_i is the y-coordinate of the ith container, W_0^b is the weight of the barge without containers and GM is the distance between the center

of gravity and the metacenter. GM can be calculated as follows:

$$GM = GM_0 + \frac{\sum_i w_i(z_i - z_0)}{W_h^b + \sum_i w_i} \tag{7}$$

Where GM_0 is the light weighted distance from the center of gravity to the metacenter, z_i is the height coordinate of the ith container, z_0 is the height of the initial center of gravity, W_h^b is the lightship weight + half of the maximum water, oil and fuel supply, w_i is the weight of the ith container.

3.3.3 Trim

The trim of a barge is the difference between the draft forward and aft (Walsh, 1972) (see Equation (9) and Figure 7). Trim as a verb is referring to the act of angular rotation about the y-axis (see Figure 6) (Tupper and Rawson, 2001), going from a certain angle to another. This angle (θ_l) is called the longitudinal trim angle (mentioned as θ in Figure 6 and 7) and can be calculated with Equation (8).

$$\theta_l = \frac{T_A + T_F}{LBP} \tag{8}$$

$$t = T_A - T_F \tag{9}$$

Where θ_l is the longitudinal trim angle, T_A is the draft aft, T_F is the draft forward, LBP (L in Figure 7) the horizontal distance between the perpendiculars at which T_A and T_F are measured and t the trim of the barge.

Trim is needed to maximize the performance of the barge while sailing. It is also im-

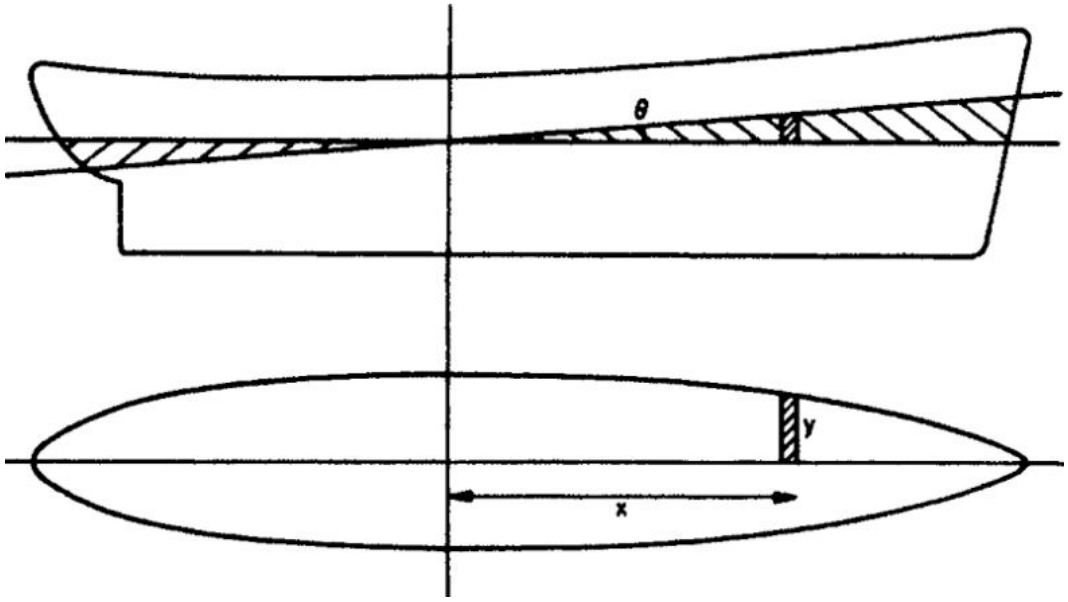

Figure 6: The y-axis of a barge (Tupper and Rawson, 2001)

portant to know the trim while passing a bridge or entering a lock/port, since it changes the height and the draft of the barge. When the forward draft is greater than the draft aft, the barge can be defined as trimmed by the stern. Vice versa the barge can be defined as trimmed by the bow. The skipper of the Victor mentioned the trim as one of the most important factors to consider while stowing. The Victor is slightly trimmed by the stern when empty and is optimally trimmed by the bow with $10cm - 15cm$ while sailing. This way it will use the least fuel. The trim is usually measured between perpendiculars or between marks (Tupper and Rawson, 2001), as can be seen in Figure 7. The exact trim can be calculated with the following equation (Zhang and Lee, 2016):

$$t = \frac{LBP * \sum_i w_i(x_i - x_0)}{(W_0^b + \sum_i w_i) * GM_L} \tag{10}$$

Where GM_L is the distance between the center of gravity G and the longitudinal meta-

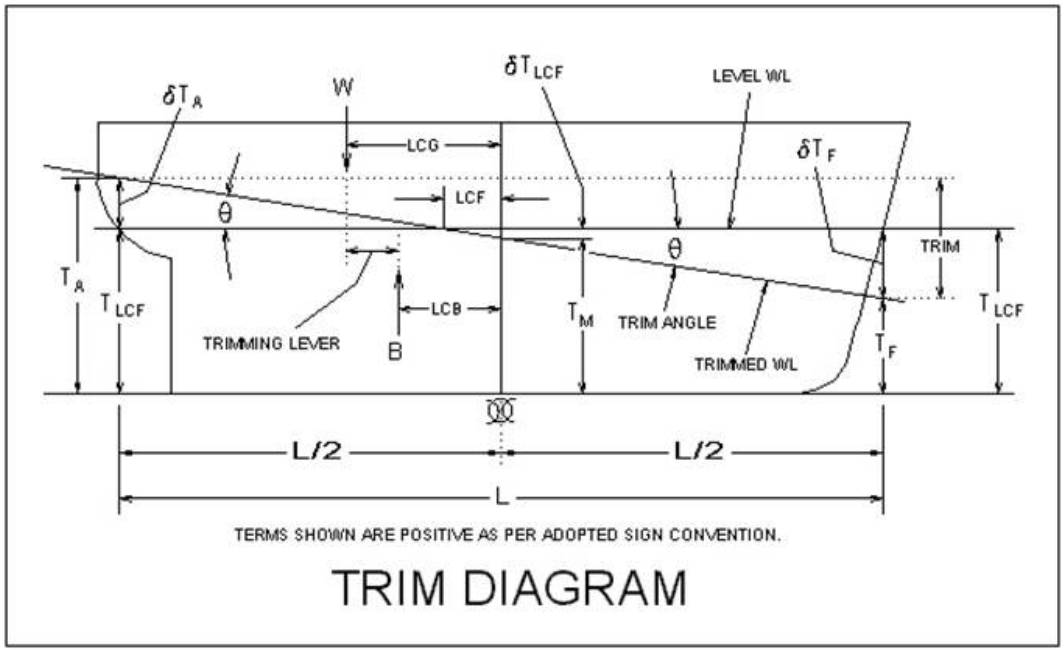

Figure 7: The trim of a barge (Tupper and Rawson, 2001)

center M_L, x_i is the x-coordinate of the ith container, x_0 is the x-coordinate of the initial center of gravity, w_i is the weight of each container and W_0^b is the weight of the barge without containers. While creating static stability curves, the actual center of gravity is still unknown. Therefore, they are based on the fact that $GM_L \simeq BM_L$. BM_L for a boxed shape ship, used when static stability curves are lacking, is computed as follows (Barrass, 2000):

$$BM_l = \frac{L^2}{12T} \tag{11}$$

Where T is the draft of the barge and L is the length of the barge.

Inserting Equation (11) into Equation (10) results in the following equation for the trim (Barrass, 2000):

$$t = \frac{12 * T * \sum_i w_i(x_i - x_0)}{(W_0^b + \sum_i w_i) * L} \tag{12}$$

The difference between the original trim and final trim is called the change of trim (cot). The change of trim can be calculated with Equation (13)

$$cot = \frac{\sum_i w_i(x_i - x_0)}{MCT} \tag{13}$$

Where MCT is the moment required to change the trim by one centimetre. A barge can be trimmed in two different ways, with and without a change in the displacement of the barge. When the barge is trimmed without the change of displacement, weight is being moved on the barge itself and the ship trims about the center of flotation. The draft at the center of flotation does not alter. However, it does alter on every other position, including amidships where the mean draft between perpendiculars occurs (Tupper and Rawson, 2001). When a barge is trimmed with the change of displacement, a weight is added to or removed from the barge. The only possibility to change the displacement without changing the trim is over the center of flotation. In this case, the center of buoyancy of the added weight has to be at the center of flotation which avoids an out-of-balance moment. The displacement of a barge is recorded for different mean drafts except for a specified design trim. According to the Dutch laws (Ministerie van binnenlandse zaken, 2016), the summation of the trim angle and the angle of the heeling of the barge may not exceed 10°.

3.3.4 Overstowage

One of the most important factors during the stowage process is, as discussed in Section 3, the prevention of overstowage. It leads to rehandles which are expensive and should always be minimized or, when possible, eliminated. In order to reach this goal, a container may not be placed on top of a container which has a later POD.

3.3.5 Types of containers

Freight containers are standardized by the International organization for standardization (ISO). The ISO is a worldwide federation of national standards bodies and their technical committee: General Purpose Containers (2013) wrote a technical report on the specifications of the standardized freight container types. They distinguished 5 different types of containers:

I General cargo containers for general purposes

II Thermal containers

III Tank containers for liquids, gases and pressurized dry bulk

IV Non-pressurized containers for dry bulk

V Platform and platform-based containers

The containers that are the most relevant for the barge transport are the general cargo con-

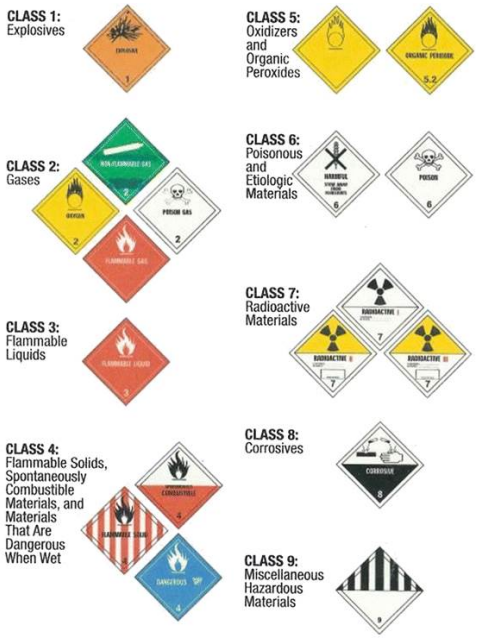

Figure 8: Dangerous container types (Ambrosino and Sciomachen, 2015)

tainers and the thermal containers. In 2012,
89.2% of the freight containers in use were containers for general purpose, and 7% of the containers were the so called thermal containers, according to a report published by Drewry Maritime Research (Research, 2012). The thermal containers are mostly refrigerated containers (reefers), which are used for products that are temperature sensitive. The cooling system of the reefers needs power and it is prohibited to locate these next to a container with a dangerous load or the fuel tank of the barge itself. Therefore the different types of containers that should be taken into account for the mathematical model are:

1. **Standard containers**
2. **Reefers**
   - Can only be placed at designated slots (Avriel and Penn, 1993). Mostly near power points and separated from hazardous containers and the barges fuel tanks (Ambrosino et al., 2006).
3. **Out of gauge containers**
   - These are containers that have a different size to the standardized container sizes as discussed in Subsection 3.3.6. They do not fit exactly into a twenty-foot equivalent (TEU) slot.
4. **Hazardous containers**
   - These containers contain dangerous loads and should be loaded according to segregation rules (Ambrosino and Sciomachen, 2015). The different types of dangerous containers can be found in Figure 8. (Ambrosino and Sciomachen, 2015) separated these segregation rules into four stowage principals, which can be found below.
5. **Open top containers & flat racks**
   - These containers can only be placed on top of a stack

CLASS		1.1 1.2 1.5	1.3 1.6	1.4	2.1	2.2	2.3	3	4.1	4.2	4.3	5.1	5.2	6.1	6.2	7	8	9
Explosives	**1.1, 1.2, 1.5**	*	*	*	4	2	2	4	4	4	4	4	4	2	4	2	4	X
Explosives	**1.3, 1.6**	*	*	*	4	2	2	4	3	3	4	4	4	2	4	2	2	X
Explosives	**1.4**	*	*	*	2	1	1	2	2	2	2	2	2	X	4	2	2	X
Flammable Gases	**2.1**	4	4	2	X	X	X	2	1	2	X	2	2	X	4	2	1	X
Non-toxic, Non-flammable Gases	**2.2**	2	2	1	X	X	X	1	X	1	X	X	1	X	2	1	X	X
Toxic Gases	**2.3**	2	2	1	X	X	X	2	X	2	X	X	2	X	2	1	X	X
Flammable Liquids	**3**	4	4	2	2	1	2	X	X	2	1	2	2	X	3	2	X	X
Flammable Solids	**4.1**	4	3	2	1	X	X	X	X	1	X	1	2	X	3	2	1	X
Substances liable to sponateous combustion	**4.2**	4	3	2	2	1	2	2	1	X	1	2	2	1	3	2	1	X
Substances which, in contact with water, emit flammable gases	**4.3**	4	4	2	X	X	X	1	X	1	X	2	2	X	2	2	1	X
Oxidizing Substances (agents)	**5.1**	4	4	2	2	X	X	2	1	2	2	X	2	1	3	1	2	X
Organic Peroxides	**5.2**	4	4	2	2	1	2	2	2	2	2	2	X	1	3	2	2	X
Toxic Substances	**6.1**	2	2	X	X	X	X	X	X	1	X	1	1	X	1	X	X	X
Infectious Substances	**6.2**	4	4	4	4	2	2	3	3	3	2	3	3	1	X	3	3	X
Radioactive Materials	**7**	2	2	2	2	1	1	2	2	2	2	1	2	X	3	X	2	X
Corrisive Substances	**8**	4	2	2	1	X	X	X	1	1	1	2	2	X	3	2	X	X
Miscellaneous Dangerous Substances and Articles	**9**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 9: Segregation table of different types of dangerous containers (Ambrosino and Sciomachen, 2015)

Figure 9 shows which types of containers are linked to the following four separation principles:

1. 'Away from': Avoid certain slots on the barge, bottom tier or outer for example
2. 'Separated from': Never place in the same stack, always have at least one slot in between.
3. 'Separated by a complete compartment from': Never place in the same stack, hold or above the same hold.
4. 'Separated longitudinally by an intervening complete compartment or hold from': minimum distance of two bays (24m) must be maintained longitudinally.

3.3.6 Size and weight of containers

The report of technical committee: General Purpose Containers (2013) also discusses the standardized sizes, max gross weights and empty weights of containers. There are basically four standardized sizes and the rest can be categorized as out of gauge containers as discussed in Subsection 3.3.5. Their dimensions, max gross weight and empty weight can be found in Table 1.

Container	**20'**	**40'**	**40' high cube**	**45' high cube**
Length	6.058m	12.192m	12.192m	13.716m
Width	2.438m	2.438m	2.438m	2.438m
Height	2.591m	2.591m	2.896m	2.896m
Max gross weight	30.480kg	30.480kg	30.480kg	30.480kg
Empty weight	2200kg	3800kg	3900kg	4800kg

Table 1: Freight container dimensions and weights

All these different types of containers result in a couple of rules that have to be followed during the stowage process.

1. 20'ft containers can not be stacked on top of 40'ft containers. Only vice versa.
2. Reefers can only be assigned to certain slots. These slots have power plugs available and are mostly located at the bottom tiers. A 40-foot reefer container must be placed in a slot with at least one reefer slot, either Fore or Aft.
3. Hazardous/dangerous containers: have to be located according to the segregation principles discussed in Subsection 3.3.5.
4. The heaviest containers should be located at the bottom as much as possible. This maintains the barges stability and the stack stability.
5. Open top containers and flat racks can only be placed on top of a stack.

3.3.7 Waterways

A difference between the CSP and the CSPB are the structural works and the dimensions of the waterways. The structural works contain bridges, locks, dams, dykes and ship lifts. These create extra limitations, like a minimum or maximum weight, and should be known to the skippers. This minimum and maximum weight are similar to a minimum and maximum height, since there is a linear relationship between the total weight and the draft of the barge.

During the council of ministers meeting at Athens on 11 and 12 June 1992, a resolution on newest classification of inland waterways was determined (see Appendix 3) (Council of ministers, 1992). This resolution is the European guideline for the governments of each country who are responsible for classifying their waterways into one of the CEMT-classes. The governments should set out a document of all their waterways considering all the characteristics like the fairway locations, maximum height under bridges, waterway outline, permissible draught, recommended dimensions for locks and other elevators for ships. The objective of this document is to: "achieve the best and as complete as possible exchange of information between each inland waterway user". The ECE and ECMT's maps of European inland waterways will also be reviewed by a group of experts, in view of the same objective.

3.3.8 Weather

The weather does have influence on the barge while sailing and should not be ignored in the stowage process. However, the boundaries for the angle of list, trim and stability, that are set by the government, do already assume extreme weather conditions. Therefore, there are no separated weather constraints that should be included in the mathematical model.

4 Mathematical model

All the possible constraints mentioned in Subsection 3.3 form overall a very complex scenario. In consultation with ITV and the skipper of the Victor, it was decided to make the following key assumptions for our model:

1. The barge makes a single trip from the port of Rotterdam back to ITV
2. Hazardous and out of gauge containers are not transported by the Victor
3. The Victor is able to drive from Rotterdam to ITV when carrying its maximum tonnage

With the first constraint, all the containers in a set have the same final destination. Hence, overstowage is left out of the scope. With respect to the second assumption, hazardous containers do not occur on the Victor and out of gauge containers are very rare. For these reasons, both will be left out of scope as well. Concerning the third assumption, there is no extra limitation of the freight's maximum weight based on the waterways. However, it is still limited by the maximum capacity of the barge. ITV aims to use the capacity of their barge fleet as efficiently as possible, hence the objective is to maximize the number of TEU stowed on the barge. We will model the CSPB as a mixed integer linear program (MILP).

4.1 Formulation

The mathematical model is characterized as follows. Consider a set of containers $I = (1...I)$ which consist of a subset of 20 ft containers $C = (1...C)$ and a subset of 40 ft containers $F = (1...F)$. Each container has weight W_i^c and height $h_i \forall i \in I$. The binaries TP_i, R_i^c and O_i^c are set 1 if the ith container happens to be a high cube, reefer or open top respectively. The set of bays from bow to stern on the barge are defined by X, the set of rows from port-side to starboard by Y and the set of tiers from the bottom up by Z. X consists of subset X_{20} containing all 20 ft bays and subset X_{40} containing all the 40 ft bays. The bay, row and tier refer to a certain slot on the barge and it contains a reefer slot when R_{xyz} is set to 1 for $x \in X$, $y \in Y$ and $z \in Z$.

In the model, we use three different weight parameters for the barge. W_{min}^b is the minimum total weight of the barge + freight needed to pass all the bridges on the concerning river. W_0^b defines the weight of a completely empty barge, whereas W_h^b defines the weight of an empty barge including half of the maximum liquid stock on board (f.e. drinking water, oil and fuel). θ_{max} is considered to be the maximum angle of list. We define the minimum and maximum trim values are by T_{min} and T_{max}. The moment that is needed to change this trim by 1 cm is considered to be MCT. The distance between the keel of the barge and the bottom, where the containers in the first tier are stowed on, is defined by h_f. The initial center of gravity of the barge is defined by X_0, Y_0 and Z_0 (we denote Z_0 as KG_0 in our model). $X_x \forall x \in X$ and $Y_y \forall y \in Y$ are the center of gravity of each bay and row respectively. The center of gravity of each tier is not tier specific, since the container heights are variable in our model. We will refer to the z-coordinate of the ith containers center of gravity as $KG_i \forall i \in I$. The final parameter M is a sufficiently large number.

To characterize the assignment of containers to a certain slot on the barge, the binary variable $\delta_{xyzi} \forall x \in X, \forall y \in Y, \forall z \in Z, \forall i \in I$ equals 1 if the ith container is assigned to slot xyz, and equals 0 otherwise. The continuous variable H_i defines the distance between the

keel of the barge and the top of the ith container. The continuous variable $KM(\delta_{xyzi})$ is the distance between the keel of the barge and the metacenter depending on the containers stowed on the barge δ. Similarly, is $KG^{max}(\delta_{xyzi})$ the distance between the keel and the center of gravity of the barge. GM is the distance between the center of gravity of the barge and the metacenter. All the sets, parameters and variables that we use in our model are shortly described in Table 4.1 below.

Sets, parameters and variables

Sets	
X	Set of bays. Skipping multiples of 4 $\{1, 2, 3, 5, 6, 7, 9, 10, ..., X\}$
$X_{20} \subset X$	Subset of 20ft bays from bow to stern. $\{1, 3, ..., X_{20}\}$
$X_{40} \subset X$	Subset of 40ft bays from bow to stern $\{2, 6, 10, ..., X_{40}\}$
Y	Set of rows from port-side to starboard $\{1, ..., Y\}$
Z	Set of tiers from the bottom to the top $\{1, ..., Z\}$
I	Set of containers $\{1, ..., I\}$
$C \subset I$	Subset of 20' containers $\{1, ..., C\}$
$F \subset I$	Subset of 40' containers $\{1, ..., F\}$
Parameters	
W^b_{min}	Minimum total weight of the barge + freight
W^b_0	Lightship weight
W^b_h	Lightship weight + half of the maximum liquid stock
W^c_i	Weight of the ith container, $\forall i \in I$
θ_{max}	Maximum angle of list
t_{min}	Minimum trim desired
t_{max}	Maximum trim desired
MCT	Moment needed to change the trim by $1cm$
$R_{xyz} \in \{0, 1\}$	Set 1 when slot $\{xyz\}$ has a reefer plug, 0 otherwise, $\forall x \in X$, $\forall y \in Y$, $\forall z \in Z$
h_f	Distance between the keel and the bottom of the first tier
h_i	Height of the ith container, $\forall i \in I$
$R^c_i \in \{0, 1\}$	Set 1 if the ith container is a reefer, 0 otherwise, $\forall i \in I$
$TP_i \in \{0, 1\}$	Set 1 if the ith container is a high cube, 0 otherwise, $\forall i \in I$
$O^c_i \in \{0, 1\}$	Set 1 if the ith container is an open top, 0 otherwise ,$\forall i \in I$
KG_0	z-coordinate of the initial center of gravity (see Figure 5)
X_0	x-coordinate of the initial center of gravity
X_x	x-coordinate of the xth bay's center of gravity
Y_0	y-coordinate of the initial center of gravity
Y_y	y-coordinate of the yth row's center of gravity
M	Sufficiently large value
Variables	
$\delta_{xyzi} \in \{0, 1\}$	Set 1 if the ith container is stowed in slot xyz, 0 otherwise, $\forall x \in X$, $\forall y \in Y$, $\forall z \in Z$, $\forall i \in I$
H_i	z-coordinate of the ith container's top, $\forall i \in I$
KG_i	z-coordinate of the ith container's center of gravity, $\forall i \in I$
$KM(\delta_{xyzi})$	Distance between the keel and the metacenter
GM	Distance between the center of gravity and the metacenter
$KG^{max}(\delta xyzi)$	Maximum z-coordinate of the barge's center of gravity

The formulation is as follows:

Objective:

$$\max \left(\sum_{x \in X_{20}} \sum_{y \in Y} \sum_{z \in Z} \sum_{i \in C} \delta_{xyzi} + 2 \sum_{x \in X_{40}} \sum_{y \in Y} \sum_{z \in Z} \sum_{i \in F} \delta_{xyzi} \right) \tag{14}$$

Subject to:

$$\sum_{x \in X_{20}} \sum_{y \in Y} \sum_{z \in Z} \delta_{xyzi} \leq 1 \qquad \forall i \in C \tag{15}$$

$$\sum_{x \in X_{40}} \sum_{y \in Y} \sum_{z \in Z} \delta_{xyzi} \leq 1 \qquad \forall i \in F \tag{16}$$

$$\sum_{i \in F} \delta_{xyzi} + \frac{1}{2} \sum_{k \in C} \delta_{(x-1)yzk} + \frac{1}{2} \sum_{m \in C} \delta_{(x+1)yzm} \leq 1 \qquad \forall x \in X_{40}, \forall y \in Y, \forall z \in Z \tag{17}$$

$$\sum_{i \in C} \delta_{xyzi} \leq 1 \qquad \forall x \in X_{20}, \forall y \in Y, \forall z \in Z \tag{18}$$

$$\sum_{i \in F} \delta_{xyzi} \leq 1 \qquad \forall x \in X_{40}, \forall y \in Y, \forall z \in Z \tag{19}$$

$$\sum_{i \in C} \delta_{xy(z-1)i} - \sum_{i \in C} \delta_{xyzi} \geq 0 \qquad \forall x \in X_{20}, \forall y \in Y, \forall z \in Z : z > 1 \tag{20}$$

$$\frac{1}{2} \sum_{i \in C} \delta_{(x+1)y(z-1)i} + \frac{1}{2} \sum_{i \in C} \delta_{(x-1)y(z-1)i} + \sum_{i \in F} \delta_{xy(z-1)i} - \sum_{i \in F} \delta_{xyzi} \geq 0 \qquad (\forall x \in X_{40}, \forall y \in Y, \forall z \in Z : z > 1) \tag{21}$$

$$\delta_{(1)(1)(1)(1)} + \delta_{(3)(1)(1)(2)} + \delta_{(21)(3)(1)(3)} + \delta_{(23)(3)(1)(4)} = 4 \tag{22}$$

$$R_i^c \delta_{xyzi} - R_{xyz} \leq 0 \qquad \forall x \in X, \forall y \in Y, \forall z \in Z, \forall i \in I \tag{23}$$

$$H_i \geq \delta_{xy1i}\left(h_f + h_i\right) - \left(\left(1 - \delta_{xy1i}\right) M\right) \qquad \forall x \in X, \forall y \in Y, \forall i \in I \tag{24}$$

$$H_i \leq \delta_{xy1i}\left(h_f + h_i\right) - \left(\left(1 - \delta_{xy1i}\right) M\right) \qquad \forall x \in X, \forall y \in Y, \forall i \in I \tag{25}$$

$$\begin{aligned} H_i \geq \delta_{xy2i} h_i + \sum_{j \in F} \left(\delta_{xy1j}\left(h_f + h_j\right)\right) + \sum_{k \in C} \left(\delta_{(x+1)y1k}\left(h_f + h_k\right)\right) \\ - \left(\left(1 - \delta_{xy2i}\right) M\right) \qquad \forall x \in X40, \forall y \in Y, \forall i \in F \end{aligned} \tag{26}$$

$$\begin{aligned} H_i \leq \delta_{xy2i} h_i + \sum_{j \in F} \left(\delta_{xy1j}\left(h_f + h_j\right)\right) + \sum_{k \in C} \left(\delta_{(x+1)y1k}\left(h_f + h_k\right)\right) \\ + \left(\left(1 - \delta_{xy2i}\right) M\right) \qquad \forall x \in X40, \forall y \in Y, \forall i \in F \end{aligned} \tag{27}$$

$$\begin{aligned} H_i \geq \delta_{xy2i} h_i + \sum_{j \in C} \left(\delta_{xy1j}\left(h_f + h_j\right)\right) - \left(\left(1 - \delta_{xy2i}\right) M\right) \\ \forall x \in X20, \forall y \in Y, \forall i \in C \end{aligned} \tag{28}$$

$$\begin{aligned} H_i \leq \delta_{xy2i} h_i + \sum_{j \in C} \left(\delta_{xy1j}\left(h_f + h_j\right)\right) + \left(\left(1 - \delta_{xy2i}\right) M\right) \\ \forall x \in X20, \forall y \in Y, \forall i \in C \end{aligned} \tag{29}$$

$$\begin{aligned} H_i \geq \delta_{xy3i} h_i + H_k + H_j - \left(\left(1 - \delta_{xy3i}\right) M\right) - \left(\left(1 - \delta_{xy2j} - \delta_{(x+1)y2k}\right) M\right) \\ \forall x \in X40, \forall y \in Y, \forall i \in F, \forall j \in F, \forall k \in C \end{aligned} \tag{30}$$

$$\begin{aligned} H_i \leq \delta_{xy3i} h_i + H_k + H_j + \left(\left(1 - \delta_{xy3i}\right) M\right) + \left(\left(1 - \delta_{xy2j} - \delta_{(x+1)y2k}\right) M\right) \\ \forall x \in X40, \forall y \in Y, \forall i \in F, \forall j \in F, \forall k \in C \end{aligned} \tag{31}$$

$$\begin{aligned} H_i \geq \delta_{xy3i} h_i + H_j - \left(\left(1 - \delta_{xy3i}\right) M\right) - \left(\left(1 - \delta_{xy2j}\right) M\right) \\ \forall x \in X20, \forall y \in Y, \forall i \in C, \forall j \in C \end{aligned} \tag{32}$$

$$\begin{aligned} H_i \leq \delta_{xy3i} h_i + H_j + \left(\left(1 - \delta_{xy3i}\right) M\right) + \left(\left(1 - \delta_{xy2j}\right) M\right) \\ \forall x \in X20, \forall y \in Y, \forall i \in C, \forall j \in C \end{aligned} \tag{33}$$

$$KG_i = H_i - \frac{1}{2}h_i \qquad \forall i \in I \tag{34}$$

$$W_0^b + \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \geq W_{min}^b \tag{35}$$

$$\sum_{j\in C}\left(\delta_{(x-1)y(z-1)}h_j\right) - \sum_{k\in C}\left(\delta_{(x+1)y(z-1)}h_k\right) \leq M\left(1-\delta_{xyzi}\right) \qquad \forall x \in X40, \forall y \in Y, \forall z \in Z : z > 1, \forall i \in F \tag{36}$$

$$\sum_{j\in C}\left(\delta_{(x-1)y(z-1)}h_j\right) - \sum_{k\in C}\left(\delta_{(x+1)y(z-1)}h_k\right) \geq -M\left(1-\delta_{xyzi}\right) \qquad \forall x \in X40, \forall y \in Y, \forall z \in Z : z > 1, \forall i \in F \tag{37}$$

$$\frac{\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}\left(\delta_{xyzi}W_i^c\left(X_0 - X_x\right)\right)}{MCT} \geq t_{min} \tag{38}$$

$$\frac{\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}\left(\delta_{xyzi}W_i^c\left(X_0 - X_x\right)\right)}{MCT} \leq t_{max} \tag{39}$$

$$\sum_{i\in I}\left(O_i^c\delta_{xyzi} + \delta_{xy(z+1)i}\right) \leq 1 \qquad \forall x \in X, \forall y \in Y, \forall z \in Z \tag{40}$$

$$KG_0 + \frac{\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}\left(W_i^c KG_i\delta_{xyzi}\right)}{W_h^b + \sum_{i\in I}\delta_{xyzi}W_i^c} \leq KG^{max}(\delta_{xyzi}) \tag{41}$$

$$KM(\delta_{xyzi}) - KG_0 + \frac{\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}\left(W_i^c KG_i\delta_{xyzi}\right)}{W_h^b + \sum_{i\in I}\delta_{xyzi}W_i^c} = GM \tag{42}$$

$$\frac{\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}\left(\delta_{xyzi}W_i^c\left(Y_y - Y_0\right)\right)}{\left(W_0^b + \sum_{i\in I}\left(\delta_{xyzi}W_i^c\right)\right)GM} \leq tan(\theta_{max}) \tag{43}$$

$$\delta_{xyzi} \in \{0,1\} \qquad \forall x \in X, \forall y \in Y, \forall z \in Z, \forall i \in I \tag{44}$$

The Objective Function (14) maximizes the TEU's stowed on the barge. The first term counts the amount of 20ft containers stowed, while the second term counts the amount of 40ft containers stowed. This second term is multiplied by 2 since a 40ft container equals two 20ft containers. Inequalities (15) and (16) ensure that the 20ft and 40ft containers can only be stowed once, where Inequalities (19) and (18) ensure that the 20ft and 40ft slots can only be used once. Inequality (19) makes sure that the overlapping 20ft and 40ft slots are not used multiple times. Inequalities (20) and (21) impose that stowed containers are supported by others, they are not allowed to float. Constraint (22) adds the four dummy containers that are permanently stowed on the Victor to the model. Additionally, Inequality (23) ensures that reefer containers can only be stowed in a reefer slot.

Equations (24)–(33) add the height of the container's top to the model for each row separately in order to calculate the z-coordinate of the container's center of gravity in Equation (34). The minimum weight of the barge is ensured by Inequality (35). Inequalities (36) and (37) make sure that a 40ft container can only be supported by two 20ft containers whenever they have the same height. The Inequalities (38) and (39) do make sure that the trim of the barge stays above the minimum and below the maximum. To ensure that there are no containers stowed on an open top, Inequality (40) is added to the model. The stability of the barge is guaranteed by the Inequality (41). The value of GM is determined by Equation (42) which is needed to calculate the angle of list. Inequality (43) makes sure that the this angle of list is smaller than the maximum. The final Constraint (44) makes sure that the decision variable δ_{xyzi} is binary.

For readability purposes, we add Constraints (41), (42) and (43) to the model above in their non-linear form. For CPLEX, we linearize them by using the mathematical rules in Subsection 4.2, see Appendix 4 for the results. For the same reason, we leave out three

extra decision variables used to determine the pre-calculated values for $KM(\delta_{xyzi})$ and $KG^{max}(\delta_{xyzi})$, they can also be found in Appendix 4.

4.2 Non-linear inequalities/constraints

To linearize the product of a binary and a continuous variable, as in Constraints (41), (42) and (43), we use the following mathematical rules (Coelho, 2013):

$$\begin{aligned} z &\leq A \\ z &\leq M * x \\ z &\geq A - (1 - x)M \end{aligned} \tag{45}$$

The notation and formulation of the actual Equations added to the model can be found in Appendix 4.

5 Numerical analysis

Our numerical analysis consists of using a commercial solver to try solve real-world instances of the proposed model. We are interested in evaluating the performances and limitations of CPLEX on this model and discussing possible implementation. In order to assess these performances of the model, we execute several experiments. The model is programmed in C++, making use of Microsoft Visual Studio 2010. Visual Studio then calls IBM's CPLEX 12.6 to solve the model. We perform the experiments on an Intel(R) Core(TM) i5-5257U CPU @ 2.70GHZ, 8,00 GB RAM and a 64-bit operating system.

5.1 Instances

In order to get the most realistic outcome of the experiments, we develop 18 instances (see Table 2) based on a real world data set provided by ITV. This data set, dating from September 2016 to November 2016, consists a list of containers, their features and the actual allocation to a barge. We develop 6 small, 6 medium and 6 large instances in terms of the amounts of containers and its equivalent TEU. Each instance differs in the amount of high cube vs. standard size, reefers, open top containers, height and weight. The weight differs between 4 and 30 tons, which is the weight of an empty 40ft container up to its maximum load (see Table 1).

Instance	**Container specifications**								
	I	***TEU***	C	F	TP	R^c	O^c	W^c_{min}	W^c_{max}
1.	**15**	***24***	6	9	5	0	0	4	30
2.	**19**	***27***	11	8	6	3	1	4	30
3.	**16**	***27***	5	11	9	2	0	4	30
4.	**21**	***28***	14	7	5	0	1	4	30
6.	**20**	***30***	10	10	8	1	0	4	30
5.	**18**	***31***	5	13	4	0	1	4	30
7.	**30**	***40***	20	10	12	1	1	4	30
8.	**34**	***42***	26	8	16	2	2	4	30
9.	**33**	***46***	20	13	19	3	1	4	30
10.	**30**	***48***	12	18	11	0	2	4	30
11.	**35**	***50***	20	15	16	5	1	4	30
12.	**34**	***56***	12	22	14	8	0	4	30
13.	**40**	***68***	12	28	20	3	4	4	30
14.	**47**	***72***	22	25	14	2	2	4	30
15.	**59**	***75***	43	16	36	1	3	4	30
16.	**62**	***88***	36	26	38	6	2	4	30
17.	**66**	***96***	36	30	32	10	2	4	30
18.	**64**	***108***	20	44	28	16	0	4	30

I: number of containers; ***TEU***: number of twenty-foot equivalent units; **C**: number of 20ft containers; **F**: number of 40ft containers; **TP**: number of high cube containers; $\mathbf{R^c}$: number of reefer containers; $\mathbf{O^c}$: number of open top containers; $\mathbf{W^c}$: weights of the containers; **Min**: minimum random weight in tons; **Max**: maximum random weight in tons

Table 2: Instances used for the numerical analysis

5.2 Parameters and settings

All the parameters values are set based on the case study and are obtained from: the skipper of the Victor, documents of the Victor, Autena and ITV (See Appendix 1). Most of the parameters are dimensions and specifications of the Victor itself, although several need some extra clarification. Firstly, the minimum and maximum trim are set to 10 and 15 centimeters respectively by the skipper of the Victor. This way the barge uses the least fuel while driving. Secondly, the total minimum weight is set to 949 ton, this is the weight needed to pass the lowest bridges on the concerning river/canal. Thirdly, the $KG^{max}(\delta_{xyzi})$ and $KM(\delta_{xyzi})$ values are, as mentioned in Subsection 3.3.1, taken from the available stability calculation report (Van Pelt & Co B.V., 2014). The pre-calculated values for $KG^{max}(\delta_{xyzi})$ depend, in primis, on the total weight of the freight, the occupied tiers and whether high cube containers are used or not (see Appendix 2). For simplicity, the amount of weight

values are reduced to 5 range classes and average values are considered (see Appendix 4). The $KM(\delta_{xyzi})$ value solely depends on the total weight and possible values are analogously considered with the same 5 range classes for weight of the loaded freight. Finally, the maximum angle of list is set to 1,51°, due to the maximum summation of the trim and angle of list. Since the maximum trim is set to 15 centimeters (which equals a longitudinal trim angle of approximately 8,49°), the summation will always stay below the maximum 10° set by the Dutch government (Ministerie van binnenlandse zaken, 2016) (see Subsection 3.3.3).

5.3 Results

We test the instances with the original model out of Section 4. Moreover, we also consider some relaxation to the model to check whether computational (CPU) time can be decreased. Specifically, some constraints are alternatively left out. As discussed in Section 2.1, Li et al. (2017) mentioned that the stability and trim are way more sensitive to the stowage plan for the CSPB compared to the CSP. Additionally, through preliminary experimentation on the 18 instances, the angle of list turned out to be very sensitive as well. Therefore, we create 4 relaxed models by firstly alternatively leaving these three constraints out, followed by eliminating all of them together. In the first relaxed model (RM1), we will take out the stability constraint (Inequality (41)). For the second relaxed model (RM2), we will exclude the angle of list constraint (Inequality (43)). The third relaxed model (RM3) will ignore the trim constraints (Inequalities (38) and (39)), whereas in the fourth relaxed model (RM4) we will leave out all of the previous mentioned constraints.

The performances and outputs per instance of the full model can be found in Table 3. The performances of RM1 and RM2 are shown in Table 4 per instance, while the performances of RM3 and RM4 are displayed in Table 5 per instance. Each table first mentions the amount of containers (I) and the equivalent (TEU) of these instances. The provided outputs from the CPLEX solver are the best integer (upper bound), the best node (lower bound), Gap (gap between the lower and upper bound) and the CPU (computation time). Some key outputs of the full model are given in Table 3. A comparison of the full model's CPU time versus the relaxed models can be found in Table 6. The instances that could not be solved in all of the models are left out of this comparison. The reason is that the short CPU time, until running out of memory, distorts the average results.

Instance			**Performances & outputs full model**								
	I	***TEU***	BI	BN	CPU	Gap	W^b	t	$\boldsymbol{\theta}$	**KG**	$\mathbf{KG_{max}}$
1.	**15**	*24*	24	24	2	0%	960	12,99	0,85	2,56	5,46
2.	**19**	*27*	27	27	5	0%	1026	14,88	0,74	2,75	4,96
3.	**16**	*27*	27	27	2	0%	990	10,11	0,41	2,68	5,46
4.	**21**	*28*	28	28	10	0%	1061	10,43	0,79	2,73	3,91
5.	**20**	*30*	30	30	10	0%	1045	10,44	1,09	2,81	4,23
6.	**18**	*31*	21	21	2	0%	1018	11,87	1,19	2,81	5,46
7.	**30**	*40*	40	40	292	0%	1171	14,87	0,87	3,01	3,91
8.	**34**	*42*	42	42	85	0%	1236	13,98	0,56	3,05	3,91
9.	**33**	*46*	46	46	90	0%	1365	13,90	0,78	3,53	3,91
10.	**30**	*48*	48	48	103	0%	1308	10,02	0,59	3,34	3,91
11.	**35**	*50*	50	50	639	0%	1415	10,8	0,08	3,54	3,91
12.	**34**	*56*	56	56	450	0%	1392	10,58	1,51	3,41	3,91
13.	**40**	*68*	68	68	241	0%	1337	13,61	1,05	3,89	3,91
14.	**47**	*72*	*	72	145	*	*	*	*	*	*
15.	**59**	*75*	*	75	245	*	*	*	*	*	*
16.	**62**	*88*	*	*	37	*	*	*	*	*	*
17.	**66**	*96*	*	*	46	*	*	*	*	*	*
18.	**64**	*108*	*	*	45	*	*	*	*	*	*

I: number of containers; ***TEU***: number of twenty-foot equivalent units; **BI**: best integer; **BN**: best node; **CPU**: computation time in seconds; **Gap**: gap to an optimal solution in %; $\mathbf{W^b}$: total weight in tons; **T**: trim in centimeters; $\boldsymbol{\theta}$: angle of list in degree; **KG**: KG value in meters; $\mathbf{KG_{max}}$: maximum KG value in meters; *****: no feasible solution has been found

Table 3: Performances and outputs of the full model per instance

Instance			**RM1**				**RM2**			
	I	***TEU***	BI	BN	CPU	Gap	BI	BN	CPU	Gap
1.	**15**	*24*	24	24	2	0%	24	24	2	0%
2.	**19**	*27*	27	27	3	0%	27	27	5	0%
3.	**16**	*27*	27	27	2	0%	27	27	2	0%
4.	**21**	*28*	28	28	9	0%	28	28	5	0%
5.	**20**	*30*	30	30	9	0%	30	30	14	0%
6.	**18**	*31*	31	31	3	0%	31	31	2	0%
7.	**30**	*40*	40	40	27	0%	40	40	20	0%
8.	**34**	*42*	42	42	96	0%	42	42	28	0%
9.	**33**	*46*	46	46	111	0%	46	46	44	0%
10.	**30**	*48*	48	48	38	0%	48	48	119	0%
11.	**35**	*50*	50	50	153	0%	50	50	60	0%
12.	**34**	*56*	56	56	411	0%	56	56	25	0%
13.	**40**	*68*	68	68	425	0%	68	0	186	0%
14.	**47**	*72*	0	72	146	*	70	72	905	2,86%
15.	**59**	*75*	0	75	114	*	*	75	1246	*
16.	**62**	*88*	*	*	31	*	*	*	30	*
17.	**66**	*96*	*	*	40	*	*	*	32	*
18.	**64**	*108*	*	*	38	*	*	*	28	*

RM1: relaxed model without stability constraints; **RM2**: relaxed model without angle of list constraints; **I**: number of containers; ***TEU***: number of twenty-foot equivalent units; **BI**: best integer; **BN**: best node; **CPU**: computation time in seconds; **Gap**: gap to an optimal solution in %; *****: no feasible solution has been found

Table 4: Performances of the relaxed models RM1 and RM2 per instance

Instance			**RM3**				**RM4**			
	I	***TEU***	BI	BN	CPU	Gap	BI	BN	CPU	Gap
1.	**15**	*24*	24	24	1	0%	24	24	1	0%
2.	**19**	*27*	27	27	2	0%	27	27	1	0%
3.	**16**	*27*	27	27	1	0%	27	27	1	0%
4.	**21**	*28*	28	28	2	0%	28	28	1	0%
5.	**20**	*30*	30	30	1	0%	30	30	1	0%
6.	**18**	*31*	31	31	1	0%	31	31	1	0%
7.	**30**	*40*	40	40	32	0%	40	40	1	0%
8.	**34**	*42*	42	42	4	0%	42	42	1	0%
9.	**33**	*46*	46	46	44	0%	46	46	1	0%
10.	**30**	*48*	48	48	52	0%	48	48	1	0%
11.	**35**	*50*	50	50	352	0%	50	50	1	0%
12.	**34**	*56*	56	56	53	0%	56	56	1	0%
13.	**40**	*68*	68	68	530	0%	68	68	1	0%
14.	**47**	*72*	23	72	1100	213%	72	72	1	0%
15.	**59**	*75*	23	75	959	226%	75	75	1	0%
16.	**62**	*88*	*	*	1308	*	88	88	1	0%
17.	**66**	*96*	*	*	32	*	96	96	1	0%
18.	**64**	*108*	*	*	34	*	108	108	1	0%

RM3: relaxed model without trim constraints; **RM4**: relaxed model without trim, angle of list and stability constraints; **I**: number of containers; ***TEU***: number of twenty-foot equivalent units; **BI**: best integer; **BN**: best node; **CPU**: computation time in seconds; **Gap**: gap to an optimal solution in %; *****: no feasible solution has been found

Table 5: Performances of the relaxed models RM3 and RM4 per instances

Instance			**FM**	**RM1**		**RM2**		**RM3**		**RM4**	
	I	***TEU***	CPU	CPU	Δ	CPU	Δ	CPU	Δ	CPU	Δ
1.	**15**	*24*	2	2	0%	2	0%	1	−50%	1	−50%
2.	**19**	*27*	5	3	−40%	5	0%	2	−60%	1	−80%
3.	**16**	*27*	2	2	0%	2	0%	1	−50%	1	−50%
4.	**21**	*28*	10	9	−10%	5	−50%	2	−80%	1	−90%
5.	**20**	*30*	10	9	−10%	14	40%	1	−90%	1	−90%
6.	**18**	*31*	2	3	50%	2	0%	1	−50%	1	−50%
7.	**30**	*40*	292	27	−91%	20	−93%	32	−90%	1	−100%
8.	**34**	*42*	85	96	13%	28	−67%	4	−95%	1	−99%
9.	**33**	*46*	90	111	23%	44	−51%	44	−51%	1	−99%
10.	**30**	*48*	103	38	−63%	119	15%	52	−50%	1	−99%
11.	**35**	*50*	639	153	−76%	60	−91%	352	−45%	1	−100%
12.	**34**	*56*	450	411	−9%	25	−94%	53	−88%	1	−100%
13.	**40**	*68*	241	425	76%	186	−23%	530	120%	1	−100%
Average					−10%		−32%		−52%		−85%

FM: full model; **RM1**: relaxed model without stability constraints; **RM2**: relaxed model without angle of list constraints; **RM3**: relaxed model without trim constraints; **RM4**: relaxed model without trim, angle of list and stability constraints; **I**: number of containers; ***TEU***: number of twenty-foot equivalent units; **CPU**: computation time in seconds; **Δ**: difference in computation time compared to the full model in %;

Table 6: Comparison of the full model's computation time versus the relaxed models

5.4 Discussion of the results

From the performances of all the models, it can be concluded that the amount of containers and its equivalent in TEU, has a significant effect on the CPU time. The full models CPU time for instance 1-6 is 4 seconds on average, while the CPU time for instances 7-12 is notably higher with 277 seconds on average. The CPU time for instances 13-18 are incomparable, since only for instance 13 a feasible solution could be found for the full model. The others were too complex and the large trees, used for the branch-and-cut procedure, made CPLEX run out of memory within 103 seconds on average. The full model running on this laptop seems to be able to solve the model up to half way of the maximum capacity, between 35-40 containers with an equivalent of 65-70 TEU.

Striking is that the unsolved experiments have the exact opposite correlation with the CPU time than the solved models do. For unsolved experiments applies: the more complex

the problem, the sooner it runs out of memory, resulting in a lower CPU time (see Table 3 for the decreasing CPU time from instance 13 to 18). For this reason, the unsolved experiments are left out of the comparison in Table 6. From this same comparison, it can be concluded that the stability constraint, excluded in RM1, has the least impact on the CPU time out of the trim, angle of list and stability. The CPU time of RM1 is 10% lower on average than the full model.

The presented model is more sensitive to the angle of list constraints, which are excluded in RM2. With a decrease of 32% in CPU time on average compared to the full model(see Table 6), RM2 was even able to find a solution for instance 14. The best integer was 70 and the best node 72, leaving a gap of only 2,86% before running out of memory. The angle of list is set fairly tight during these experiments, in order to apply to both the Dutch laws and the optimal trim desired by the skipper of the Victor. As can be seen in Table 3, the values of KG and $KG^{max}(\delta_{xyzi})$ approach each other when the weight of the total freight increases. Hence, the effect of the stability constraint is the largest on instances 13-18. Nevertheless, with the stability constraint excluded in RM1, CPLEX was still not able to find a solution for instances 14-18 before running out of memory.

Out of the three constraints, the trim has the largest impact on the CPU time of the model. RM3 completely ignores the trim constraints, resulting in a 52% decrease on average of the CPU time compared to the full model (see Table 6). Additionally, it was able to find a feasible solution for instance 14 and 15. In these experiments, the trim was fully excluded, but enlarging the gap between t_{min} and t_{max} will relax the model as well.

RM4 excludes the trim, stability and angle of list constraints, leading to a CPU time of ≤ 1 second on average for all 18 instances (see Table 5). CPLEX solves RM4 85% faster on average than the FM (see Table 6). However, in reality CPLEX found a solution for RM4 even faster, since most CPU times were close to 0 but rounded to 1. Next to that, RM4 is the only model where CPLEX was able to find a solution for all of the instances, up to the maximum capacity of the barge in instance 18. The average CPU times for RM4 show

that the trim, angle of list and stability constraints, are the only constraints significantly impacting the CPU time. Without these constraints, CPLEX could find a solution within a second for each instance. However, these solutions are presumably unfeasible.

Overall, the results show that solving the model with the CPLEX solver is currently unsatisfying in terms of real world application. The branch and cut trees grow extremely large, leading to impractical CPU times. Our mathematical model lays a foundation for future research, to focus on the creation of a heuristic or algorithm reducing the CPU time, while still guaranteeing a feasible stowage plan. Lastly, in addition to the literature mentioning the trim and stability having a large effect on the stowage plan (Li et al., 2017; Hu and Cai, 2017), the angle of list was proven to have a large effect as well.

6 Conclusion

Nowadays, over 80% of the world trade is transported via containers (Zhang and Lee, 2016). Research underlines that this will dominantly be shaped by inland transport systems (Notteboom and Rodrigue, 2009). The response of the terminal operators and shipping companies is investments in new technologies to improve the container handling and operational efficiency, which are both, largely effected by loading and unloading operations (Imai et al., 2002) (Rashidi and Tsang, 2013). The core of these operations is stowage planning (Steenken et al., 2004), which is often referred to as the container stowage planning (CSP). Unfortunately, the CSP on barges is in the scientific literature a low explored topic.

In this thesis, the container stowage process on a barge, including all possible limitations, is discussed in depth and thereafter mathematically modelled. The information was obtained by a case study on the barge Victor, sailing for ITV. After the identification of all the possible constraints for the stowage process, several assumptions were made which shaped the scope of the presented mathematical model. The most important assumption being, that the barge makes a single trip from the port of Rotterdam back to ITV. Although the model presented is based on the Victor, all the constraints, apart from the dummies, are generic.

In order to asses the performances of CPLEX to solve the model, several experiments were executed based on real world data sets and barge parameters. In addition, we tested 4 relaxations of the original model for specific stability constraints. The results showed that by removing the trim constraints, CPLEX is able to solve more instances to optimality, followed by removing the angle of list and finally by the stability constraint itself. Previous literature of Li et al. (2017) and Hu and Cai (2017) did mention the trim and stability to have a large effect on the stowage plan, although nobody emphasized on the angle of list. Additionally, the computation times are still unpractical for real world application whenever the full model has to solve instances larger than 50% of the barges capacity.

Overall, it can be concluded that the aim is achieved by the presented mathematical

model being a good representation of the stowage process on a barge. It lays a foundation for the transition of the stowage responsibility from the skipper of the barge to the planner of the terminal. Currently, the stowage is created by the skipper of the barge based on trial and error. Ideally the planner of the inland terminal assigns the containers for a barge and additionally creates the stowage plan by means of a computer program. This will increase the capacity utilization of the inland terminal their fleet and makes it more flexible to changing schedules.

Future research should mainly focus on the reduction of the computation time while still guaranteeing a feasible stowage plan. For real life application, the computation time should ideally be a few minutes. This can be achieved by creating a heuristic or algorithm. Reduction of the computation time becomes even more important when mixed destination slot planning instead of single destination slot planning, hazardous containers and out of gauge containers will be included in the model. However, hazardous and out of gauge containers are expected to have a very limited effect on the computation time in comparison to the mixed destination slot planning. Furthermore, in our model, the trim, angle of list and the stability are forced to stay within certain boundaries. However, to reach the optimum of these constraints, they should be included as optimization indexes in the model.

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Appendix

Appendix 1

Confidential

Appendix 2

Confidential

Appendix 3

CLASSIFICATION OF EUROPEAN INLAND WATERWAYS

Type of inland waterways		Classes of navigable waterways	Motor vessels and barges: Type of vessel: General characteristics					Pushed convoys: Type of convoy: General characteristics					Minimum height under bridges 2/	Graphical symbols on maps
			Designation	Maximum length	Maximum beam	Draught 7/	Tonnage		Length	Beam	Draught 7/	Tonnage		
				L(m)	B(m)	d(m)	T(t)		L(m)	B(m)	d(m)	T(t)	H(m)	
1		2	3	4	5	6	7	8	9	10	11	12	13	14
OF REGIONAL IMPORTANCE	To West of Elbe	I	Barge	38.5	5.05	1.80-2.20	250-400						4.0	
		II	Kampine-Barge	50-55	6.6	2.50	400-650						4.0-5.0	
		III	Gustav Koenigs	67-80	8.2	2.50	650-1,000						4.0-5.0	
	To East of Elbe	I	Gross Finow	41	4.7	1.40	180						3.0	
		II	BM-500	57	7.5-9.0	1.60	500-630						3.0	
		III	6/	67-70	8.2-9.0	1.60-2.00	470-700		118-132	8.2-9.0	1.60-2.00	1,000-1,200	4.0	
OF INTERNATIONAL IMPORTANCE		IV	Johann Welker	80-85	9.5	2.50	1,000-1,500		85	9.5 5/	2.50-2.80	1,250-1,450	5.25 or 7.00 4/	
		Va	Large Rhine vessels	95-110	11.4	2.50-2.80	1,500-3,000		95-110 1/	11.4	2.50-4.50	1,600-3,000	5.25 or 7.00 or 9.10 4/	
		Vb							172-185 1/	11.4	2.50-4.50	3,200-6,000		
		VIa							95-110 1/	22.8	2.50-4.50	3,200-6,000	7.00 or 9.10 4/	
		VIb	3/	140	15.0	3.90			185-195 1/	22.8	2.50-4.50	6,400-12,000	7.00 or 9.10 4/	
		VIc							270-280 1/ 195-200 1/	22.8 33.0-34.2 1/	2.50-4.50 2.50-4.50	9,600-18,000 9,600-18,000	9.10 4/	
		VII						8/	285	33.0-34.2 1/	2.50-4.50	14,500-27,000	9.10 4/	

Figure 10: Classification table of inland waterways

Appendix 4

Additional parameters and variables

Parameters	
$KGMAX_{kmn}$	Pre-calculated $KG^{max}(\delta_{xyzi})$ values. $\forall k \in \alpha 5$, $\forall m \in \alpha 2$, $\forall n \in \alpha 2$
KM_j	Pre-calculated $KM(\delta_{xyzi})$ values. $\forall j \in \alpha 5$
$\alpha 2$	Integer values $\{1, 2\}$
$\alpha 5$	Integer values $\{1, ..., 5\}$
Variables	
ZC_i	Used to bypass multiplication of $KG^{max}(\delta_{xyzi})$ and δ_{xyzi}, $\forall i \in I$
KC_i	Used to bypass multiplication of KG_i and δ_{xyzi}, $\forall i \in I$
$GMZC_i$	Used to bypass multiplication of GM and δ_{xyzi}, $\forall i \in I$
$GMKC_i$	Used to bypass multiplication of $KM(\delta_{xyzi})$ and δ_{xyzi}, $\forall i \in I$
ZL_i	Used to bypass multiplication of GM and δ_{xyzi}, $\forall i \in I$
$u_k \in \{0, 1\}$	Set 1 if tonnages fall in weight class k, 0 otherwise $\forall k \in \alpha 5$
$s_m \in \{0, 1\}$	$\begin{cases} s_1 = 1 \ \& \ s_2 = 0 & \text{No high cube containers are stowed} \\ s_1 = 0 \ \& \ s_2 = 1 & \text{High cube containers are stowed} \end{cases}$
$s_m \in \{0, 1\}$	$\begin{cases} s_1 = 1 \ \& \ s_2 = 0 & \text{No high cube containers are stowed} \\ s_1 = 0 \ \& \ s_2 = 1 & \text{High cube containers are stowed} \end{cases}$
$\beta_n \in \{0, 1\}$	$\begin{cases} \beta_1 = 0 \ \& \ \beta_2 = 0 & \text{Containers only on row 1} \\ \beta_1 = 1 \ \& \ \beta_2 = 0 & \text{Containers up to row 2} \\ \beta_1 = 0 \ \& \ \beta_2 = 1 & \text{Containers up to row 3} \end{cases}$

$$\sum_{x \in X} \sum_{y \in Y} \sum_{i \in I} \delta_{xy2i} \leq \beta_1 M + \beta_2 M \tag{46}$$

$$\sum_{x \in X} \sum_{y \in Y} \sum_{i \in I} \delta_{xy2i} \geq \beta_1 + \beta_2 \tag{47}$$

$$\sum_{x \in X} \sum_{y \in Y} \sum_{i \in I} \delta_{xy3i} \leq \beta_2 M \tag{48}$$

$$\sum_{x \in X} \sum_{y \in Y} \sum_{i \in I} \delta_{xy3i} \geq \beta_2 \tag{49}$$

$$\beta_1 + \beta_2 \leq 1 \tag{50}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(\delta_{xyzi}TP_i) \leq s_2 M \tag{51}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(TP_i\delta_{xyzi}) - 0.1 \geq (1-s_2)\,M - (2s_1 M) \tag{52}$$

$$s_1 + s_2 = 1 \tag{53}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \leq 400 + ((1-u_1)\,M) \tag{54}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \geq 401 - ((1-u_2)\,M) \tag{55}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \leq 800 + ((1-u_2)\,M) \tag{56}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \geq 801 - ((1-u_3)\,M) \tag{57}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \leq 1200 + ((1-u_3)\,M) \tag{58}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \geq 1201 - ((1-u_4)\,M) \tag{59}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \leq 1600 + ((1-u_4)\,M) \tag{60}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \geq 1601 - ((1-u_5)\,M) \tag{61}$$

$$\sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}) \leq 2000 + ((1-u_5)\,M) \tag{62}$$

$$u_1 + u_2 + u_3 + u_4 + u_5 = 1 \tag{63}$$

$$KG^{max}(\delta_{xyzi}) \geq KGMAX_{kmn} - (1-u_k)\,M - (1-s_m)\,M - (1-\beta_n)\,M \qquad \forall k \in \alpha 5, \forall m \in \alpha 2, \forall n \in \alpha 2 \tag{64}$$

$$KG^{max}(\delta_{xyzi}) \leq KGMAX_{kmn} + (1-u_k)\,M + (1-s_m)\,M + (1-\beta_n)\,M \qquad \forall k \in \alpha 5, \forall m \in \alpha 2, \forall n \in \alpha 2 \tag{65}$$

$$\begin{aligned}
&ZC_i \leq KG^{max}(\delta_{xyzi})\\
&ZC_i \leq \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}(\delta_{xyzi}M)\\
&ZC_i \geq KG^{max}(\delta_{xyzi}) - \left(1 - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\delta_{xyzi}\right)M \qquad \forall i \in I\\
&KC_i \leq KG_i\\
&KC_i \leq \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}(\delta_{xyzi}M)\\
&KC_i \geq KG_i - \left(1 - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\delta_{xyzi}\right)M
\end{aligned} \tag{66}$$

$$\frac{\sum_{j\in I}\left(W_j^c KC_j\right) + \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c\delta_{xyzi}KG_0) - \sum_{m\in I}(W_m^c ZC_m)}{W_h^b} + KG_0 \leq KG_{max}(\delta_{xyzi}) \tag{67}$$

$$KM_j - (1-u_j)\,M \leq KM(\delta_{xyzi}) \qquad \forall j \in \alpha 5 \tag{68}$$

$$KM_j + (1-u_j)\,M \geq KM(\delta_{xyzi}) \qquad \forall j \in \alpha 5 \tag{69}$$

$$
\begin{aligned}
&GMZC_i \leq GM \\
&GMZC_i \leq \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}(\delta_{xyzi}M) \\
&GMZC_i \geq GM - \left(1 - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\delta_{xyzi}\right)M \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \forall i \in I \\
&GMKC_i \leq KM(\delta_{xyzi}) \\
&GMKC_i \leq \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}(\delta_{xyzi}M) \\
&GMKC_i \geq KM(\delta_{xyzi}) - \left(1 - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\delta_{xyzi}\right)M
\end{aligned}
\tag{70}
$$

$$
\frac{\sum_{k\in I}(W_k^c GMKC_k) - \sum_{j\in I}\left(W_j^c KC_j\right) - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\sum_{i\in I}(W_i^c \delta_{xyzi} KG_0) - \sum_{m\in I}(W_m^c GMZC_m)}{W_h^b}
$$

$$
-KG_0 + KM = GM \tag{71}
$$

$$
\begin{aligned}
&ZL_i \leq GM \\
&ZL_i \leq \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}(\delta_{xyzi}M) \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \forall i \in I \\
&ZL_i \geq GM - \left(1 - \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z}\delta_{xyzi}\right)M
\end{aligned}
\tag{72}
$$

$$
u_k \in \{0,1\} \qquad \forall k \in \alpha 5 \tag{73}
$$

$$
s_m \in \{0,1\} \qquad \forall n \in \alpha 2 \tag{74}
$$

$$
\beta_n \in \{0,1\} \qquad \forall n \in \alpha 2 \tag{75}
$$

All the above Equations are mentioned here to improve the readability of this document. In Subsection 4.1, these Equations are substituted for the Inequalities (41), (43) and Constraint (42). The Inequalities (46) - (50) determine which tiers of the barge are used for the stowage plan. The Inequalities (51) - (53) determine whether high cube containers have been stowed. Followed by Inequalities (54) - (63), which determine the weight-class based on the total weight of the freight. The layers used, the presence of high-cube containers in the stowage plan and the weight-class together determine the $KG^{max}(\delta_{xyzi})$ value, as is designated in Constraints (64) and (65).

in Inequality (67), the previously determined $KG^{max}(\delta_{xyzi})$ value imposes the KG value to be smaller or equal. However, CPLEX is not able to multiply or divide two decision variables. Therefore, Inequalities (66) are added to avoid the multiplication of $KG^{max}(\delta_{xyzi})$ and KG_i with δ_{xyzi} specifically. Similarly to the determination of the right pre-calculated $KG^{max}(\delta_{xyzi})$ value, do Inequalities (68) and (69) determine the pre-calculated KM value. The Inequalities (70) bypass the multiplication of GM and $KM(\delta_{xyzi})$ with δ_{xyzi}. These values, together with the $KM(\delta_{xyzi})$ value, compute the value of GM in Equation (71). Also, Inequalities (72) are used to avoid a multiplication between the decision variables GM and δ_{xyzi}. Finally, the Inequalities (73) - (75) ensure that the concerning decision variables are binary.