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## Discussion paper

# Integrated maritime bunker management with stochastic fuel prices and new emission regulations

BY  
**Yewen Gu, Stein W. Wallace AND Xin Wang**

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*Yewen Gu<sup>1</sup>, Stein W. Wallace<sup>1</sup>, Xin Wang<sup>2</sup>*

<sup>1</sup>Department of Business and Management Science, Norwegian School of Economics, Bergen, Norway

<sup>2</sup>Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway

## Abstract

Maritime bunker management (MBM) controls the procurement and consumption of the fuels used on board and therefore manages one of the most important cost drivers in the shipping industry. At the operational level, a shipping company needs to manage its fuel consumption by making optimal routing and speed decisions for each voyage. But since fuel prices are highly volatile, a shipping company sometimes also needs to do tactical fuel hedging in the forward market to control risk and cost volatility. From an operations research perspective, it is customary to think of tactical and operational decisions as tightly linked. However, the existing literature on MBM normally focuses on only one of these two levels, rather than taking an integrated point of view. This is in line with how shipping companies operate; tactical and operational bunker management decisions are made in isolation. We develop a stochastic programming model involving both tactical and operational decisions in MBM in order to minimize the total expected fuel costs, controlled for financial risk, within a planning period. This paper points out that after the latest regulation of the Sulphur Emission Control Areas (SECA) came into force in 2015, an integration of the tactical and operational levels in MBM has become important for shipping companies whose business deals with SECA. The results of the computational study shows isolated decision making on either tactical or operational level in MBM will lead to various problem. Nevertheless, the most server consequence occurs when tactical decisions are made in isolation.

**Keywords:** Maritime bunker management, SECA, risk management, stochastic programming, fuel hedging, sailing behavior

## 1 Introduction

Maritime transportation is one of the major freight transportation modes in the world. As of 2015, more than 90 percent of the global trade is carried by sea (ICS, 2015). The shipping industry is indispensable for global trade and the world economy, as it is, by far, the most cost effective choice for intercontinental transport of large-volume goods.

Marine fuel costs represent a major portion of a ship's operating costs. It is estimated that bunker costs may constitute more than half of the operating costs of a vessel (Stopford, 2009; Ronen, 2011). Based on this, as well as environmental concerns, bunker management has become vital for both financial and environmental reasons.

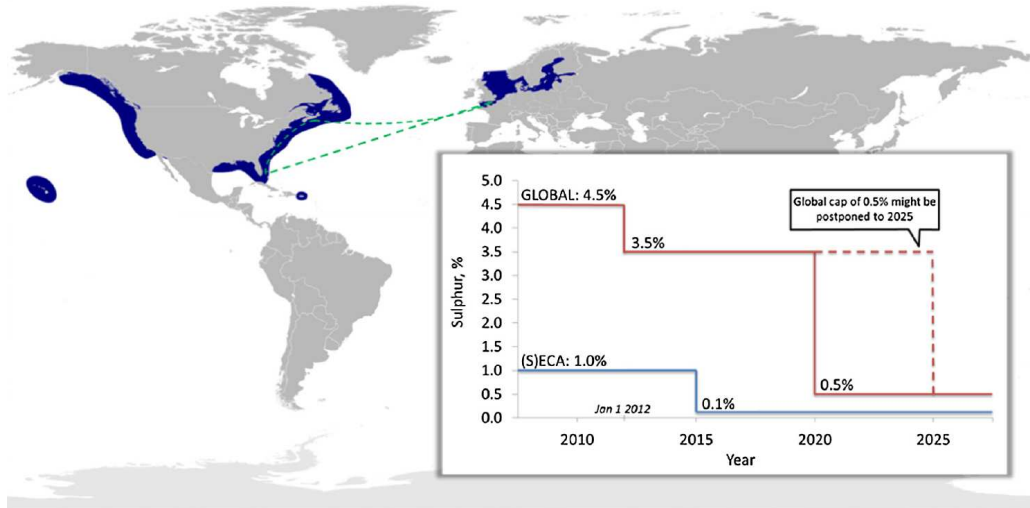
Maritime bunker management (MBM) normally addresses decisions and management policies at both operational and tactical levels. At the operational level, a shipping company needs to manage its fuel consumption by making optimal routing and speed decisions on each voyage, while obeying some time constraints. On the other hand, since fuel prices are highly volatile, shipping companies sometimes also need to hedge their fuels, at a tactical level, by purchasing bunker in the forward market to control risk. The two levels in MBM are connected through fuel allocation decisions which allocate the actual fuel consumption to different fuel sources, in our case the spot- and forward-fuel markets. The total bunker costs, including fuels from both spot- and forward markets, can then be obtained, and minimizing these costs, taking financial risks into account, is the main goal of MBM.

It is standard in most industrial settings, as well as in the operations research literature, to take operational decisions into consideration when tactical decisions are made, and certainly to consider tactical decisions already made when making operational decisions. After all, tactical decisions are mostly made to prepare the ground for operations, and operations must live with the tactical decisions made, whether they are good or not. Good examples would be location-routing problems ([Prodhon and Prins, 2014](#)) and fleet composition and routing problems ([Hoff et al., 2010](#)). The former combines tactical depot allocations and operational vehicle routing, while the latter considers both tactical fleet composition and operational routing decisions. Other examples in maritime transportation, such as ship routing and scheduling problems, can be found in [Meng et al. \(2013\)](#) and [Christiansen et al. \(2004\)](#). However, this common practice is not generally witnessed in MBM. For most shipping companies, the two levels of MBM are separated, i.e., the tactical fuel hedging decisions and the operational routing-speed decisions do not interact with each other. Under normal circumstances, no matter how much fuel the purchasing department hedged with forward contracts, the operation team would always sail a vessel along its usual (often also the shortest) path between two ports with the lowest possible speed as long as the agreed arrival time between shippers and the shipping company is fulfilled. On the other hand, the purchasing department normally does not pay too much attention to future fleet operations, since the sailing patterns are relatively fixed. They would make their hedging decisions mainly based on such as the shipping company's risk aversion, historical fuel consumption data and their judgement about future fuel market developments. So there have been good reasons for this rather unusual separation.

This disconnection is also found in the literature. At tactical level, [Wang and Teo \(2013\)](#) provided an overview of the available bunker hedging instruments and developed a model that considers fuel hedging in liner network planning. [Pedrielli et al. \(2015\)](#) developed a game theory based model to optimize the hedging strategy for both bunker suppliers and shipping companies. [Alizadeh et al. \(2004\)](#) examined the hedging effectiveness of futures contracts among different fuel commodities. [Menachof and Dicer \(2001\)](#) compared the effectiveness of bunker surcharges and oil commodity futures contracts. More papers on bunker management at the operational level can be found in the literature. [Wang et al. \(2013\)](#) offered a comprehensive literature review on this topic. [Norstad et al. \(2011\)](#), [Ronen \(2011\)](#), [Fagerholt et al. \(2010\)](#), [Xia et al. \(2015\)](#) and [Wang and Meng \(2012\)](#) focused on sailing speed optimization and fuel cost minimization; [Psaraftis and Kontovas \(2010\)](#) and [Lindstad et al. \(2011\)](#) investigated the relationship between slow steaming and fleet size in container shipping; [Yao et al. \(2012\)](#), [Plum et al. \(2014\)](#) and [Wang and Meng \(2015\)](#) proposed optimization models regarding bunkering port choice. However, most of these papers focus on only one of the two levels. Very few works have studied the MBM problem with an integrated point of view involving both tactical and operational considerations. To the best of our knowledge, only one paper ([Ghosh et al., 2015](#)) has included considerations from both levels of MBM. In their problem, the authors aim to find the optimal bunkering strategy at the operational level, but using forward contracts (of given amounts) with the bunker supplier only as input to their model. In contrast to their settings,

the hedging strategy is also an important decision in our paper.

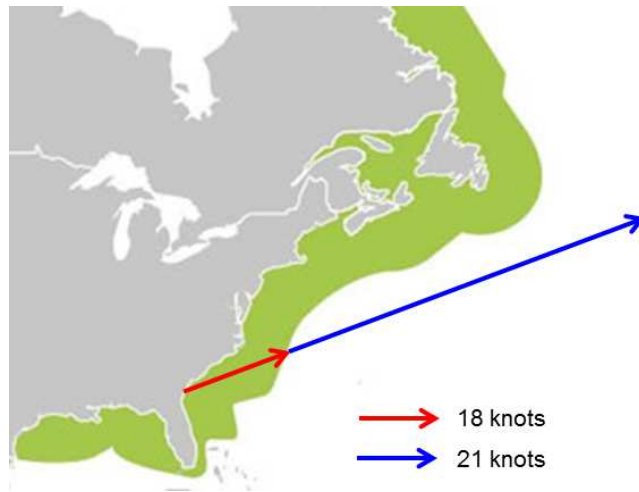
Significant changes have taken place in maritime transportation after the Sulphur Emission Control Areas (SECA) were introduced by Annex VI of the 1997 MARPOL Protocol, which was finally implemented in May 2005. The geographical locations of the SECA are marked by the dark areas in Fig. 1. These regions include the North Sea, the Baltic Sea, and the North American and US Caribbean coasts. The SECA were established to apply stricter controls over the emission of sulphur oxides, such as sulphur dioxide ( $\text{SO}_2$ ), from ships. The latest regulation applied in SECA came into effect on 1<sup>st</sup> January 2015. For vessels sailing inside the regulated areas, the new regulation restricts the level of sulphur content in the bunker fuel to a maximum of 0.1%. Therefore, the conventional marine fuel – heavy fuel oil (HFO) – which has about 3.5% sulphur content, is no longer permitted inside the SECA. This forces some shipping companies to switch to the marine gasoline oil (MGO) in these areas by carrying both types of fuel on board and performing a fuel change-over when crossing the SECA border. MGO has a sulphur content level that meets the SECA requirements, but a much higher price. Other methods for SECA compliance, such as liquefied natural gas (LNG) powered propulsion or scrubber systems are also used in the shipping industry. In this paper we only consider the fuel switching approach.



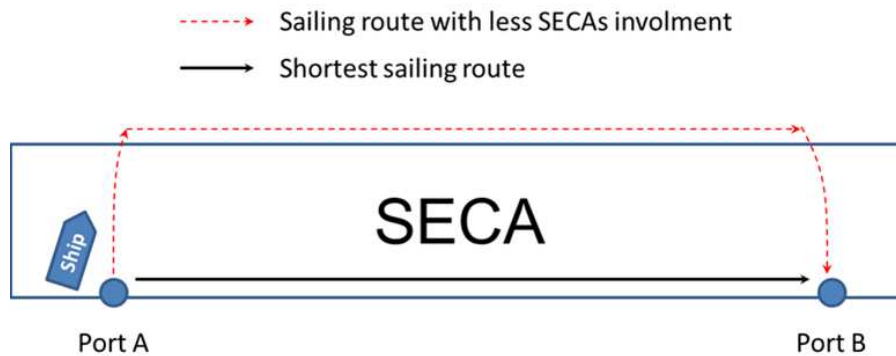
**Figure 1:** Map of the current Sulphur Emission Control Areas (Patricksson et al., 2015)

Due to the considerable price difference between the two fuels, shipping companies no longer necessarily sail their ships in the old-fashioned way. They now have an incentive to change their sailing behavior in order to minimize costs while simultaneously complying with SECA regulations. The changes in sailing behavior can be classified into two categories: speed differentiation and SECA-evasion (Doudnikoff and Lacoste, 2014; Fagerholt et al., 2015). For instance, when a voyage involves both SECA and normal sea areas, the ship may prefer to apply different speeds inside and outside the SECA. It may slow down when sailing inside the SECA so as to consume less MGO which is far more expensive. The speed may then be increased during the rest of the voyage outside the SECA so that the total travel time is maintained. The consumption of HFO will increase, but it is much cheaper. Such a strategy is referred to as speed differentiation, see Fig. 2(a). Furthermore, if a vessel needs to sail from port-A to port-B and both ports are located inside the same SECA, it may choose to first leave the SECA zone after departing from port-A, then sail along the edge of the SECA zone and re-enter the zone when approaching port-B, rather than taking the shortest route between the two ports. Such changes in sailing patterns are called SECA-evasion, as illustrated in Fig. 2(b). SECA-evasion normally leads to a longer total sailing distance and requires a higher average speed to stay inside the schedules, it however avoids a substantial involvement of SECA sailings and thus reduces the need for

expensive MGO. To what extent these two strategies will be applied depends on the price gap between the two fuels. As a whole, the application of these two types of changes in sailing behavior may result in lower total fuel costs.



(a) Speed Differentiation



(b) SECA Evasion

**Figure 2:** Two classifications of ship’s sailing behaviour changes

It is important to notice that adopting speed differentiation and SECA-evasion strategies at the operational level may affect the tactical bunker management (hedging) decisions for the two fuels (MGO and HFO), because the demand for the two fuels is no longer fixed but depends on the routing and speed decisions made while operating the ships. Similarly, different fuel hedging strategies at tactical level have impacts on future operations, as forward contracts lock in purchasing prices for some amounts of the fuels, and the amounts hedged affect the price gap between MGO and HFO (relative to the gaps in the spot markets). Hence, with the complexity of MBM increasing dramatically with SECA taken into account, the MBM problem needs to be treated from a new integrated angle. It is no longer appropriate to make tactical and operational decisions in isolation when managing bunker in maritime transportation, and one should include simultaneous considerations at both levels in MBM.

This paper presents a stochastic programming model for MBM that integrates tactical level (fuel hedging) decisions and operational level (routing and speed optimization) decisions, which takes into account uncertain fuel prices and the latest SECA regulations. We apply the model to the case of Wallenius Wilhelmsen Logistics (WWL), one of the world’s largest liner service providers for rolling equipment. Our main contribution is to analyze *to what extent* better decisions can be made by integrating the two levels of MBM rather than separating the two.

We also investigate *how* tactical and operational decisions in MBM interact with each other after considering uncertain fuel prices and the introduction of SECA regulations.

The paper is organized as follows. Section 2 describes the problem and the relevant assumptions. We then present the mathematical formulation of the model in Section 3. Section 4 introduces the test case and the scenario generation process. In Section 5 we show and analyze the results of the computational study. We then conclude in Section 6.

## 2 Problem description and Assumptions

In this section a detailed description of the MBM problem is given. Section 2.1 defines some important terms used in the paper. Section 2.2 describes the problem setting, and the relevant assumptions are stated in Section 2.3.

### 2.1 Terminology

We refer to a *loop*, see Fig. 3(a), as a round trip involving several port calls in a pre-determined sequence. A *leg* is then defined as the voyage between two consecutive ports within a loop. Fig. 3(b) further shows three *leg options* for one of the legs, each representing a possible path for navigating the leg. The leg options for the same leg normally differ both in the total travelling distance and in the sailing distance inside SECA.

A leg option may contain one or more *stretches*, as shown in Fig. 3(c). The first stretch starts when the vessel departs from the origin port and the last stretch ends when the vessel arrives at the destination port. According to the chosen leg option, a new stretch starts whenever the vessel enters or leaves SECA, at which point fuel switching is performed. Although one leg option may have numerous stretches, we assume that the same sailing speed is adopted on stretches of the same type. For example in Fig. 3(c), we assume the ship sails the same speed on stretches inside SECA, i.e. on Stretches 1 and 3. Therefore, we combine the stretches of the same type for every leg option, and hence characterize each leg option with two parts: the SECA stretch and the non-SECA stretch.

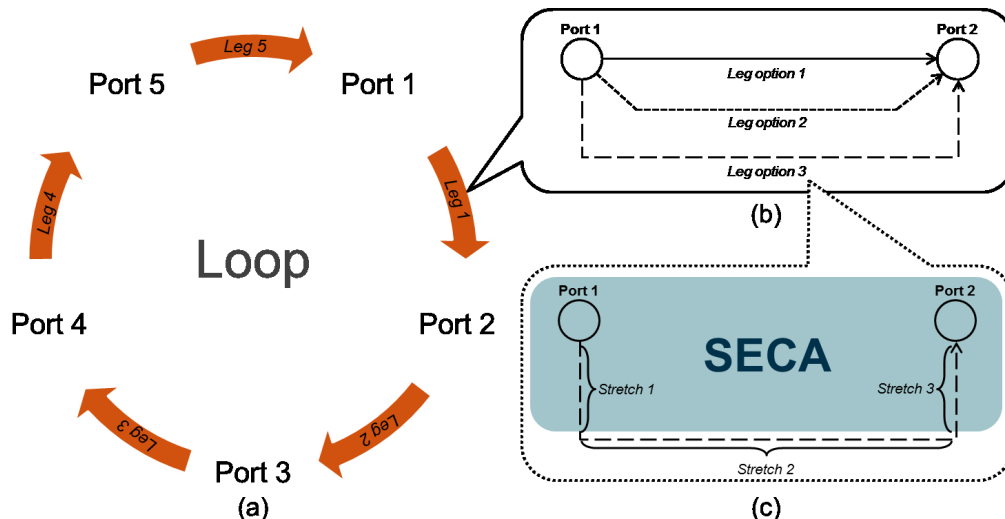


Figure 3: Illustration of loop, leg, leg option and stretch

## 2.2 Problem setting

A typical liner company offers services with fixed routes, schedules and frequencies, like bus services. The number of ships involved in a particular service route depends on the desired service frequency. Our problem is based on a trading loop operated by a liner company which involves SECA sailings, and considers the company's bunker hedging strategy as well as its routing, speed and fuel allocation decisions for the next planning period on the trading loop. The aim is to minimize the expected total bunker costs with uncertain fuel prices taken into account, while restricting the risk in total bunker costs within a desired level.

In order to reduce their exposure to cost volatility with regards to fuel consumption, fuel hedging is the most common approach used by large fuel consumers, such as air lines and shipping companies. The hedging instrument considered in this paper is the *forward-fuel contract with exit terms and physical supply* (FFC in the following), which is one of the most widely used hedging tools in the shipping industry. In an FFC, the shipping company has the right to purchase a certain amount of a specified type of bunker with a fixed price during a given time period, while the bunker supplier has the obligation to deliver regardless of future spot price developments. The agreed amount, price, fuel type and delivery period will be stated in the contract. However, during the execution of an FFC, if the shipping company realizes that it no longer needs the remaining fuel in the FFC, and decides to quit the contract, a penalty must be paid for the unused amount. On the other hand, the shipping company may still purchase fuel from the spot market during the operational phase in the cases where the hedged amount is not sufficient or the spot price is very low.

## 2.3 Assumptions

The following assumptions are made when developing the model.

- For simplicity, we only consider one ship in our problem. The length of a complete planning period for the MBM problem is set to be the time needed for the ship to finish a round trip on a specific trading loop.
- The service network design (port visit sequence) and the corresponding leg information (such as the leg options for each leg, and the characteristics of the associated stretches for every leg option) of the trading loop are assumed to be given and used as input to our model.
- The unused fuel left in an FFC during the planning period cannot be stored for future use or sold in a spot market, but is assumed to be sold back to the bunker supplier with a certain penalty.
- The shipping company cannot enter a new FFC during the operational stage.
- The fuel market is assumed to be exogenous and transparent, in which the fuel prices are public information.

## 3 The Model

In this section we present the mathematical model for the MBM problem. Section 3.1 introduces several important components of the model. The mathematical formulation is presented in Section 3.2.

### 3.1 Model development

We propose a two-stage stochastic programming model. The uncertain phenomena we seek to capture are the spot prices for MGO and HFO fuels during the planning period, which are represented using scenarios. The first-stage decisions, made before the planning period, are the amounts of both fuels to hedge in an FFC (forward contract), which belong to the tactical level of MBM. In the second stage, where the two spot fuel prices (which are assumed to be constant during the planning period in each scenario) are realized, operational decisions will be made based on the realized scenario and the already made first-stage decisions. These operational decisions include: (a) the speed and routing choices on each leg; and (b) the fuel allocation decisions regarding how much spot- and forward-fuels should be used, respectively, in order to satisfy the ship's actual fuel consumption based on the chosen speeds and routes. The aim of the model is to minimize the total bunker costs, which comprises the costs of forward-fuels hedged, and the *expected* costs of spot-fuels purchased, with penalties for unused forward amounts (if any), and financial risk taken into account.

To model the risk attitude of the shipping company, we include *conditional value-at-risk* (CVaR) constraints which are imposed on the total bunker costs. Two key parameters, a confidence level and a maximum CVaR value, are predetermined for our model. The confidence level and the maximum CVaR value, together, reflect the degree of risk aversion held by the shipping company. In our problem, for example, given a confidence level of 95% and a maximum CVaR value of \$300,000, the CVaR constraints would restrict the likelihood of the total bunker costs exceeding \$300,000 to under 5%.

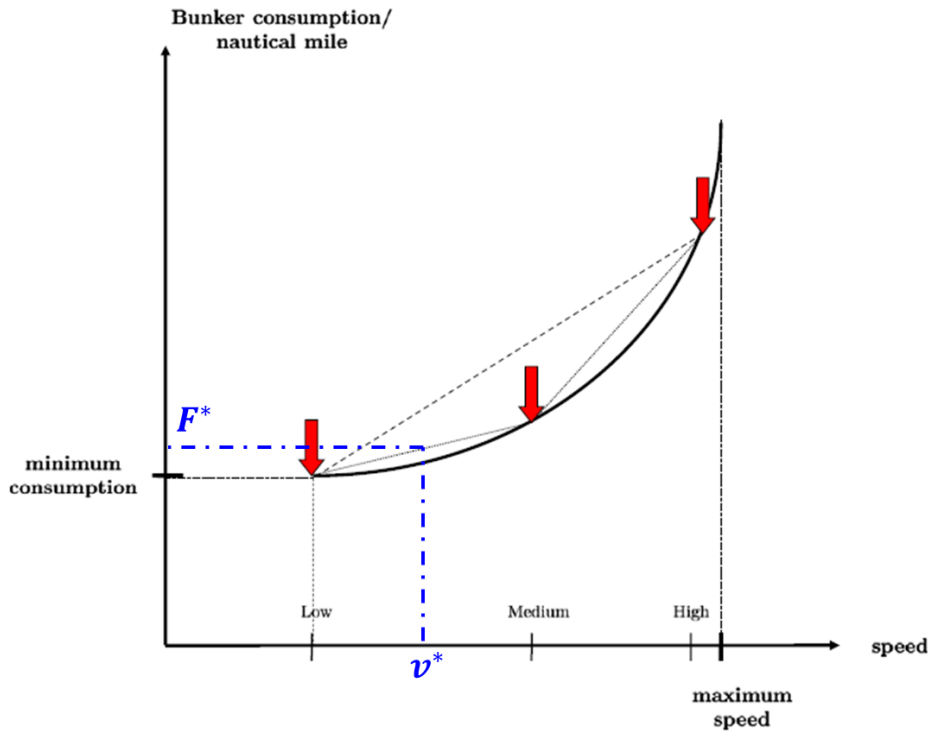


Figure 4: Piecewise linearisation of fuel consumption (Andersson et al., 2015)

Another challenge is the modeling of the fuel consumption rate relative to speed. It has been shown in the literature that fuel consumption per time unit for a cargo ship is approximately proportional to the third power of its sailing speed (Ronen, 1982; Psaraftis and Kontovas, 2013), and the cubic function can be transferred to a quadratic function that provides a good estimation of the relationship between fuel consumption per distance unit and speed (Norstad et al., 2011). Nevertheless, shipping companies normally have fuel consumption data only for



a group of discrete speed points rather than a function, which is also the case in our study. We therefore use the piecewise linearisation approach, proposed by [Andersson et al. \(2015\)](#), to approximate the fuel consumption rate under different sailing speeds. This approach uses linear combinations of the fuel consumption rates at given speed points to provide an estimation between these speed points, as shown in [Fig. 4](#). For instance, if some particular speed  $v^*$  can be written, using two weight values  $a, b, a + b = 1$ , and two speed points  $v_{Low}, v_{Medium}$ , as  $v^* = a * v_{Low} + b * v_{Medium}$ ; then the estimated fuel consumption rate  $F^*$  at speed  $v^*$  can be calculated as  $F^* = a * F_{Low} + b * F_{Medium}$ . Although this approach normally leads to an overestimation (see [Andersson et al.](#) for explanations), the gap is usually acceptable as long as enough discrete speed points are used. This method also gives a proper approximation of the sailing time-speed relation on each leg and stretch.

### 3.2 Mathematical formulation

The notation used in the formulation is as follows:

#### Sets

$J$	Set of sailing legs along the loop
$R_j$	Set of leg options for Leg $j$
$V$	Set of feasible discrete speed points for the ship
$S$	Set of price scenarios

#### Parameters

$P^{MGO-F}$	Price per ton of MGO agreed in the forward-fuel contract
$P^{HFO-F}$	Price per ton of HFO agreed in the forward-fuel contract
$P_s^{MGO-S}$	Price per ton of MGO on spot market under scenario $s$
$P_s^{HFO-S}$	Price per ton of HFO on spot market under scenario $s$
$P^{MGO-P}$	Penalty per ton for the unused MGO left in the forward-fuel contract
$P^{HFO-P}$	Penalty per ton for the unused HFO left in the forward-fuel contract
$\bar{W}_j$	Latest starting time for Leg $j$
$W_j^S$	Service time for Leg $j$ in the departing port
$W_{jrv}^{SECA}$	Sailing time on SECA stretches on Leg $j$ under Leg option $r$ with speed $v$
$W_{jrv}^N$	Sailing time on non-SECA stretches on Leg $j$ under Leg option $r$ with speed $v$
$D_{jr}^{SECA}$	Sailing distance on SECA stretches on Leg $j$ under Leg option $r$
$D_{jr}^N$	Sailing distance on non-SECA stretches on Leg $j$ under Leg option $r$
$F_v$	Fuel consumption per unit distance sailed with speed alternative $v$ (same for both HFO and MGO)
$p_s$	Probability of scenario $s$ taking place
$\gamma$	Confidence level applied in CVaR
$A_\gamma$	The maximum tolerable CVaR value under confidence level $\gamma$

## Decision variables

$x_{jrvs}^{SECA}$	Weight of speed choice $v$ used on SECA stretches on Leg $j$ with Leg option $r$ under scenario $s$
$x_{jrvs}^N$	Weight of speed choice $v$ used on non-SECA stretches on Leg $j$ with Leg option $r$ under scenario $s$
$y_{jrs}$	Binary variables representing the decisions on route selection, equal to 1 if Leg option $r$ is sailed on Leg $j$ under scenario $s$ , and 0 otherwise
$z_{js}^{MGO-S}$	Amount of MGO from spot market used on Leg $j$ under scenario $s$
$z_{js}^{MGO-F}$	Amount of MGO from forward contract used on Leg $j$ under scenario $s$
$z_{js}^{HFO-S}$	Amount of HFO from spot market used on Leg $j$ under scenario $s$
$z_{js}^{HFO-F}$	Amount of HFO from forward contract used on Leg $j$ under scenario $s$
$u_s^{MGO-F}$	Amount of unused forward MGO left at the end of the planning period under scenario $s$
$u_s^{HFO-F}$	Amount of unused forward HFO left at the end of the planning period under scenario $s$
$m^{MGO-F}$	Agreed amount of MGO in the forward contract
$m^{HFO-F}$	Agreed amount of HFO in the forward contract
$\alpha$	Artificial variable for CVaR constraints
$h_s$	Artificial variables for CVaR constraints under scenario $s$

The mathematical formulation is as follows:

$$\begin{aligned}
\min \quad & P^{MGO-F} m^{MGO-F} + P^{HFO-F} m^{HFO-F} \\
& + \sum_{s \in S} P_s \left\{ \sum_{j \in J} (P_s^{MGO-S} z_{js}^{MGO-S} + P_s^{HFO-S} z_{js}^{HFO-S}) \right. \\
& \left. - (P^{MGO-F} - P^{MGO-P}) u_s^{MGO-F} - (P^{HFO-F} - P^{HFO-P}) u_s^{HFO-F} \right\}
\end{aligned} \tag{1}$$

Subject to

$$\bar{W}_{j+1} \geq \bar{W}_j + W_j^S + \sum_{r \in R_j} \sum_{v \in V} (W_{jrv}^{SECA} x_{jrvs}^{SECA} + W_{jrv}^N x_{jrvs}^N) \quad s \in S, j \in J \tag{2}$$

$$\sum_{v \in V} x_{jrvs}^{SECA} = y_{jrs} \quad s \in S, j \in J, r \in R_j \tag{3}$$

$$\sum_{v \in V} x_{jrvs}^N = y_{jrs} \quad s \in S, j \in J, r \in R_j \tag{4}$$

$$\sum_{r \in R_j} y_{jrs} = 1 \quad s \in S, j \in J \tag{5}$$

$$z_{js}^{MGO-F} + z_{js}^{MGO-S} = \sum_{r \in R_j} \sum_{v \in V} F_v D_{jr}^{SECA} x_{jrvs}^{SECA} \quad s \in S, j \in J \quad (6)$$

$$z_{js}^{HFO-F} + z_{js}^{HFO-S} = \sum_{r \in R_j} \sum_{v \in V} F_v D_{jr}^N x_{jrvs}^N \quad s \in S, j \in J \quad (7)$$

$$\sum_{j \in J} z_{js}^{MGO-F} + u_s^{MGO-F} = m^{MGO-F} \quad s \in S \quad (8)$$

$$\sum_{j \in J} z_{js}^{HFO-F} + u_s^{HFO-F} = m^{HFO-F} \quad s \in S \quad (9)$$

$$y_{jrs} \in \{0, 1\} \quad s \in S, j \in J, r \in R_j \quad (10)$$

$$x_{jrvs}^{SECA}, x_{jrvs}^N \geq 0 \quad s \in S, j \in J, r \in R_j, v \in V \quad (11)$$

$$z_{js}^{MGO-F}, z_{js}^{MGO-S}, z_{js}^{HFO-F}, z_{js}^{HFO-S} \geq 0 \quad s \in S, j \in J \quad (12)$$

$$u_s^{MGO-F}, u_s^{HFO-F} \geq 0 \quad s \in S \quad (13)$$

*CVaR constraints:*

$$\alpha + \frac{1}{1-\gamma} \sum_{s \in S} p_s h_s \leq A_\gamma \quad (14)$$

$$h_s \geq 0 \quad s \in S \quad (15)$$

$$\begin{aligned} h_s \geq & P^{MGO-F} m^{MGO-F} + P^{HFO-F} m^{HFO-F} \\ & - (P^{MGO-F} - P^{MGO-P}) u_s^{MGO-F} - (P^{HFO-F} - P^{HFO-P}) u_s^{HFO-F} \\ & + \sum_{j \in J} (P_s^{MGO-S} z_{js}^{MGO-S} + P_s^{HFO-S} z_{js}^{HFO-S}) - \alpha \quad s \in S \end{aligned} \quad (16)$$

The objective function (1) minimizes the sum of the forward-fuel costs, the expected spot-fuel costs and the penalty for unused forward-fuels. The first line in the objective function refers to the initial costs for the agreed amounts of MGO and HFO in the forward contracts, while the expected costs for spot-fuels consumed in the second stage are expressed as the second line of the objective function. The last line represents selling the unused forward-fuels back to the bunker supplier at the end of the planning period at their “buyback prices”, which are calculated as their initial forward prices minus the penalty rates.

Constraints (2) ensure that the time constraints for all sailing legs are respected. Constraints (3) and (4) connect x- and y-variables with respect to the speed-routing choices in SECA and non-SECA stretches, respectively. They ensure that the sums of the speed weights,  $x_{jrvs}^{SECA}$  and  $x_{jrvs}^N$  respectively for SECA and non-SECA stretches, are equal to 1 if Leg option  $r$  is chosen for Leg  $j$  in Scenario  $s$ , and 0 otherwise. Constraints (5) ensure that only one leg option is used on any specific leg. Constraints (6) - (9) are bookkeeping constraints. Constraints (6) and (7) make sure that for each scenario the sum of the spot- and forward-fuels used on each leg equals the actual fuel consumption on that leg based on the speeds and leg options chosen. Constraints (8) and (9) ensure that the forward-fuels used plus the leftovers equal the agreed

amounts in the forward contract. Constraints (10) - (13) define the domains of the decision variables. Constraints (14) - (16) are the CVaR constraints representing the risk (aversion) attitude of the shipping company, restricting the risk on the total bunker costs to be within an acceptable level.

## 4 Test case and scenario generation

In this section, we describe our test case in Section 4.1, followed by the scenario generation process in Section 4.2.

### 4.1 Basic information of the case

We consider a case based on Wallenius Wilhelmsen Logistics (WWL), a major roll-on roll-off (RoRo) liner shipping company for transporting cars, trucks and other heavy rolling equipment. The service loop and the corresponding schedules are adopted from one of WWL’s Europe-Americas trade lanes, see Fig. 5. The port visit sequence of the loop is shown in Table 1. In reality, this service loop has several more port calls in Europe besides the Port of Bremerhaven. However, these ports are close to each other, and are all located inside the North Sea SECA. There are, therefore, no feasible alternative leg options and different types of stretches for the shipping company to carry out SECA-evasion or speed differentiation strategies among these ports, apart from the direct (shortest) routes with the same slowest possible speed. We therefore only use one port inside the North Sea SECA, and the schedule information in that area is aggregated and adjusted accordingly to this effect. The time needed to finish a round trip in this case is 35 days. Hence, the planning period here is also set to be 35 days according to the assumption made in Section 2.3.

**Table 1:** Port visit sequence of the considered service loop

	From	To
Leg 1	Brunswick	Galveston
Leg 2	Galveston	Charleston
Leg 3	Charleston	New York
Leg 4	New York	Bremerhaven
Leg 5	Bremerhaven	Brunswick

The fuel consumption data for a number of discrete speed points used in this paper is collected from historical data of a real RoRo ship under normal conditions. From the raw data, we have selected 7 discrete speed points ranging from 15 knots to 24 knots. Fig. 6 shows the fuel consumption values (in tons/nautical mile) for the selected speed points. Note that, since the fuel consumption function is monotonically increasing and convex, the discrete speed points are placed more densely towards higher speeds.

For the considered service loop in our case study, we have constructed five leg options for each leg of the loop. When constructing these leg options, the main principle can be described as follows: for each leg, Leg option 1 is to sail the shortest possible distance without any consideration of reducing SECA involvement, which is also the sailing route used before SECA regulation was established; Leg option 5 has the lowest possible SECA involvement in spite of a significant increase in total sailing distance; and the other three leg options are in between the two extreme cases. An illustration of all five leg options of Leg 3 (Charleston-New York) is shown in Fig. 7. The solid black line is the SECA border (IMO, 2016), while the dotted lines marked with numbers refer to Leg options 1, 2, 3, 4 and 5, respectively. Leg option 1 has

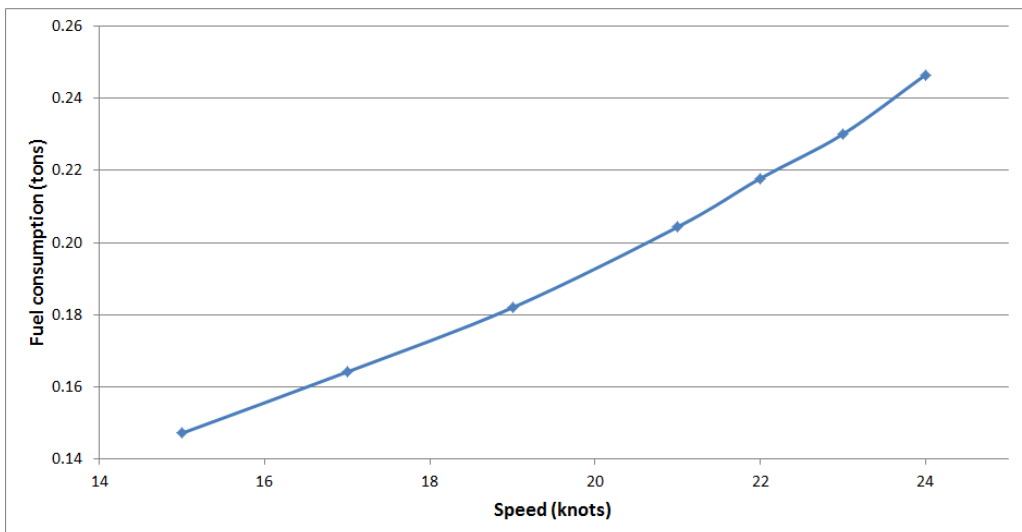


(a) Trade lanes from Europe to Americas



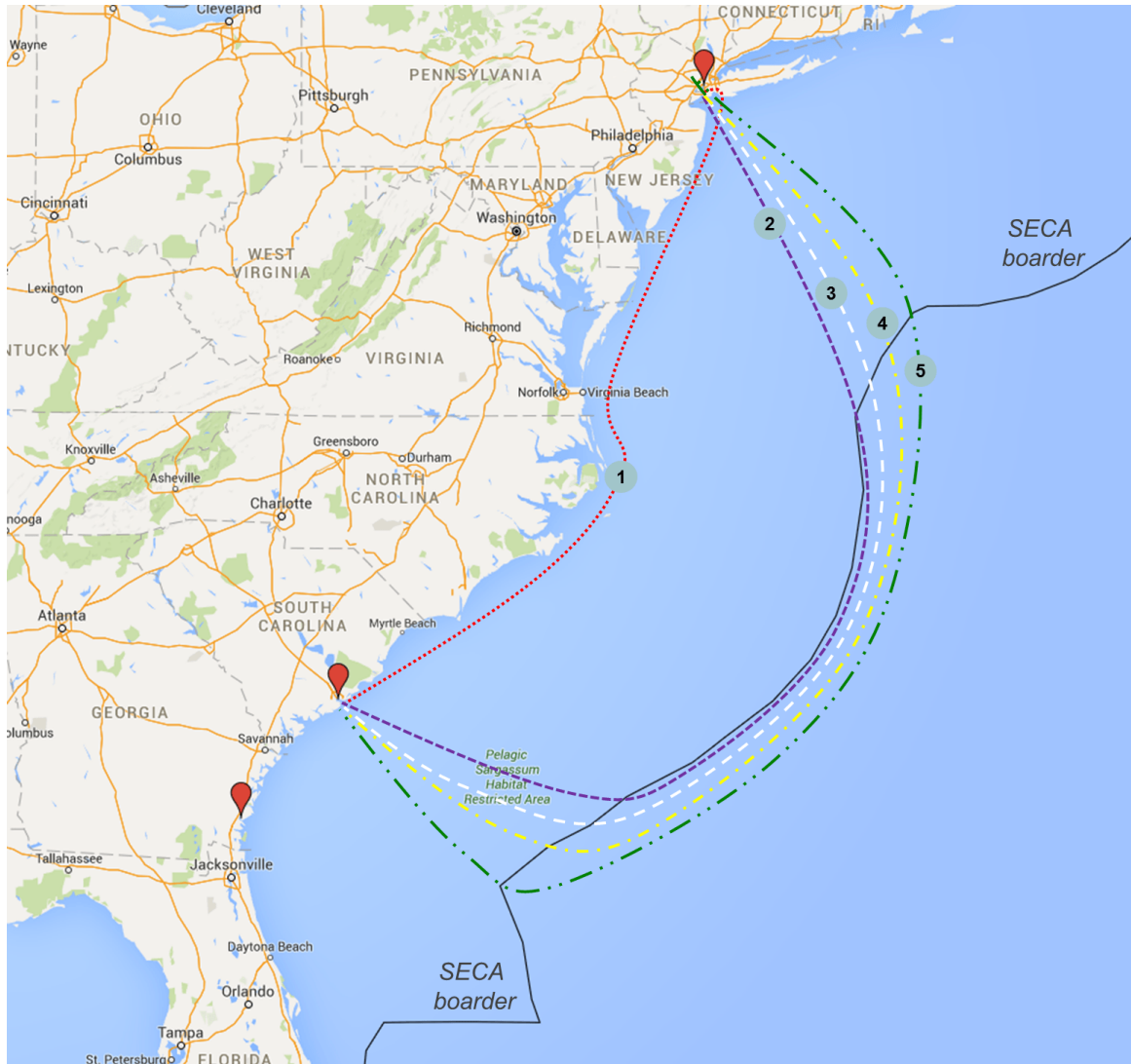
(b) Trade lanes from Americas to Europe

**Figure 5:** All trade lanes operated by WWL between Europe and Americas (WWL, 2016)



**Figure 6:** Fuel consumption (tons/nautical mile) for the selected discrete speed points

the shortest sailing distance and Leg option 5 has the lowest SECA involvement. The detailed sailing distances within SECA and non-SECA for each leg option of every leg are presented in [Table 2](#).



**Figure 7:** Illustration of the five leg options for Leg 3 (Charleston - New York). (Google Maps, 2016)

**Table 2:** Sailing distances within SECA/non-SECA for each leg option of every leg

SECA/non-SECA (nautical mile)	Option 1	Option 2	Option 3	Option 4	Option 5
Leg 1	1191/35	569/774	495/870	469/905	408/1062
Leg 2	1271/34	686/704	524/906	458/1083	397/1241
Leg 3	632/0	560/330	499/429	443/515	423/602
Leg 4	1767/1629	1379/2125	1042/2503	899/2652	752/2903
Leg 5	2393/1626	1110/2984	1013/3109	817/3337	751/3428

## 4.2 Scenario generation

The stochastic phenomena in our problem are, as mentioned earlier, the spot prices for MGO and HFO. Given their individual distributions and the correlation between the two prices, we use a version of the scenario-generating heuristic proposed by [Høyland et al. \(2003\)](#). This heuristic

approach matches the first four moments of the marginal distributions plus correlations. When constructing the scenarios for the spot fuel prices for the next planning period, we use the latest observed prices on the spot market as base prices, and generate (positive or negative) price increments to be added to the base prices. The reason is that fuel prices are highly dependent over time. It would be problematic to directly use the raw data of the historical fuel prices from the past booming period (e.g. 2008) to generate future fuel price scenarios since the market is in depression. However, the development of fuel price can be considered as a Lévy process (Krichene, 2008; Gencer and Unal, 2012) which has independent increments.

To obtain appropriate distributions and correlation for the price increments of the two types of fuels, we use the historical data provided by Clarkson Research Services Limited (Clarkson, 2015), which is one of the largest data and consulting service providers in the shipping industry. The raw data contains the average value of the monthly prices of three major ports, Rotterdam, Houston and Singapore, from January 2000 to December 2015. Then we use the the raw data to calculate the historical monthly price increments which are used as the final input data for scenario generation process.

The correlation between the HFO and MGO price increments is estimated at 0.75, which is also derived from the historical fuel data. Moreover, the marginal distributions of the random price increments are assumed to be triangular and symmetric. The marginal distributions used in the scenario-generating heuristic are controlled by the lower limit, mode and upper limit which are  $(-40, 0, 40)$  for HFO and  $(-120, 0, 120)$  for MGO. The symmetry, estimated correlation and estimated marginal distributions are all interpreted from the monthly average of the fuel price increments observed in the three ports during the last 16 years. For December 2015, we ended up with 150 USD/ton for HFO, while for MGO it was about 375 USD/ton. These latest prices are used as the basis for the fuel price scenarios in the planning period. Since the expected values of the price increments equal 0, the expected value of the spot-fuel prices in the second stage are assumed to be equal to the latest observed fuel prices. This is a reasonable assumption for our model, since if there is a known increase or decrease in expected prices, which means a guaranteed expected gain or loss, speculation may occur and that is not what we analyze.

Furthermore, we also check the reliability of the scenario generation approach we use. The in-sample stability test (Kaut and Wallace, 2007) is performed in order to ensure that the solution of the stochastic model does not depend too much on the particular scenario tree used. We generate 10 scenario trees, each consisting of 100 scenarios, using the same generating approach and parameters. We then solve the problem with each scenario tree and are able to observe approximately the same objective function values. The gap among the objective values in the in-sample stability test is less than 0.02%, which is small enough to ensure stability when using 100 scenarios in our problem.

## 5 Computational study

This section presents our computational study. Section 5.1 introduces the comparison and analysis tests. Section 5.2 offers other important details applied in the computational study. Numerical results and managerial insights are given in Section 5.3.

### 5.1 Tested situations

In order to understand the interaction between the tactical and operational levels of MBM, and the importance of integrated decision-making, we introduce several situations in the following, representing different types of integration between the two levels.

**Situation 1.** *Decisions on both tactical and operational levels are made with complete integration.*

In **Situation 1**, the tactical and operational levels of MBM are well connected. This means that the hedging department will take the potential sailing behaviour changes during future fleet operation into account when making hedging decisions, while the operation team makes routing decisions, such as leg option and speed choices, based on not only the realized spot fuel prices but also the tactical fuel hedging decisions which have already been made. Note that this situation is represented by solving the problem with the proposed formulation in Section 3 without any changes.

We then introduce **Situation 2** where the tactical and operational levels of MBM are somewhat disconnected. We consider three sub-situations.

**Situation 2.a.** *Decisions on both tactical and operational levels are made in isolation.*

In **Situation 2.a**, the tactical and operational levels of MBM are completely separated. Neither of them includes the other party in its decision-making. On the tactical level, the hedging department assumes that the operation team will still sail their fleet in the traditional way, i.e., according to patterns used before SECA regulations were implemented. The operational SECA-related strategies including SECA evasion and speed differentiation are therefore not taken into account at the tactical level. On the other hand, the operation team also ignores the amounts of forward-fuels hedged and makes its routing plans solely based on the spot-fuel prices.

To implement this sub-situation, we first obtain the tactical hedging decisions the way they would be made in isolation. We keep only Leg option 1 for each leg (removing all the others), representing the traditional route sailed before SECA was introduced. Moreover, an additional group of constraints (17) are added to the model in order to ensure the speeds used on SECA and non-SECA stretches are the same, which means no speed differentiation. We then solve the problem and observe the first-stage tactical decisions, i.e. the amounts of MGO and HFO hedged in the “traditional” way, denoted  $m_{\text{traditional}}^{MGO-F}$  and  $m_{\text{traditional}}^{HFO-F}$ , respectively.

$$x_{jrvs}^{SECA} = x_{jrvs}^N \quad s \in S, j \in J, r \in R_j, v \in V \quad (17)$$

We then obtain the operational decisions as they would be if made in isolation, disregarding any hedging decisions made. We start with the original formulation, i.e. without constraints (17), but take out the CVaR constraints (14) - (16) since they are intended for risk control when making the tactical hedging decisions. We solve the problem with both  $m^{MGO-F}$  and  $m^{HFO-F}$  set to zero and with full leg options for every leg, and observe the purchased amounts of spot fuels in each scenario  $s \in S$ , denoted  $z_{js}^{*MGO-S}$  and  $z_{js}^{*HFO-S}$ . In fact, these values are also the actual consumption in operation as the hedging amounts are set to zero, and therefore represent the operational decisions made in isolation.

To evaluate this sub-situation in terms of total costs, we combine the tactical and operational decisions obtained ( $m_{\text{traditional}}^{MGO-F}$ ,  $m_{\text{traditional}}^{HFO-F}$  and  $z_{js}^{*MGO-S}$ ,  $z_{js}^{*HFO-S}$ ), and recalculate the objective function value using the scenarios for spot fuel prices and the following Equations (18) - (20).



$$\begin{aligned}
\text{Recalculated Total Cost} &= m_{\text{traditional}}^{MGO-F} P^{MGO-F} + m_{\text{traditional}}^{HFO-F} P^{HFO-F} \\
&+ \sum_{s \in S} p_s \left\{ \left[ \sum_{j \in J} z_{js}^{*MGO-S} - \theta_s^{MGO-F} \right]^+ P_s^{MGO-S} \right. \\
&\quad + \left[ \sum_{j \in J} z_{js}^{*HFO-S} - \theta_s^{HFO-F} \right]^+ P_s^{HFO-S} \\
&\quad - \left[ m_{\text{traditional}}^{MGO-F} - \min \left( \sum_{j \in J} z_{js}^{*MGO-S}, \theta_s^{MGO-F} \right) \right]^+ (P^{MGO-F} - P^{MGO-P}) \\
&\quad \left. - \left[ m_{\text{traditional}}^{HFO-F} - \min \left( \sum_{j \in J} z_{js}^{*HFO-S}, \theta_s^{HFO-F} \right) \right]^+ (P^{HFO-F} - P^{HFO-P}) \right\}
\end{aligned} \tag{18}$$

where

$$\theta_s^{MGO-F} = \begin{cases} m_{\text{traditional}}^{MGO-F}, & \text{if } P_s^{MGO-S} \geq P^{MGO-F} - P^{MGO-P} \\ 0, & \text{otherwise} \end{cases}, s \in S \tag{19}$$

$$\theta_s^{HFO-F} = \begin{cases} m_{\text{traditional}}^{HFO-F}, & \text{if } P_s^{HFO-S} \geq P^{HFO-F} - P^{HFO-P} \\ 0, & \text{otherwise} \end{cases}, s \in S \tag{20}$$

The  $[ \ ]^+$  operator in Equation (18) outputs the original value of the expression inside the operator if it is positive, and 0 otherwise. The values for additional variables  $\theta_s^{MGO-F}$  and  $\theta_s^{HFO-F}$  are determined by the comparison between the realized spot-fuel prices in each Scenario  $s$  and the buyback prices of unused forward-fuels, see Equations (19) & (20). These two sets of additional variables indicate the priority of using fuels from the forward contract. If the spot price is higher than the buyback price of a certain forward-fuel, it is reasonable to use up the forward-fuel first. But if in some scenario a certain fuel's spot price is lower than its buyback price in the forward contract, the shipping company will choose to operate solely on spot-fuel under that scenario and pay the penalty for the entire amount of the forward-fuel hedged. The first line and last two lines of the right-hand-side expression of Equations (18) make up the expenses of the two forward-fuels and corresponding penalties if any, while the middle part of the expression stands for the expected costs for spot-fuels.

**Situation 2.b.** *Decisions on the tactical level are made with integration while decisions on the operational level are made in isolation.*

In *Situation 2.b*, we assume that tactical hedging decisions are made with operational considerations taken into account, while the operation team still makes its decisions in isolation. To implement this sub-situation, we obtain the operational decisions the same way as in *Situation 2.a*. However, instead of the “traditional” hedging amounts without SECA considerations, we recalculate the total costs with Equations (18) - (20) using the “smart” hedging amounts as in [Situation 1](#).

**Situation 2.c.** *Decisions on the tactical level are made in isolation while decisions on the operational levels are made with integration.*

In *Situation 2.c*, the tactical hedging decisions are made assuming “traditional” sailing patterns, but the operation team optimizes its sailings in the light of both SECA consideration and the hedging decisions already made. To implement, we set the variables  $m^{MGO-F}$  and  $m^{HFO-F}$  to  $m_{traditional}^{MGO-F}$  and  $m_{traditional}^{HFO-F}$ , respectively, which are the “traditional” amounts of MGO and HFO hedged as obtained in *Situation 2.a*. We then solve the problem (without the CVaR constraints), and observe the objective function value.

## 5.2 Other important details

Before we show the numerical results, some other important details applied in the computational study must be stated.

In all tested situations the forward price is set to be slightly higher than the expected value of the stochastic spot price over the planning period, which means there is no free lunch for removing the risks. Moreover, the penalty levels for both fuels are ideally set so that only risk averse companies will buy FFC.

In order to ensure the comparability of different situations, we apply the same level of risk aversion in all of our tests, whenever the CVaR constraints (14) - (16) are active. The maximum CVaR value ( $A_\gamma$ ) is set to be 1% higher than the expected costs obtained under a risk neutral assumption<sup>1</sup>, and the confidence value ( $\gamma$ ) is set to 95%. These parameters can of course be adjusted according to the shipping company’s actual risk attitude. However, since the minimized expected costs in the risk neutral case are the lowest costs that the shipping company can get, we argue that restricting the total costs in the extreme cases to a maximum of 1% increase is a reasonable risk control setting for the test purpose in this paper.

## 5.3 Numerical results

The aggregated numerical results for all tested situations are displayed in Table 3. For each situation, the first-stage hedging decisions as well as the (average) second-stage fuel allocation decisions are presented in detail.

The average consumption of different fuels equals the sum of the actual fuel consumption of that type in each scenario multiplied by the probability of the scenario. Similar logic applies to the average unused fuels. Moreover, the expected total costs is the objective value of the optimization while the standard deviation refers to the cost volatility among all the scenarios. Given a 95% confidence level, the last row in the table shows the risk level in extreme cases (CVaR value) which equals the average of the realized total costs in the worst 5% scenarios in that situation.

### 5.3.1 Comparison between Situation 1 and Situation 2.a

To compare *Situation 2.a* with *Situation 1*, we use a box plot to show the scope and variability of the total costs produced across all 100 scenarios for each of the two situations, see Fig. 8. The whisker on either side of a box represents the 5% scenarios with the highest (right whisker) or the lowest (left whisker) total costs, while the box represents the remaining

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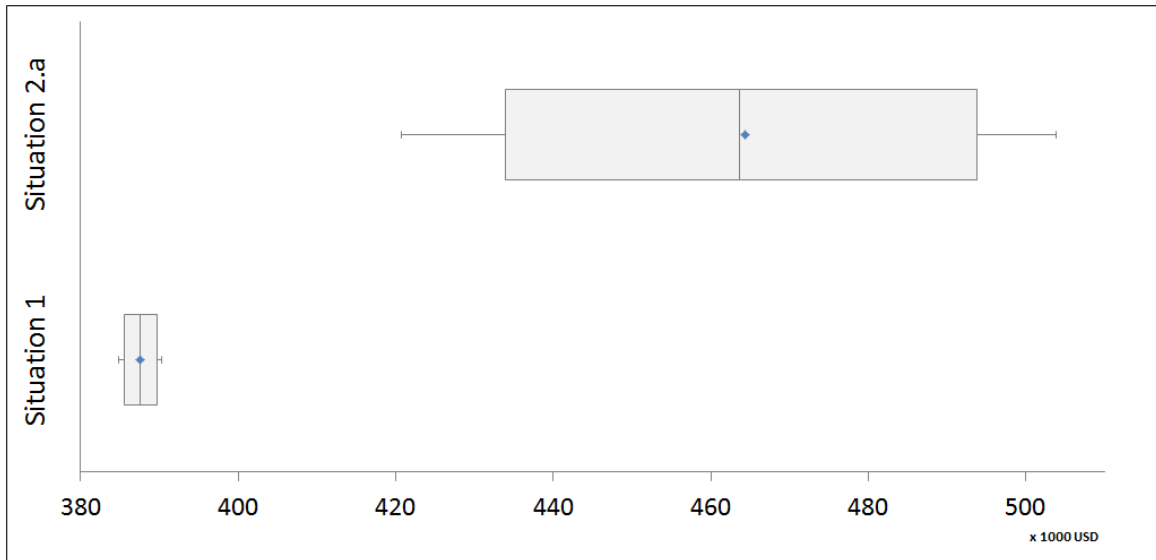
<sup>1</sup>Since the forward-fuel prices are only set marginally higher than the expected prices of the spot-fuels, it is feasible and reasonable to restrict the risk level to such extent in this test. We also need to point out that the comparison between risk neutral and risk averse cases is not the focus of this paper.

**Table 3:** Major numerical results of optimization in different situations

	Situation 1	Situation 2.a	Situation 2.b	Situation 2.c
<b>First-stage</b>				
<i>Amount of MGO hedged (tonne)</i>	455.40	1145.20	455.40	1145.20
<i>Amount of HFO hedged (tonne)</i>	1379.42	314.43	1379.42	314.43
<b>Second-stage</b>				
<b><i>forward managing</i></b>				
<i>Average consumption of forward MGO (tonne)</i>	455.38	466.62	455.403	502.333
<i>Average consumption of forward HFO (tonne)</i>	1379.42	314.43	1379.42	314.43
<i>Average unused forward MGO (tonne)</i>	0.02	678.59	0	642.87
<i>Average unused forward HFO (tonne)</i>	0	0	0	0
<b><i>spot managing</i></b>				
<i>Average consumption of spot MGO (tonne)</i>	17.95	0	11.21	0
<i>Average consumption of spot HFO (tonne)</i>	23.24	1106.83	41.83	1025.41
<b>Overview</b>				
<i>Expected total costs (USD)</i>	387575	464323	388567	461754
<i>Difference (%)</i>	-	19.8%	0.3%	19.1%
<i>Cost standard deviation</i>	1222	17806	2597	16825
<i>Difference (%)</i>	-	1357%	113%	1277%
<i>CVaR value (95%) (USD)</i>	390000	499486	396072	494622
<i>Difference (%)</i>	-	28.1%	1.6%	26.8%

90%. From the results in Table 3 and Fig. 8, we can clearly see severe consequences when the decisions on both levels are made in isolation (*Situation 2.a*). The total cost on average (of all 100 scenarios) in *Situation 2.a* is 19.8% higher than that in **Situation 1**. Also, the total costs in *Situation 2.a* are much more volatile. The standard deviation of the total costs across all scenarios in *Situation 2.a* is 13.6 times higher than that in **Situation 1**. Moreover, the CVaR value under a 95% confidence level in *Situation 2.a* is 28.1% higher than that in **Situation 1**.

Hence, we see that the shipping company will face considerably higher expected total costs as well as higher cost volatility and risk in extreme cases under uncertain fuel prices if both tactical and operational decisions of MBM are made in isolation. In *Situation 2.a*, the shipping company tends to hedge too much MGO and too little HFO, compared to **Situation 1**, as the hedging department assumes the fleet will sail the shortest routes as before, i.e. assumes a lot of sailings in SECA. However, this turns out to be incorrect since the operation team will try to reduce their SECA involvement by applying speed differentiation and SECA-evasion.



**Figure 8:** Box plot for cost comparisons between Situation 1 and Situation 2.a

As a result, the amounts of MGO and HFO hedged in *Situation 2.a* are too high and too low, respectively, compared to the “optimal” amounts in **Situation 1**, which leads to large amounts of both unused forward MGO (high penalty) and spot HFO purchased (high volatility and risk). We can see this from the *Average unused MGO* and *Average spot HFO consumption* values in [Table 3](#).

### 5.3.2 Comparison between Situation 1 and Situation 2.b

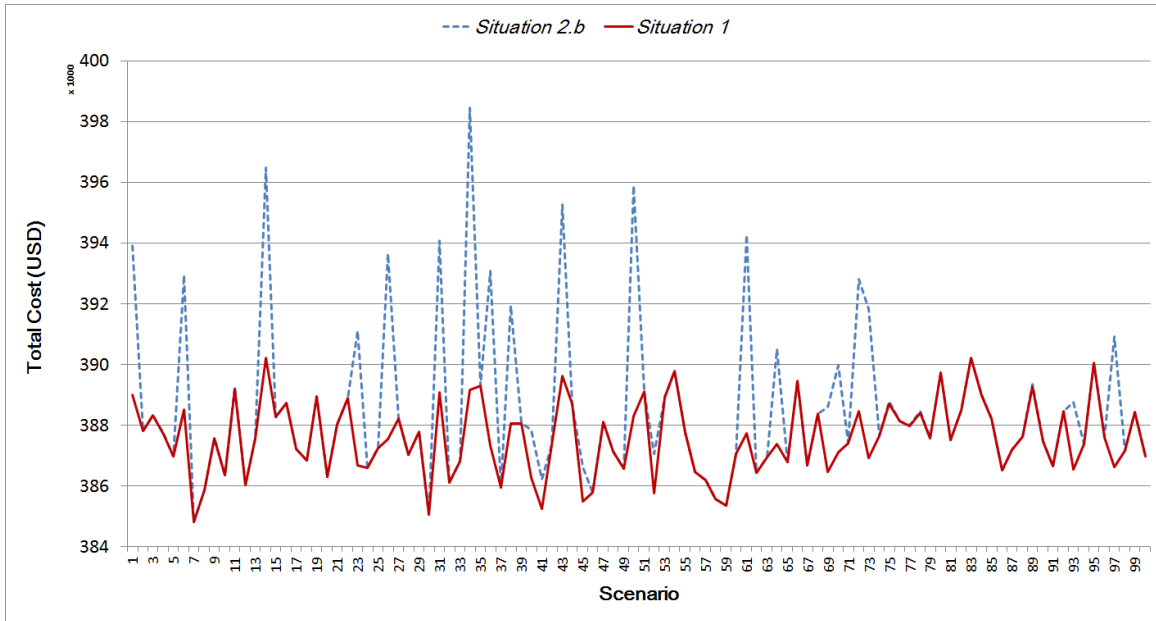
We now investigate the consequences of the case where only the decisions at the operational level are made in isolation, i.e. *Situation 2.b*. We show in [Fig. 9\(a\)](#) a scenario-by-scenario comparison of total costs between *Situation 2.b* and **Situation 1**, and in [Fig. 9\(b\)](#) a box plot comparing the two situations similar to [Fig. 8](#).

From [Fig. 9](#) and [Table 3](#), we see that although the expected total costs in *Situation 2.b* is still higher than that in **Situation 1**, the difference (0.3%) is not significant. Even so, the cost volatility in *Situation 2.b* is twice as high as that in **Situation 1**. And [Fig. 9\(a\)](#) shows that increased cost volatility is solely caused by cost increases in some of the scenarios. Higher total costs, ranging from 0.3% to 2.4%, are observed in 23 (out of all 100) scenarios and 15 of them have cost increases larger than 1%.

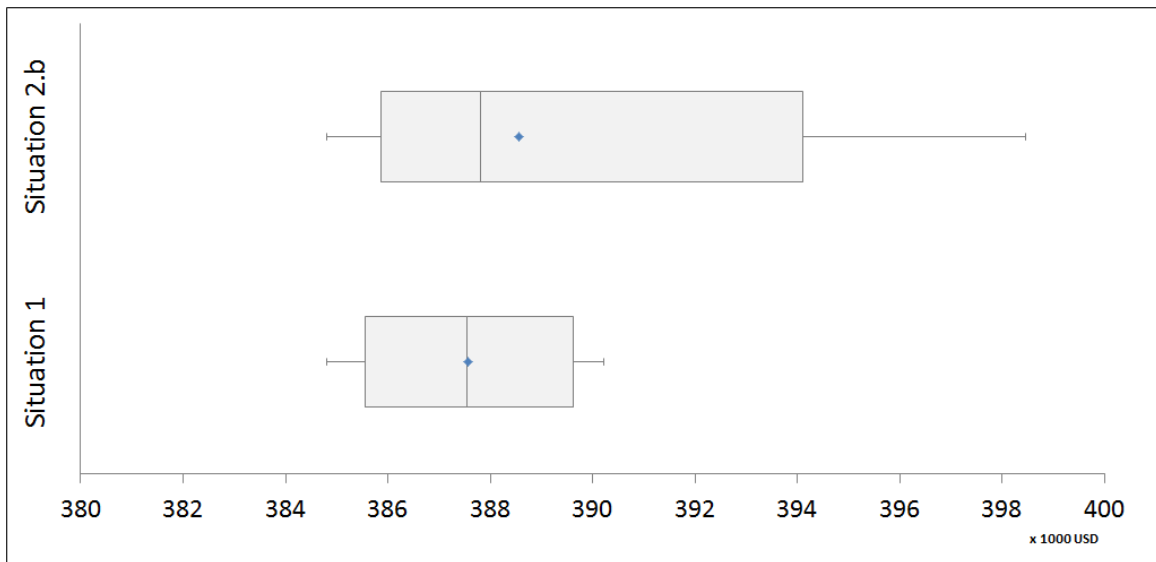
From a risk perspective, [Table 3](#) and [Fig. 9\(b\)](#) also show that the CVaR value (95%) in *Situation 2.b* is 1.6% higher than in **Situation 1**. Therefore, although the consequences caused by the ignorance in the operational decision-making are not as severe as the ones witnessed in *Situation 2.a*, it is still problematic for the shipping company since they will face a much higher risk in the extreme cases.

By looking into the experimental results in detail, we have learned that although the hedged amounts in *Situation 2.b* are the same as the “optimal” amounts in **Situation 1**, the sailing choices (leg option or speed) in the scenarios with a higher total cost are “incorrect” because they are made without taking hedged amounts into consideration.

To further illustrate, we present the detailed sailing operations under **Situation 1** and *Situation 2.b* for two particular scenarios, scenario No.34 and scenario No.52, in [Figure 10](#). Only the differences in sailing behaviors of the two situations are shown here, more details can be found in the [Appendix](#). For scenario No.34 in [Fig. 10\(a\)](#), *Situation 2.b* makes incorrect leg option choices on both Leg 3 and Leg 4 which are unnecessarily “aggressive” compared to the optimal ones, i.e., with less SECA involvement but longer total sailing distance. In addition, a



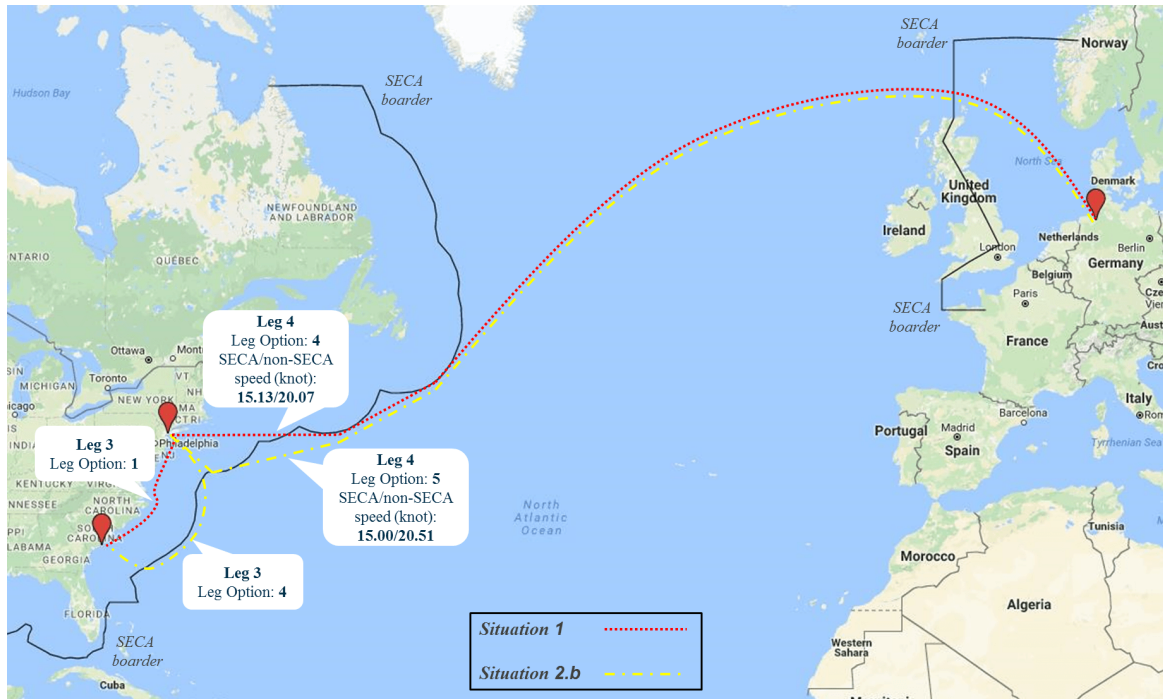
(a) Total cost comparisons across all scenarios for Situation 1 and Situation 2.b



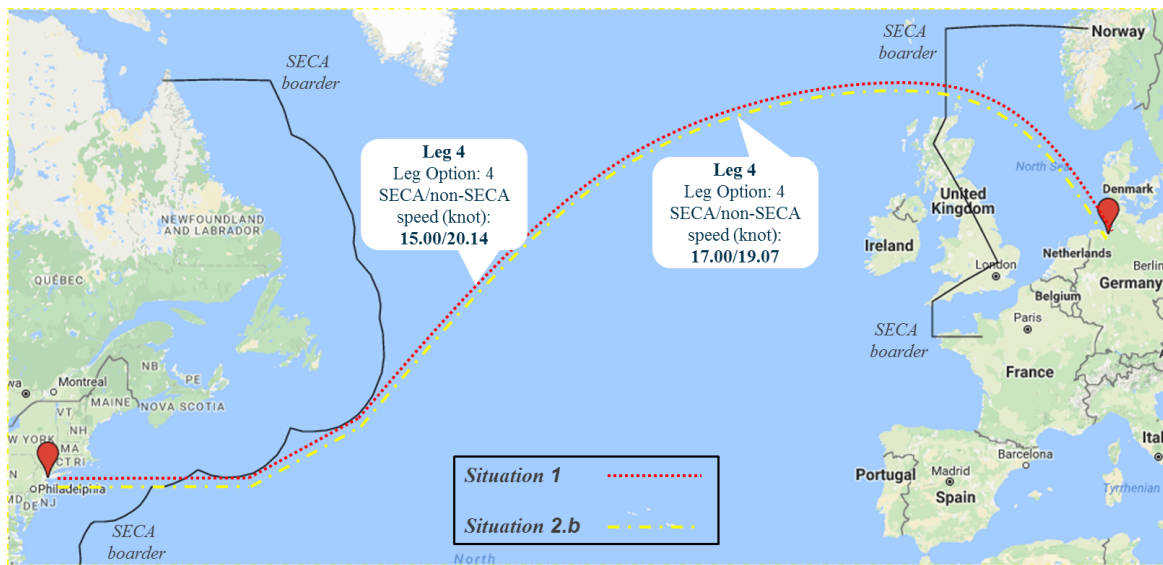
(b) Box plot for cost comparisons between Situation 1 and Situation 2.b

**Figure 9:** Comparison between Situation 1 and Situation 2.b

larger speed difference when sailing in and out of SECA is also seen on Leg 4 under *Situation 2.b*. For scenario No.52 in Fig. 10(b), although the same leg option is chosen for Leg 4 in both situations, an unnecessarily “conservative” speed combination, i.e. small speed difference in and out of SECA, is used in *Situation 2.b* which also results in a higher total cost.



(a) Different sailing behaviors between Situation 1 and Situation 2.b in Scenario No.34

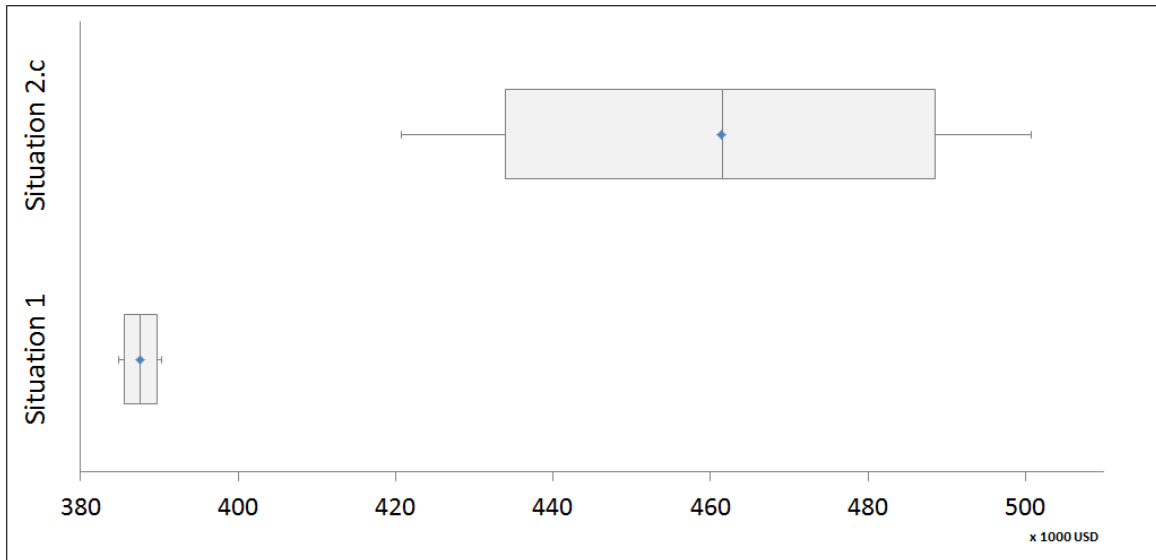


(b) Different sailing behaviors between Situation 1 and Situation 2.b in Scenario No.52

**Figure 10:** Comparison between Situation 1 and Situation 2.b

### 5.3.3 Comparison between Situation 1 and Situation 2.c

The results from comparing *Situation 1* and *Situation 2.c* are also shown with a box plot in Fig. 11. Recall that in *Situation 2.c*, the tactical hedging decisions are made in isolation and thus assume “traditional” sailing patterns. The amounts hedged are therefore the same as in *Situation 2.a*, while the operation team actually optimizes its sailings based on both SECA consideration and the “traditional” (and incorrect) forward-fuel amounts hedged.



**Figure 11:** Box plot of comparison between Situation 1 and Situation 2.c

From Fig. 11 and Table 3, we can see that the expected total costs in *Situation 2.c* are 19.1% higher than that in **Situation 1**, while the standard deviation is 12.8 times higher. The CVaR value under 95% confidence level in *Situation 2.c* is also 26.8% higher than that in **Situation 1**.

### 5.3.4 Other remarks on the comparison of situations

From Table 3, we see that although the operation team optimizes its sailings, taking the tactical hedging decisions already made into consideration in *Situation 2.c*, its performance, in terms of both expected total costs and volatility, is still as bad as *Situation 2.a*. This is mainly due to the fact that the shipping company made their first-stage tactical decisions in isolation. This led to significant mistakes regarding the hedged amounts of both fuels (too much MGO and too little HFO hedged), which dramatically decreased the operational flexibility in the second stage. After that, not much can be done by the operation team to remedy this mistake. In fact, the operation team in *Situation 2.c* usually has to take a more “conservative” sailing pattern due to the excess MGO and insufficient HFO hedged in the forward contracts, which resembles the traditional behavior before the introduction of SECA regulations – sailing the shortest distance. Whereas in **Situation 1**, the operation team can carry out a more “aggressive” sailing pattern (less SECA involvement but longer total distance), which is proved to be more cost-efficient if supported with better fuel-hedging decisions.

Furthermore, when comparing *Situation 2.b* and *Situation 2.a*, one may notice that as long as the tactical hedging decisions are made with integration, the consequences brought by the isolation of operational decision-making are much less critical. However, if operating under *Situation 2.b*, the shipping company still has to face increased cost volatility (110%) and risk (1.6%) compared to the optimal case, which means isolated decision-making in operation is still problematic and should be avoided.

## 6 Conclusion

Maritime bunker management is one of the most important issues in the shipping industry. It involves decision-making on both tactical level (fuel hedging) and operational level (routing and speed). These two levels are usually treated separately in the literature as well as in the

industry. After the latest SECA regulation came into force, the complexity of MBM increased dramatically. The new challenges include not only the involvement of the expensive MGO required for the voyages inside SECA but also the possible changes in sailing behavior induced by the price gap between MGO and the traditional bunker HFO which can still be used outside SECA. Therefore we study the MBM problem with a new integrated point of view.

In this paper, we have proposed a stochastic programming model integrating the tactical and operational levels of MBM, taking SECA into account. We utilize the model to explore how the tactical and operational decisions in the problem interact. Through a computational study we have pointed out that the tactical and operational levels in MBM do affect and interact with each other. Isolated decision-making on either tactical or operational level in MBM will lead to various problems such as higher expected total costs, higher cost volatility and higher risk. However, the most critical situation is when tactical decisions are made in isolation. Therefore, it is important for the shipping company to have an integrated approach to MBM in light of SECA. Such an integrated view is standard in most businesses, but was not necessary in MBM before the introduction of SECA.

This work has two major contributions. Firstly, it fills a gap in the present literature, where only very few studies include and integrate both tactical and operational considerations in MBM. Secondly, it demonstrates that tactical and operational decisions must be integrated in MBM after SECA regulations were introduced, and shows the consequences for a company if the integration does not happen.

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# Appendix

In this appendix, all the detailed information about the sailing patterns under **Situation 1** and *Situation 2.b* in scenario No.34 and No.52 are offered in **Table 4** and **Table 5** respectively.

**Table 4:** Fuel consumption and sailing pattern in the scenario No.34

<b>Scenario No.34</b>	<i>Situation 1</i>	<i>Situation 2.b</i>
<b>Leg 1</b>		
Leg Option	5	5
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	408/1062/ <i>1470</i>	408/1062/ <i>1470</i>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 2</b>		
Leg Option	5	5
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	397/1241/ <i>1638</i>	397/1241/ <i>1638</i>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 3</b>		
Leg Option	<b>1</b>	<b>4</b>
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	<b>632/0/632</b>	<b>443/515/958</b>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 4</b>		
Leg Option	<b>4</b>	<b>5</b>
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	<b>899/2652/3551</b>	<b>752/2903/3655</b>
SECA/non-SECA speed (knot)	<b>15.13/20.07</b>	<b>15.00/20.51</b>
<b>Leg 5</b>		
Leg Option	5	5
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	751/3428/ <i>4179</i>	751/3428/ <i>4179</i>
SECA/non-SECA speed (knot)	15.00/18.09	15.00/18.09
Total SECA distance (nautical mile)	3087	2751
Total non-SECA distance (nautical mile)	8383	9149
MGO consumption (tonne)	455	405
HFO consumption (tonne)	1450	1589
Total costs (USD)	389151	398456

**Table 5:** Fuel consumption and sailing pattern in the scenario No.52

<b>Scenario No.52</b>	<i>Situation 1</i>	<i>Situation 2.b</i>
<b>Leg 1</b>		
Leg Option	4	4
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	469/905/ <i>1374</i>	469/905/ <i>1374</i>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 2</b>		
Leg Option	3	3
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	524/906/ <i>1430</i>	524/906/ <i>1430</i>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 3</b>		
Leg Option	1	1
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	632/0/ <i>632</i>	632/0/ <i>632</i>
SECA/non-SECA speed (knot)	15.00/15.00	15.00/15.00
<b>Leg 4</b>		
Leg Option	4	4
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	899/2652/ <i>3551</i>	899/2652/ <i>3551</i>
SECA/non-SECA speed (knot)	<b>15.00/20.14</b>	<b>17.00/19.07</b>
<b>Leg 5</b>		
Leg Option	5	5
SECA/non-SECA/ <i>Total</i> distance (nautical mile)	751/3428/ <i>4179</i>	751/3428/ <i>4179</i>
SECA/non-SECA speed (knot)	15.00/18.09	15.00/18.09
Total SECA distance (nautical mile)	3275	3275
Total non-SECA distance (nautical mile)	7891	7891
MGO consumption (tonne)	497	482
HFO consumption (tonne)	1348	1379
Total costs (USD)	385773	387047