# The Liner Shipping Routing and Scheduling problem under environmental considerations: The Case of Emissions Control Areas

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**Abstract.** This paper deals with the Liner Shipping Routing and Scheduling Problem (LSRSP), which consists of designing the time schedule for a vessel to visit a fixed set of ports while minimizing costs. We extend the classical problem to include the external cost of ship air emissions and we present some results of our work investigating the impact of Emission Control Areas in the routing and scheduling of liner vessels.

**Keywords:** liner shipping, emissions, emission control areas

## 1 Introduction

Maritime transportation is essential for the global trade of today. In 2015 total seaborne trade was almost 10.047 billion tonnes, a remarkable 68 percent increase since 2000. Containerized freight, in particular, has gotten an increased importance on the international seaborne trade market. In addition, the container fleet grew by 240 percent, from 64 millions to 216 millions from 2000 to 2014, measured in deadweight tonnage (UNCTAD 2016, [24]).

Although one would assume that this growth in container shipping has left liner shipping companies in full glory, the recent economic developments have impacted the business significantly and left many industry players struggling. The latest economical crisis hit the liner shipping industry in 2008 and 2009, as reflected by the negative growth of TEUs traded in 2009. Not only did the decreasing demand hit shipping companies on the top line but several other significant complications suddenly hit the industry. Over the recent years shipping companies have been exposed to increased market capacity, declining freight rates and increasing bunker prices, which led shipping operators to focus on cutting costs and improving the efficiency of their operations.

Besides overcapacity, another perilously development for the liner shipping industry has been the fluctuation and, in particular, the step increase of bunker prices. Bunker prices have a huge effect on the overall transportation costs (Stopford (2009, [23]) and Notteboom (2006 and 2009, [15], [16]). Notteboom 2006 argues that the fuel cost can be as much as 50% of total costs. Hence the price of bunker fuel is of great concern to the industry. Liner shipping companies have fought to keep bunker consumption down due to the rigorous prices. In 2007 Maersk Line introduced *slow steaming* as a concept to decrease bunker usage. In all its simplicity slow steaming is a question of reducing the speed of the vessels. Maersk Line (2010, [13]) claims that reducing speed by 20% leads to a bunker usage reduction of 40%. Hence slow steaming is seen as a very competitive strategy which is here to stay as indicated by Maersk Line (2010, [13]).

Besides the economic performance, the environmental effects from shipping activities and, especially air pollution, are getting increasing focus in the maritime Operations Research (OR) community (Kontovas 2014, [12]). According to the latest IMO study (IMO, 2014) shipping emitted 796 million tonnes in 2012, which corresponds to around 2.2% of global CO2 emissions. $CO_2$ emissions are not the only air pollution front. In areas of dense population pollutants such as $SO_x$ and $NO_x$ can have a high effect on local air quality. For this reason a set of Emission Control Areas, hereafter ECAs, has been introduced. In ECAs vessels are only allowed to use bunker fuel with lower sulphur content (0.1 % from year 2015). Moreover a global limit on sulphur in bunker at 3.5 % has been applied in 2015 in order to reduce pollution. In some ECAs the emission of $NO_x$ is also restricted. The bunker with 0.1% sulphur has a significantly higher price than the bunker with 3.5%. Shipping companies have, thus, a desire to decrease the usage of this type of bunker in order to decrease total cost. Discussions on a taxation system on $SO_x$ pollution is considered as a possibility by authorities in the industry.

The described issues have left the entire container shipping industry craving cost reductions. Therefore, the role of OR in reducing the environmental externalities of maritime transport is getting increased attention from liner shipping companies.

To that extent, this paper deals with use of OR tools to design liner shipping routes and schedules in order to minimize the total cost for the ship operator. In particular, we present some results of our work investigating the impact of emission control areas in the routing and scheduling of liner vessels.

### 1.1 Literature Review

In the early 1980s Ronen presented the first review of operations research papers on ship routing and scheduling (Ronen, 1983 [21]). Several reviews of the literature available have been published since, Christiansen et al. (2007, [4]) and Christiansen et al. (2013, [5]). The latter points out the increased focus of the literature on bunker consumption optimization and emission minimization. This is due to the increasing bunker prices since 2000 and an extensive focus on the environmental impact. Kjeldsen (2011, [10]) develops an extensive classification method for models and literature for ship routing and scheduling problems in liner shipping. Finally Meng et al. (2014, [14]) evaluates a significant amount of literature on OR within maritime transportation and conclude that there is a gap between the academic studies and industry practices. Brouer et al. (2014, [2]) present a benchmark suite consisting of relevant data on several important factors in the shipping industry. Data on an extensive list of ports is included as well as specifications for different types of vessels.

Network design is a problem that is widely approached in literature. Agarwal and Ergun (2008, [1]) provide a mixed integer LP that solves the ship scheduling and cargo routing problems with weekly frequency constraints simultaneously. To solve the problem three different algorithms; greedy heuristic, column generation, and two-phase Bender decomposition, are used. This model is slightly updated by Christiansen et al. (2013, [5]). Brouer et el. (2014, [2]) present an integer programming model to solve the Liner Shipping Network Design Problem (LSNDP) and prove that it is *NP-hard*. Routing and scheduling in liner shipping has attracted much attention from researchers. The routing part, mainly consisting of determining the sequence of port visits, is among others treated by Chu et al. (2003, [6]), who develop a mixed integer programming model for routing container ships and present numerical examples for some trans Pacific routes. Hsu and Hsieh (2007, [9]) present a two-objective model with the purpose of minimizing costs by choosing optimal route, ship size and sailing frequency. Scheduling of liner shipping services is seen in many different varieties. Wang and Meng (2011, [25]) seek to optimize cost and service level by solving the scheduling and container routing problem simultaneously. The outcome is a nonlinear model which minimizes transshipment and other penalty costs. In 2012, Wang and Meng introduce a mixed integer nonlinear stochastic model that determines arrival time of a vessel at each port and the sailing speed, somewhat like it is done in this study but with a fixed sequence of port visits (Wang and Meng 2012, [27]). Wang and Meng (2012, [27]) include uncertainties at sea and in port. Finally, Wang et al. (2014, [29]) design a model that can solve the scheduling problem with port time windows. The authors formulate the problem as a mixed-integer nonlinear nonconvex optimization model and suggest a holistic solution approach. The order of which the ports are visited is fixed and thus further differentiates the model from the investigations made in the report at hand. Yan et al. also give an example of a scheduling with fixed port call sequence (Yan et al. 2009, [30]).

Lowering bunker consumption by optimizing speed and routing has been a popular topic over the past years. Notteboom and Vernimmen (2009, [16]) state that managing bunker consumption gives incentive to reduce speed, but highlight that this incentive is dependent on the bunker price. While reducing speed improves bunker performance it also comes at a cost in terms of transit time and thus also service level as mentioned by Notteboom (2006, [15]). As mentioned above Wang and Meng (2011, [25]) use speed optimization to optimize costs. In another paper from 2011, Wang and Meng optimize sailing speed while considering transshipment and container routing (Wang and Meng 2011, [26]). Additionally the bunker consumption is calibrated and an outer-approximation method is proposed to model the usage. Psaraftis and Kontovas (2014, [19]) clarify important issues regarding ship speed modeling and incorporate some fundamental parameters that are essential in ship owners' speed decisions. Bunker consumption optimization methods are reviewed by Wang et al. (2013, [28]). The authors discuss different methods of modeling bunker consumption and suggest among others a linear static secant-approximation method closely related to that used in this study.

Emission of $CO_2$ and $SO_x$ is a topic that has gotten more and more interest from scientists and researchers in the OR field of maritime transportation (Christiansen 2013, [5]). This statement is further supported by Wang et al. (2013, [28]). Psaraftis and Kontovas (2010, [18]) investigate how emission reduction policies can have negative implications due to economic desires. Kontovas (2011, [11]) investigate the reduction of emissions by reducing speed and look into how the lost time can be made up for by reducing service time in ports and waiting time before berthing. Recent papers include minimization of cost implied by emission regulations, such as the implementation of emission control areas. Kontovas (2014, [12]) conceptualizes the formulation of the "Green Ship Routing and Scheduling Problem" and introduces among others the relationship between bunker consumption and emissions. Moreover Kontovas presents two ways of incorporating emission minimization in existing formulations of routing and scheduling problems. The method of internalizing external costs of emissions is applied in this study. Fagerholt et al. (2010, [7]) apply speed optimization to reduce emissions using discrtized arrival times. Fagerholt et al. (2015, [8]) present a model that minimizes cost for shipping companies by being able to select between different legs between ports that have varying interaction with ECAs. Thus costs are minimized by determining sailings paths and speeds for vessels along a sequence of ports. This is to the best of my knowledge one of the first modeling approaches where ECAs are an actual part of the model, and the paper is furthermore also the most recent in this field.

In this paper we introduce a model that minimizes costs by optimizing the port visit sequence and the time schedule, and hence also speed. In addition, this model will also minimize the external cost of pollution from bunker consumption. Since the cost of emissions is directly proportional to the amount of bunker consumed, emissions are also reduced.

## 2 Problem definition and mathematical model

The *Liner Shipping Routing and Scheduling Problem* (LSRSP) consists of designing the time schedule for a vessel to visit a fixed set of ports while minimizing costs. A subproblem of the LSRSP is additionally to define the sequence of which the vessel must visit the ports.

The key decisions in an LSRSP model are the following:

1. the order in which the vessel should visit the given set of ports,
2. the vessel's arrival time at each port and the appurtenant speed of the vessel,
3. the roundtrip time and thus the number of vessels needed to ensure a weekly frequency,

Liner shipping operates with a weekly frequency, i.e. each port must be visited once every week. Thus, a set of homogeneous vessels must be assigned to the service to achieve this, however, there exists an upper limit to the number of vessels deployed.

In our model we introduce emission control areas to the LSRSP by minimizing the total cost for the liner shipping company when servicing areas under emission control regulations. The impact of emissions is introduced as described in Kontovas (2014, [12]) by internalizing the external costs of emissions in the model. This means that the impact from emissions will be monetized and, thus, the external cost of emissions will be included in the objective function. The term *external cost* refers to the total societal cost, i.e. this is not necessarily the actual cost that liner shipping companies would be paying if a tax system is implemented. However, in a similar way, by using the tax price instead of the external cost in the model, the results can also reflect how the routing and scheduling of the services will be impacted by a future taxation scheme.

### 2.1 Model

The model is formulated as a compact model and the emission and bunker costs are combined in an objective optimizing both using the estimated value of the external costs of emissions. The model optimizes the routes and also includes functionality to consider transit time requirement between two ports.

In order to ensure a weekly frequency the number of vessels sailing a service must be the number of weeks it takes to complete a round trip. Moreover the service duration must be equal to a whole number of weeks. The duration of a service in weeks is indicated by the integer variable $S$. Each vessel has a weekly charter rate Which is the parameter $T_r$.

**Bunker Consumption and Cost**

The cost of bunkers is a scalar of the bunker consumption divided into the different bunker types. The consumption of bunker fuel depends on several factors; speed being the most important one.

Let $\mathbf{Z}$ be the set of emission control areas. For tests in later sections the set contains $ECA_0$ and $ECA_1$ meaning outside ECA and inside ECA respectively. The price of bunker is varying with the bunker type required in the different zones.

The consumption of bunker fuel when idle at port is linear, depending mainly on the time spend in port, and thus simple to include in a mathematical model. We assume that any vessel type has an individual constant fuel consumption $c^z$. For any given time period $a_i^z$, at port $i \in P$, where $P$ is the set of ports to be visited, the bunker cost is $c^z a_i^z$.

The relationship between speed and bunker consumption when the vessel is sailing is nonlinear. There are many different analytic formulations presented in the literature, but the most commonly used is the cubic one. With $F(s)$ as the hourly consumption, $s_*$ as the design speed of the vessel, and $f_*$ as the hourly fuel consumption at design speed the cubic law of the speed $s$ is given as

$$F_s^z = \frac{f_*}{s_*^3} \cdot s^3 = \left(\frac{s}{s_*}\right)^3 \cdot f_* \tag{1}$$

Equation (1) is clearly not linear. The method used in our model to linearize this term is a inner approximation with secants. As the speed is distance divided time, we here have selected to use time as a variable instead of the speed $s$. Let $\theta_{ij}^z$ be the time used on sailing from port $i \in P$ to port $j$ in emission zone $z \in Z$ and let $N$ be the set of secants then the bunker consumption is

$$F_{ij}^z = w_{ij}^{nz}\theta_{ij}^z + \delta_{ij}^{nz} \tag{2}$$

For some $n \in N$ Where $w_{ij}^{nz}$ and $\delta_{ij}^{n,z}$ is respectively the slope and intesection of secant $n \in N$ for sailing from port $i$ to port $j$ using bunker type $z \in Z$. For the cost let $f^z$ be the cost of a ton of bunker of type $z$.

The reader could refer to Vial (2014, [**?**]) and Wang et al. (2013, [28] for more on the lineraziation of the fuel consumption formula.

In the objective function we also include the external cost of emissions as described above. The set **E** consists of the two emission types considered in this study, $SO_x$ and $CO_2$. To include costs of the emitted pollutant, the factor $\lambda_{z,e}$ is introduced. This factor determines how much of each pollutant $e \in E$ is emitted per ton of each fuel type in $z \in Z$. Moreover let $\mu_{z,e}$ be the external cost for emission $e \in E$ when using bunker type $z \in Z$. Thus, the model is constructed in such a way that other emission types, e.g. $NO_x$ can be easily included.

Note that the distance between two ports $i, j \in P$ may now both be inside and outside ECA zones. Therefore the distance parameter $d$ is split such that it describes how long the distance from port $i$ to $j$ is in ECA $z$. Thus $\sum_{z \in Z} d_{ij}^z$ is equal the the distance total distance sailed between $i$ and $j$.

**Objective**

In this work, we study and compare two different objectives: In the one objective function we minimize the company costs and in the other we also include the external costs of emissions. We then compare both the emissions produced in these two cases.

The bunker cost objective (without the cost of emissions) can be written using the above notation as follows:

$$OB1 : Minimize \sum_{i,j \in P} \sum_{z \in Z} f^z(F_{ij}^z + c^z a_i^z) + T_r S \tag{3}$$

The other model where we minimize the overall costs, including the externalities of the emissions, can be formulated as follows:

$$OB2 : Minimize \sum_{i,j \in P} \sum_{z \in Z} (f^z(F_{ij}^z + c^z a_i^z) + \sum_{e \in E} \mu_e^z \lambda_e^z (F_{ij}^z + c^z a_i^z)) + T_r S \tag{4}$$

**Route selection, speed and bunker requirements**
To find the route for the service we introduce the binary variable $x_{ij}$ which is 1 if the vessel sails directly from port $i$ to port $j$ and zero otherwise. Moreover, let the parameter $q_i$ be one for the first port visited on a service and zero otherwise and let $M_2$ be a large number greater than the fuel needed to sail the longest leg at maximum speed. The parameter $\hat{\theta}^z_{ij}$ is the time needed to sail the distance $d^z_{ij}$ at max speed and the parameter $\bar{\theta}^z_{ij}$ is the time used on traversing the distance $d^z_{ij}$ at the minimum speed. Note that these parameters can be calculated in preprocessing. The parameter $I_w$ is the number of hours in a week (168) and $M_2$ and $M_3$ are Big-M parameters. Note that $\sum_{z\in Z}\theta^z_{ij} + a^z_j$ is the total time used on sailing from $i$ to $j$. Since the problem deals with liner shipping then some of the berth times may not be available to reschedule then a variable $t_i$ is introduced to represent the time the port $i \in P$ is visited and it also can be used to model subtour elimination. The variable $t_i$ is also used to ensure that the transit times are satisfied. Let $s_i$ be a fixed parameter indicating the time needed for loading and unloading in port $i \in P$. The constraints ensuring route selection and round trip are (6), (10), (11) and (13) in the model. Moreover the constraints are (8), (9) and (12), and the constraints related to bunker consumption are (7).

**Berth time and transit time restrictions**
A berth time may already be booked at a port and in case of a busy port this berth time might be impossible to chance. Thus the company may want to lock the time of the visit at selected ports. Let $L$ be the set of port visits with locked berthing times. Then for a port $i \in L$ there is a parameter $p_i$ which indicates the time the port visit is locked to. Since this time is a time within a week an integer variable $b_i$ is introduced which indicates the number of whole weeks the vessel has sailed before visiting the port $i$. To include transit time requirements we let the set $R$ contain the port pairs $i$ to $j$ for which a transit time requirement exists. For each pair $(i, j) \in R$ we have a parameter $r_{ij}$ representing the transit time limit from port $i$ to port $j$. A variable $\tau_{ij}$ is introduced to represent the transit time from $i$ to $j$ in the solution in the model. The constraints ensuring a locked berth time are the constraints (15) and (16). The constraints ensuring transit time satisfaction are the constraints (17), (18), (19), (20) and (21)

The model is then formulated as follows:

$$OB1 \quad or \quad OB2 \tag{5}$$

*Subject to:*

$$\sum_{i\in P} x_{ij} + \sum_{k\in P} x_{jk} = 2, \qquad \forall j \in P \tag{6}$$

$$F^z_{i,j} \geq w^{n,z}_{i,j} \cdot \theta^z_{i,j} + \delta^{n,z}_{i,j} - M_2\,(1 - x_{i,j}) \qquad \forall i, j \in \mathbf{P}, n \in \mathbf{N}, z \in \mathbf{Z} \tag{7}$$

$$\theta^z_{i,j} \geq \hat{\theta}^z_{ij} x_{i,j} \qquad \forall i, j \in \mathbf{P}, z \in \mathbf{Z} \tag{8}$$

$$\theta^z_{i,j} \leq \bar{\theta}^z_{ij} x_{i,j} \qquad \forall i, j \in \mathbf{P}, z \in \mathbf{Z} \tag{9}$$

$$t_j + M_3\,(1 - x_{i,j} + q_i) \geq t_i + a_i^z + s_i + \sum_{z\in\mathbf{Z}} \theta_{i,j}^z \qquad \forall i,j \in \mathbf{P}, z \in \mathbf{Z} \tag{10}$$

$$t_j + M_3\,(2 - x_{i,j} - q_i) \geq t_i + a_i^z + s_i + \sum_{z\in\mathbf{Z}} \theta_{i,j}^z - I_w S \qquad \forall i,j \in \mathbf{P}, z \in \mathbf{Z} \tag{11}$$

$$I_w S = \sum_{z\in\mathbf{Z}} \big( \sum_{i,j\in\mathbf{P}} \theta_{i,j}^z + \sum_{i\in P} (a_i^z + s_i) \big) \tag{12}$$

$$I_w S \geq t_i, \qquad \forall i \in P \tag{13}$$

$$x_{i,i} = 0 \qquad \forall i \in \mathbf{P} \tag{14}$$

$$t_j \geq p_j + I_w b_j, \qquad \forall j \in L \tag{15}$$

$$t_j \leq p_j + I_w b_j, \qquad \forall j \in L \tag{16}$$

$$\tau_{ij} \leq r_{ij}, \qquad \forall (i,j) \in R \tag{17}$$

$$\tau_{ij} \geq t_j - t_i - s_i, \qquad \forall (i,j) \in R \tag{18}$$

$$\tau_{ij} \geq t_j - t_i - s_i + I_w S - M_3 u_{ij}, \qquad \forall (i,j) \in R \tag{19}$$

$$t_i - t_j \geq -M_3 u_{ij}, \qquad \forall (i,j) \in R \tag{20}$$

$$t_i - t_j \geq M_3(1 - u_{ij}) \qquad \forall (i,j) \in R \tag{21}$$

$$S, b_j \leq S_{UP} \tag{22}$$

$$S, b_j \in \mathbb{Z}_0 \tag{23}$$

$$u_{ij}, x_{ij} \in \{0,1\} \tag{24}$$

$$F_{ij}^z, \theta_{ij}^z, a_i^z, t_i \geq 0 \tag{25}$$

## 3 Computational Results

The testing of the models $OB1$ and $OB2$ is done on the service illustrated in Figure 1. The visited ports are the following: Antwerp (Belgium), Bremerhaven (Germany), Agadir (Morocco), Casablanca (Morocco), Rotterdam (Netherlands), Gdansk (Poland), Skt. Petersburg (Russia), and Gothenburg (Sweden.) On this service the two ports in Morroco are placed outside the ECA while the remaining ports are located inside an ECA zone.

We utilize our model to investigate two interesting aspects.Firstly, how the ECAs and the usage of different fuels will impact the results. Secondly, the impact of including the external costs of emissions which is an interesting topic mainly due to the recent discussions on policies to reduce emissions.

### 3.1 Data

The data used for this test are mostly extracted from Linerlib, see Brouer et al. (2014, [2]), but also modified to include the emission control areas. The legs are split into two, one within the ECA and the other outside them. Distances are thus taken from Linerlib and partly from the virtual map and geographical information program *Google Earth*©.

The vessel type used for testing is the Panamax 2400 from Linerlib data. Additionally the test specifications 10.0.1.8 represents an instance of 10 ports 0 locked berth times and one transit time where the bunker consumption is approximated using 8 secants.

Bunker prices are one of the most important parameters as the greatly fluctuate over time. At the beginning of June 2017, the average world price for $BW380$ fuel was around 336 \$/ton and for $BW0.1\%$, the fuel used within the ECAs, was


**Fig. 1.** Illustration of service used for test of the models. Note that the sequence of port visits is not fixed in the problem (Seago Line, [22]).

around 580 \$/ton (see Bunkerworld [17]). In our runs we use a mid-range fuel prices of 370 and 620 for $BW380$ and $BW0.1\%$ respectively.

Regarding the external costs of emissions, although there is no single acceptable figure for that, there exists a number of works on the estimation of the social costs of emissions; see for example Miola et al. (2008) which presents a methodological approach to estimate the external costs of maritime transport. This is also related to the on-going discussions at the International Maritime Organization (IMO) regarding the so-called Market Based Measures (MBM); see Psaraftis (2013) for more. Placing a price on GHG emissions through an MBM (this could be for instance a tax on emissions or fuel consumption or the inclusion of shipping in an emissions trading scheme which would force owners to buy allowances that will essentially give them the right to pollute, or actually offset for the damage cause) is still a hot topic at the IMO, and also the European Commission. Given that such an MBM is not in place right now, the values we assume are taken from the Handbook of External Costs of Transport, a report for the DG-MOVE of the European Commission (Ricardo-AEA (2014) [20]). The external costs of emissions used are presented in Table 1.

**Table 1.** External cost $\tau_e$ used for testing.

| **Pollutant** | $\tau_e$ **[\$/ton]** |
|---|---|
| $CO_2$ | 37 |
| $SO_x$ | 12,700 |

The actual emitted amount of pollutant is given by the parameter $\lambda_{z,e}$.Air emissions are proportional to the fuel consumption of the main and auxiliary engines. To estimate CO2 emissions one should multiply total bunker consumption by an appropriate empirical emissions factor that depends on the fuel time. SOx emissions depend also on the type of fuel used and in particular on the amount of sulfur present in the fuel. One has to multiply total bunker consumption by the percentage of sulphur present in the fuel and subsequently by the exact factor of 0.02, which derived from the chemical reaction of sulphur with oxygen. The values for this parameter are presented in Kontovas (2014, [12]) and can be found in Table 2. The reader is also referred to the paper for more information on how to estimate emissions from shipping and the emission factors used.

**Table 2.** Values of emission factor $\lambda_{z,e}$ used for testing. The unit is [tonton].

| **Bunker type (ECA)** | **$CO_2$** | **$SO_x$** |
|---|---|---|
| BW380 (*outside*) | 3.114 | 0.07 |
| BW0.1% (*inside*) | 3.206 | 0.002 |

### 3.2 Comparison of the Results

***OB*1 - Without including the emission costs** Test results for objective $OB1$ are shown in Table 3. We present the operational cost for the sea leg, i.e. the bunker cost and operational running costs. In addition, for illustrative purposes only, the emission costs for $CO_2$ and $SO_x$ are listed although they are not taken into account in the objective function. For each emission control area the average speed and the distance traveled are stated. Finally the two final columns show the total active sailing time (not including idling) and the number of vessels deployed for the service. Note that in the following Tables, the legs inside the ECA areas are denoted as $ECA_1$, and that outside the ECA as $ECA_0$.

**Table 3.** Test results for $OB1$. The emission costs are not included in the objective function for this model.

| **ID** | **Specs** | **Sailing Cost [$]** | **Emissions Cost [$]** | | | **Total Cost [$]** | **Avg. speed [nmi/h]** | | **Distance [nmi]** | | | **Sailing Time [hours]** | **# vessels** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CO_2$ | $SO_x$ | *Total* | | $ECA_0$ | $ECA_1$ | $ECA_0$ | $ECA_1$ | *Total* | | |
| (8.1) | 8.0.0.10 | 832,486 | 91,012 | 333,005 | 424,017 | 1,256,478 | 16.0 | 13.7 | 2,434 | 3,790 | 6,224 | 429.0 | 3 |
| (8.2) | 8.0.5.10 | 1,257,941 | 178,450 | 469,101 | 647,551 | 1,905,492 | 18.1 | 17.3 | 2,434 | 5,082 | 7,516 | 429.0 | 3 |
| (8.3) | 8.0.8.10 | 838,815 | 92,580 | 340,194 | 432,774 | 1,271,559 | 16.1 | 13.7 | 2,434 | 3,808 | 6,242 | 429.0 | 3 |
| (8.4) | 8.4.0.10 | 881,138 | 67,165 | 229,943 | 297,107 | 1,178,245 | 12.8 | 12.0 | 2,434 | 3,790 | 6,224 | 505.4 | 4 |
| (8.5) | 8.4.5.10 | 1,539,336 | 173,258 | 413,900 | 587,158 | 2,126,494 | 15.5 | 15.8 | 2,434 | 5,407 | 7,841 | 500.4 | 5 |
| (8.6) | 8.4.8.10 | 1,378,470 | 180,164 | 601,350 | 781,515 | 2,159,985 | 20.2 | 16.6 | 2,434 | 4,509 | 6,943 | 391.8 | 4 |

One important finding is that the average speed, in all cases but for (8.5), is higher outside the ECA (see $ECA_0$) compared to the one inside the ECA (see $ECA_1$), which is in line with Psaraftis and Kontovas (2010, [18]). The reason for this is the higher bunker price inside the ECA which induces operators to speed up outside the ECA in order to maintain the schedules. The speed increase inside the ECA for example in cases (8.5) is attributed to the berth and transit time restrictions of the particular case.

Moreover, the distance traveled outside the ECA stays the same in all cases. This is expected as the vessel will only sail to/from Morocco only once during the service, as sailing back and forth between the continent twice will increase costs tremendously. Interestingly enough, the active sailing time stays the same or increases in all cases as we add more restrictions to the model, see for instance case (8.1) that is without any berth or transit time restrictions. For case (8.6), where both berth and transit time restrictions are applied, the number of vessels increases from three to four, meaning that round trip time will increase significantly. As the active sail time is low in this case, the vessel must be idling for a long time. Both the sailing and emission costs are very high compared to the other cases. Case (8.5) also has a high sailing cost but here five vessels are deployed and the total actual sailing time is long, meaning that the average speed and emissions costs are lower.

Finally we should note that for case (8.2) and (8.5) the round-trips are very long in terms of distance sailed. This is most likely due to restrictions and this means that the vessel will sail along a complex route.

***$OB2$* - The cost of emission is included** In $OB2$ the external emission costs are included in the objective function, meaning that the vessel will sail in such a way that the sum of both the cost of emissions and the sailing costs will be minimised.

The test results of $OB2$ are listed in Table 4. The columns of this table are the same as described for 3.

**Table 4.** Test results using $OB2$ where external emission costs are included in the objective function.

| ID | Specs | Sailing Cost [$] | Emissions Cost [$] | | | Total Cost [$] | Avg. speed [nmi/h] | | Distance [nmi] | | | Sailing Time [hours] | # vessels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CO_2$ | $SO_x$ | $Total$ | | $ECA_0$ | $ECA_1$ | $ECA_0$ | $ECA_1$ | $Total$ | | |
| (8.10) | 8.0.0.10 | 871,833 | 63,391 | 190,340 | 253,731 | 1,125,564 | 12.0 | 12.0 | 2,434 | 3,790 | 6,224 | 518.667 | 4 |
| (8.11) | 8.0.5.10 | 1,281,900 | 179,499 | 400,560 | 580,059 | 1,861,959 | 15.5 | 18.7 | 2,434 | 5,082 | 7,516 | 429.0 | 3 |
| (8.12) | 8.0.8.10 | 876,078 | 93,937 | 228,196 | 322,133 | 1,198,211 | 13.0 | 15.8 | 2,434 | 3,808 | 6,242 | 429.0 | 3 |
| (8.13) | 8.4.0.10 | 890,706 | 67,321 | 197,401 | 264,722 | 1,155,428 | 12.0 | 12.5 | 2,434 | 3,790 | 6,224 | 507.1 | 4 |
| (8.14) | 8.4.5.10 | 1,545,079 | 173,444 | 396,169 | 569,613 | 2,114,692 | 14.7 | 16.1 | 2,434 | 5,407 | 7,841 | 500.4 | 5 |
| (8.15) | 8.4.8.10 | 1,392,332 | 180,353 | 553,467 | 733,820 | 2,126,151 | 19.3 | 17.0 | 2,434 | 4,509 | 6,943 | 391.8 | 4 |

For all cases, the total costs using objective $OB2$ are lower than those for $OB1$, since in this case we also take into account the monetised social cost of emissions. This is further reflected to the average speed of the vessel. Outside the ECA (see leg $ECA_0$) the vessels in all cases under objective $OB2$ sail slower than compared to the scenario where the emission costs are not included i.e. under $OB1$. This shows the tremendous impact of the $SO_x$ costs. The model decreases the speed outside the ECAs to reduce $SO_x$ emissions. It is currently debated in the academic community that the ECAs give incentive to increase speed outside of ECAs and thus emit more emisions outside them. This model also proves that the increased emissions could be reduced by implementing some sort of taxation/monetary cost on the amount of pollutants emitted.

Under $OB2$, in all six cases, the vessels sail the same distance as under $OB1$. This implies that most of the optimization is in terms of speed optimisation. The model can also make some changes to the sequence of port visits but the purpose of this will more likely be to shift the arrival times slightly to comply with restrictions rather than changing the distance sailed or the routing. For the actual sailing time one can also notice that just one of the six cases is longer under objective $OB2$. This further supports our assumption that the optimization is mainly tied to speed adjustments rather than routing. Moreover it is clear that Objective $OB2$ decreases speed outside the ECA and increases it inside.

Regarding the computational time, in general the model solves the problem fairly fast. For the cases tested, $OB2$ the solver used between ten and 30 seconds to solve the problem. Running times of this magnitude are acceptable and could be used in practice. This is also a sign that the introduction of the extra sets, parameters, and variables do not add significant complexity to this model compared to $OB1$.

## 4 Discussion

For discussion purposes, we will further analyze the results in cases (8.3) and (8.12) with specifications 8.0.8.10, which are some scenarios without berth time restrictions but with transit time restrictions which are shown in Table 5.

**Table 5.** Transit time restrictions for cases (8.3) and (8.12).

| **TTR** | |
|---|---|
| **Port Pair** | **Transit time** |
| DEBRV - MAAGA | 200 |
| DEBRV - MACAS | 200 |
| DEBRV - NLRTM | 83 |
| MAAGA - BEANR | 240 |
| MAAGA - RULED | 240 |
| MACAS - BEANR | 240 |
| MACAS - RULED | 240 |
| RULED - SEGOT | 80 |

The order in which the ports are visited and the arrival time of the vessel at each port are listed in Table 6 under the two objective functions $OB1$ and $OB2$.

The total cost of the service is the sum of sailing and emissions cost, that are \$838,815 and \$432,774, respectively for $OB1$, which totals to \$1,271,559. For $OB2$ these costs are reduced to the sum of \$876,078 and \$322,133, this is a total of \$1,198,211. There is therefore a cost reduction of \$73,348 or 5.8 %. In addition, the sailing cost of the latter model is actually increased by roughly \$37,000. On

**Table 6.** Arrival time at each port for test with ID 8.0.2.10 for $OB1$ and $OB2$.

| | Model [5] | | | Model [6] | | |
|---|---|---|---|---|---|---|
| **Order** | **Port UN/LO** | **Port name** | **Arrival time $t_j$ [hours]** | **Port UN/LO** | **Port name** | **Arrival time $t_j$ [hours]** |
| 1 | DEBRV | Bremerhaven | 475.074 | DEBRV | Bremerhaven | 472.430 |
| 2 | NLRTM | Rotterdam | 0.000 | NLRTM | Rotterdam | 0.00 |
| 3 | MAAGA | Agadir | 128.736 | MAAGA | Agadir | 113.694 |
| 4 | MACAS | Casablanca | 159.497 | MACAS | Casablanca | 140.916 |
| 5 | BEANR | Antwerp | 271.683 | BEANR | Antwerp | 241.986 |
| 6 | PLGDN | Gdansk | 337.135 | PLGDN | Gdansk | 317.459 |
| 7 | RULED | St. Petersburg | 380.736 | RULED | St. Petersburg | 365.694 |
| 8 | SEGOT | Gothenburg | 443.140 | SEGOT | Gothenburg | 436.746 |

the other hand, the emission costs have decreased by a total of $110,642 or 25.6 %. This is a significant reduction of emissions cost for the shipping company and shows the environmental benefit of taking the externalities into account.

The distance traveled in both cases is 6,242 nautical miles. The active sailing time is the same, 429 hours, and the number of vessels is also the same as 3 vessels are used in both cases, leading to a total round-trip time of 504 hours. This implies that the reduction in cost comes entirely from speed optimization. It is also clear that the average speed is shifted from being highest outside the ECA for $OB1$ to being higher inside the ECA for $OB2$.

The results are good for the shipping company that seems to reduce the operating expenses, but what effect does it actually have on the amount of pollutants emitted and, thus, to the environment? The actual amount of pollutants emitted in each area is listed in Table 7.

**Table 7.** Amount of emitted $CO_2$ and $SO_x$ for $OB1$ and $OB2$ on test 8.0.8.10.

| | $OB1$ | | $OB2$ | |
|---|---|---|---|---|
| **ECA** | $\mathbf{CO_2}$ **[ton]** | $\mathbf{SO_x}$ **[ton]** | $\mathbf{CO_2}$ **[ton]** | $\mathbf{SO_x}$ **[ton]** |
| *outside* | 1,154 | 25.946 | 750 | 16.852 |
| *inside* | 1,348 | 0.841 | 1,789 | 1.116 |
| Total | 2,502 | 26.787 | 2,539 | 17.968 |

Based on the results, there is an increase of $CO_2$ emissions by 1.5%. Although the increase is very small it is definitely not desired. On the other hand, the $SO_x$ emissions have been reduced from 26.8 tonnes to 18 tonnes, which is a significant reduction of roughly 33%. This means that the implementation of external costs has the desired effect, as $SO_x$ emissions are reduced and speed is decreased outside ECAs. What speaks against it, is the increase of $CO_2$ emission that we see in the case above. $CO_2$ emission is not affected by the sulphur content of bunker fuel. Therefore the emission of $CO_2$ is more reflected by the bunker consumption, and thus the speed of the vessel. Since the distance sailed and the total active sailing time is the same for $OB1$ and $OB2$ in this case, the speed adjustments has been conducted such that the average speed between the two ECAs has been equalized more. This also means that the total amount of consumed bunker fuel must be more or less the same between the two models in this case. For this reason the $CO_2$ emission does not change significantly.

The decrease of $SO_x$ emission is a result of the decreased average speed outside the ECA. In this area the cheaper bunker with a high content of sulphur is used, and the lower consumption here has a natural impact on the emitted $SO_x$.

## 5 Conclusion

In this paper we have presented a model for optimizing routes and speeds both with respect to bunker costs and the external costs of emission. We show that the emission costs can be reduced significantly by including the emission costs in the routing model while the bunker cost is only increased slightly. Thus we must concluded that considering the costs of emissions along side the bunker cost when planning and scheduling a route is desirable in order to insure lower emission.

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