Robust and sustainable full-shipload routing and scheduling problem considering variable speed: A real case study

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Abstract
This paper presents a sustainable multi objective routing and scheduling for maritime transportation considering ship variable speeds under uncertainty. The proposed model is aimed to satisfy three individual dimensions of sustainability including economic, environmental and social aspects simultaneously while it is finding the best routes and schedule for each ship. The first objective is placed to meet economic goal by minimizing shipping cost. The second objective goes to social respect of sustainability by maximizing job creation due to number of intransitive workers in ships and ports and, the third one is minimizing CO\textsubscript{2} emission to cover environmental target. Several test problems are applied to validate the proposed model and sensitivity analysis is used to demonstrate effects of model’s parameters on objective function value. Augmented $\varepsilon$-constraint is implemented as a solution method to solve the multi-objective mathematical model. This is the first ship routing and scheduling paper which is considered three aspect of sustainability under uncertainty and solved by augmented $\varepsilon$-constraint. To solve the model in larger size, factual input data from a real case study is considered. Computational results show a significant positive managerial effects of this paper contributions.

Keywords: Maritime transportation, Speed optimization, Carbon emission, Sustainability, Fuzzy, Robust optimization

1. Introduction

Maritime transportation is one of the most popular and beneficial modes among different types of transportation modes in global trade for so many reasons. For example, it is economical way of transporting for most of shipments and industries, maritime transportation is an only way to transport huge or irregular shipment and etc. Ship transportation has highly increased recently as a result of globalization [1]. According to recent reports, more than 80\% of universal businesses in terms of volume and about 70\% of them in terms of value are
performed through shipping and this estimations is even higher in developing countries [2]. There are three kinds of ships for shipping cargoes in the literature: industrial, linear and tramp [3]. Industrial cargo shipping is a kind of shipping in which cargo owner plays main role to transport his own shipment in order to minimize the cost. Linear shipping is a kind of shipping in which travels are done in a fixed sequence frequently and these fixed route are announced by shipping companies. Tramp ships are like taxis; they are looking forward any port with available shipments. Unlike linear shipping, in tramp shipping a ship is able to sail in different route and with variable transportation speeds in order to maximize benefits or minimize the cost.

Significant improvements in shipping industry have raised competitive field in universal economy. Ocean shipping is a kind of industry with high capitalization and considerable operation cost, so among these features it is becoming critical to find ways to maximize this industry benefits like changing fleet sizing, routing, scheduling, ship network design and etc.[4]. Moreover, due to importance of global environment and moving industries towards being green industries rapidly, some decision-makers and researchers are showing interest in sustainability and green approach in ship industry. One of the important concern is emissions of greenhouse gasses in ship transportation like high NO\textsubscript{x} and CO\textsubscript{2} emission which is in result of fuel consumption has a lot of negative influence on climate and pollutions. According to reliable research and datasets, we have faced 86% increase in CO\textsubscript{2} emissions from shipping industry in 2007 in compared with 1990. In case of taking no actions, expectations indicates that it is continuing to increase up to 150%-250% [5].

One of the most important factors in controlling ship’s emission along with fuel consumption and fuel cost is transporting speed. Lots of study in literature indicate the rule of optimization of sailing speed in gaining more benefits and having more green ship industry. For instance, interested readers can refer to [6-8].

Generally, ship transportation total cost consists of transportation expenses, consumption expenses, operation expenses, depreciation and so forth. In order to consider sustainability and also carbon emission in maritime transportation problems, it is necessary to integrate sustainability and shipping cost in a single model [9]. Integrating some of decisions which are necessary to address sustainable factors is a critical topic for researchers in last decades. Three related decisions to develop sustainability as structure, culture and technology is introduced by Jansen [10]. In 2008, sustainability presented by integrating environment and social factors by Vachon and Mao [11]. Čuček, Klemeš [12] published a review paper for three dimensions of sustainability: social, environment and economic integration.

This paper is aimed to define a maritime routing and scheduling problem with respect to considering three dimensions of sustainability (see Figure 1.): (1) Economic: to minimize costs in order to increase benefits by noticing sailing cost, fuel cost and revenue of sailing shipments. (2) Environment: to minimize carbon emission of ships by finding proper route and speed of each ship. (3) Social: every industries including shipping industry has some social aspects, in this study job creation is considered as maritime transportation social effect and maximizing job opportunities belonging to ships and ports number is indicated. These three objectives are represented simultaneously to define ship transportation problem. Fuzzy development and robust programming is considered for modeling of this paper in order to make it closer to the real world cases. To the best of our knowledge this is the first ship
routing and scheduling paper which considers three aspects of sustainability and variable speed in fuzzy concept.

The reminder of this paper is structured as follow: after this section, Section 2 is dedicated to literature review of different aspect of this paper. Section 3 is related to problem description of this study in order to explain and implication of problem understanding. Section 4 goes to mathematical modeling and explaining notations and problem model in details. Solution methodology is presented in Section 5, and numerical result and case study explanation is conducted in Sections 6 and 7, respectively. Section 8 demonstrates managerial insights. Finally, conclusion remarks and future research directions are provided in Section 9.

{Please insert Figure 1 about here}

2. Literature review

Maritime transportation problems which are more important for this paper background can be divided in some categories. Some of this studies are mentioned in the following subsections:

2.1. Routing and scheduling

Maritime transportation routing and scheduling can be taken as a whole different subject because of how ships operate under various circumstances [13, 14]. A review on ship routing and scheduling papers is published to seeking on theoretical and practical papers of this subject [15]. Brønmo, Christiansen [16] proposed a ship problem with time window and flexible cargo sizes and a partitioning approach as a methodology to solve of this problem. Results indicated that using flexible cargo sizes has economical influence. Routing and scheduling for a fleet of ships and single product is designed in order to minimize the cost of operations without any time out in ports [17]. A dynamic programming model was developed in routing and scheduling in liner shipping [18]. Bendall and Stent [19] presented a model to obtain optimal number of vessels and fleets in shipping cargoes. Also, Azaron and Kianfar [20] examined climate ship routing problem. An ocean transportation inventory routing problem for multiple product was considered and different section was defined in ships for various product [21]. By proposing split load the restriction for carrying shipments with different ships is removed and ship routing and scheduling problem with split loads was examined by a neighborhood heuristic search [22]. Fagerholt, Christiansen [23] introduced methodology for strategic routing and scheduling for tramp and industrial ships. A routing and scheduling problem for split loads with time window is presented to maximize benefit and minimize cost together [24]. A continuous and discrete time horizon ship routing and scheduling with multiple product and different fuel consumption in various ports as a mathematical model is indicated in literature [25]. Moon, Qiu [26] resolved an integrated ship routing problem of fleet extensions with network design, for this NP-hard problem a genetic algorithms was suggested.
2.2. Environment and social consideration

Comparing to other aspects of maritime transportation, carbon emission of ships is not considered in large amount of papers, and due to importance of environmental issues these days CO₂ emission is a noteworthy topic for researchers. Some of related researches about this subject are mentioned in this subsection.

Corbett and Koehler [27] introduced a method of manufacturing inventories which are fuel based and examined its effect with ships emissions. In order to maximizing ship industry profit by increasing fuel price, optimal speed will decrease, and also CO₂ emissions of ships will reduce [28, 29]. Eyring, Köhler [30] proposed an emission inventory for global shipping industry. Endresen, Sørgård [31] studied about passengers and cargo ships emission. Corbett, Wang [28] concluded that decreasing ships speed can led to reducing sailing emissions. A profit maximizing model by considering speed optimization and ships emissions was proposed. Yin, Fan [32] investigated the relationship between slow steaming, fuel consumption and environmental aspects. A real analysis is developed to measuring carbon emission effects [33]. De, Mamanduru [9] indicated a ship routing and scheduling problem for multiple product and various ports by considering CO₂ emission, and solved with a meta-heuristic due to complexity of the model.

One of the sustainability objectives is considering social aspects, but to the best of our knowledge this is the first paper which is considering this objective as evaluating and maximizing job creation in shipping industry.

2.3. Variable speeds and fuel consumption

Speed of each transporting arcs was presented as a decision variable in a tramp ship routing and scheduling problems with speed optimization, two different algorithm was proposed to solve this problem and computational results showed tramp routing and scheduling problem had a high improvement by considering variable speeds [34]. Rate of relation between fuel consumption and ship speed is indicated in some papers [6, 7]. Gatica and Miranda [35] suggested a full-shipload routing with speed optimization by applying discrete time windows. Wang and Meng [36] studied sailing speed of ships for each one of ship route in a liner shipping, in the meantime routing and transshipment are considered. Psaraftis and Kontovas [37] considered crucial elements in ship various speed and optimizations to find a proper results. In case of any increase in fuel costs, ships speed should decrease in order to save costs balance and maximize benefits, other speed decreasing influence is reducing fuel emissions of ships [28]. The optimal route and speed is examined in a ship routing problems in which route, originations and destinations were considered as fixed parameter [36]. A novel routing model by considering speed optimization is suggested for a real world case study and solved with a heuristic [38]. Wen, Ropke [8] considered a routing and scheduling for full-shipload by considering variable speeds, computational results showed that optimizing speeds is a practical way to increase total income up to 16%, and fuel cost is a critical factor in selecting proper speed and reaching to total profit.
2.4. Uncertainty consideration

Dubois, Fargier [39] indicated that uncertainty in mathematical problems can be divided in two groups:

- uncertainty in input data
- flexibility in constraint or objectives

First group is the most common one in literature and stochastic programming is a useful method to deal with it. Second group is divided to two group itself, flexibility in objectives as a flexibility on target, and flexibility in constraint as a soft limitation. Flexible mathematical programming is a well-known approach to cope with these kinds of flexibility in constraint or objectives [40, 41].

Not all input parameters can be defining as exact parameters in real world cases for so many reasons. Firstly, some inputs data are accidental innately, and secondly lack of knowledge and poor data sets leads to stochastic programming [40, 42].

There are three principal approaches in literature to deal with uncertainty in mathematical programming: 1) stochastic programming 2) fuzzy programming 3) robust optimization. According to problem structure, uncertainty type and incompleteness in parameters, one of these approaches or combination of some of them can be used in problems.

Searching in literature shows that there are studies in maritime transportation which are considered uncertainty. To find some of these studies see: container port problem by TOPSIS approach under fuzzy environment [43], a fuzzy genetic approach for ships routing [5], robust ship routing problem [44] using multiple time window in ship scheduling [45].

In this paper, according to lack of reliable datasets, input parameters are not considered exact in study, and some of limitation are flexible naturally like time windows, so a mixed flexible-possibilistic robust programming is used to cope with uncertainty in this paper mathematical model [46]. Considering gaps in maritime transportation literature and to the best of our knowledge this is the first sustainable ship routing and scheduling paper which considered variable speed, fuel consumption and robust-possibilistic formulation. Table 1 shows this paper features compared with the closest studies in literature.

{Please insert Table 1 about here}

3. Problem description

In this paper a full-shipload problem is defined to transport shipments, between different nodes. Routing and scheduling problem determines the best feasible routes in rational time to transport shipments from loading port to unloading port [8]. Objectives are defined to minimize total cost, to maximize social impact by creating job and to minimize CO$_2$ emission in order to protect environment, simultaneously. In this problem, a shipping line transports liquid products. To transport liquid, tramp ships in full-shipload mode are most popular kind of transporting due to its features. Ships are different in speed, fuel cost, CO$_2$ emission, size, load capacity, number of personals and cost parameters. Ship operator receives shipment orders from different pickup and delivery ports. Each order has its specific pickup and delivery ports with specific time window when each ship must start to load shipments. Our
model determines whether operator accept the order, which ship should pick up the order in which time at which speed and sail in which route. Schematic view of this paper problem is shown in Figure 2.

To establish each industry, the first and most important question is how much the industry is beneficial, so finding an optimal solution to minimizing cost and maximizing benefit are the first step to evaluate this study problem. Ship cost, fuel cost, worker salary and transportation incomes are considered to find the optimal routing and scheduling from economic point of view.

Man power plays a critical role in maritime transportation in both ships and ports. In this problem, according to social aspect of sustainability objective, job creation of this routing and scheduling is to be maximized by considering workers in ships and nodes. Moreover, manpower cost is addressed as their salaries.

Ship's speed, fuel consumption and greenhouse gasses emissions are three different concepts in shipping which are closely related to each other. It is proven that ship emissions like CO$_2$ can be reduced by finding an optimal speed [28, 48]. It is needed to pay attention that higher speed leads to more fuel consumption and more emissions per traveling unit, but it is also leads to less transit time. So finding optimal trade-off between these two factors is critical to satisfying both environmental and economic objectives of this paper.

Different ships have different origin and destination ports. The origin and destination is not pre-determined for each ship. Ships have different speeds. They can pick shipments and move them to their destination with different speeds. High speeds, save times but increase the cost and produce more amount of CO$_2$. Fuel cost depends on which ship is loaded (laden) or sails empty (ballast) and it depends on ship speed.

Each node is considered as an individual port. Also, each port has different platform for loading and unloading shipments. Ports can be each ship’s origin or destination or both of them. Each tramp ship should start its travel from its origin port and deliver as much shipment as it can collect from middle ports to its destination port. The port where ship should end its journey, is not predetermined. Dummy nodes are supposed for this aim. Model gives a sequence of ports with shipments to each ship. If the destination port of a shipment were not being the origin port of the next shipment in a given sequence, the ship must travel empty. The model tries to minimize this empty trips. Each journey has its costs and advantages.

(Please insert Figure 2 about here)

Figure 2 shows the schematic view of presented problem. This network with three ports shows a small sample for the problem. Ships travel between ports and they emit CO$_2$ in their route. Their emission amount are different due to different speed and fuel consumption. Ports and ships have specific number of workers according to size of port and their amount of loading/unloading in ports and number of used ships.

### 4. Mathematical formulation
In this section objectives, assumptions, notations and mathematical model of this problem are indicated. Also, mixed flexible-possibilistic robust programming is proposed at the end of this section.

4.1. Objective functions

Presented routing and scheduling problem is a multi-objective problem, which is addressed three dimensions of sustainability, simultaneously. The first objective function minimizes the total cost including traveling cost of ships, fuel cost, ship cost, workers’ salary. Also, revenue of transporting shipments by ships are considered. Since our problem is full ship load mode, the cost of fuel is equal to its maximum amount. Finally, cost of workers corresponds to salary of workers in ships and workers in port to transfer shipments in or out of the ship.

The second objective maximizes the total number of workers in order to create job opportunities and maximize social responsibility. Each ships have a defined number of workers and ports need to number of workers.

Last but not least objective considers the environmental effects which is produced by ship transportations. Through minimizing total CO$_2$ emitted from ship trips and minimizing transport hazardous materials (i.e., gas and oil).

4.2. Assumptions

In order to present mathematical modeling of the stated problem, some assumptions for this problem is needed to be clarified as follows:

- Our problem is not a complete graph. Which means that there are some ports that cannot connect to each other directly. For example, it is not feasible to sail directly from port A to port B, some middle port is necessary due to obstacles in direct route or some available contracts, and some routes are not feasible in stated problem.
- An origin node could be the shipment node and also it could be a destination node for different ships.
- It is not feasible for all ships to serve all shipments.
- Time window is only considered for pick up time (began of the service) for the shipments. And it is determined by contracts.
- The benefit gained from serving each shipment is fixed, so minimizing the total cost, maximizing the total benefit.

4.3. Mathematical model

The presented model in this paper is an extension to a routing and scheduling model which is published recently [8]. Only cost objective was considered in previous study, two other sustainability sides namely environment which is indicated as minimizing ships CO$_2$ emission, and social side as maximizing job creations is proposed in this study. Also, in order
to cope with the lack of proper data and considering uncertainty in this study model is formulated with fuzzy approach.

**Sets:**
- \( N \) set of all the nodes
- \( A \) set of feasible routes
- \( V \) set of speeds
- \( S \) set of ships
- \( O \) set of all origins of the ships
- \( D \) set of all destination of the ships

**Parameters:**
- \( l_i \) distance between load and unload port
- \([a_i, b_i]\) time window
- \( d_{ij} \) distance between two nodes \( i \) and \( j \)
- \( b_i^v \) time of traveling one distance unit at speed \( v \)
- \( g_v \) fuel cost of ship \( s \) traveling one distance unit at speed \( v \)
- \( p_i \) a port service time
- \( f_{is} \) 1 is feasible for ship \( s \) to serve shipment \( i \), 0 otherwise
- \( n_s \) number of available ship \( s \)
- \( CO2_{sv} \) CO2 emission from ship \( s \) with speed \( v \)
- \( h_i \) Risk of serve hazardous material
- \( ws_s \) Number of personals work at each ship \( s \)
- \( M_s \) Amount of payment for each personal work at each ship \( s \)
- \( e_i^v \) Cost of accepting shipment \( i \) to serve with ship \( s \) at speed \( v \) (include tax and personal payments)

**Variables:**
- \( t_{is} \) time when ship \( s \) starts loading shipment \( i \)
- \( x_{ijs} \) time span of ship \( s \) from arriving at the loading port of shipment \( i \) to arriving at the loading port of shipment \( j \)

**Binary variables**
- \( z_{ij}^v \) 1 if ship \( s \) sails from shipment node \( i \) to shipment node \( j \) at speed \( v \), 0 otherwise
- \( w_{is}^v \) 1 if ship \( s \) serves shipment \( i \) at speed \( v \), 0 otherwise

Objective functions and constraints are presented as follow:

\[
\text{Min} \sum_{(i,j) \in A} \sum_{s \in S} \sum_{v \in V} c_s^v d_{ij} z_{ij}^v + \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} e_i^v w_{is}^v - \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} b_i^v w_{is}^v \tag{1}
\]

\[
\text{Max} \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} w_{is}^v (n_s + ws_s) + \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} ws_s z_{ij}^v \tag{2}
\]
\[
\text{Min } \sum_{(i,j) \in A} \sum_{s \in S} \sum_{v \in V} z_{ij s} v \text{CO}_2 s \gamma d_{ij} + \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} w_{is} v h_i \tag{3}
\]

Subject to:
\[
\sum_{j \in N} \sum_{s \in S} \sum_{v \in V} z_{ij s} \leq 1 \quad \forall i \in N_0 \tag{4}
\]
\[
\sum_{j \in N} z_{o(s) js} = n_s \quad \forall s \in S \tag{5}
\]
\[
\sum_{j \in N} \sum_{v \in V} z_{ij s} - \sum_{j \in N} \sum_{v \in V} z_{jis} = 0 \quad \forall i \in N, s \in S \tag{6}
\]
\[
\sum_{j \in N} \sum_{v \in V} z_{jd(s)s} = 1 \quad \forall s \in S \tag{7}
\]
\[
p_i + \sum_{v \in V} l_i g_v w_{is} v + \sum_{v \in V} d_{ij} g_v z_{ij s} v = x_{ijs} \quad \forall (i,j) \in A, s \in S \tag{8}
\]
\[
t_{is} + x_{ijs} - M(1 - \sum_{v \in V} z_{ij s} v) \leq t_{js} \quad \forall (i,j) \in A, s \in S \tag{9}
\]
\[
a_i \leq t_{is} \leq b_i \quad \forall i \in N, s \in S \tag{10}
\]
\[
\sum_{v \in V} w_{is} v \leq f_{is} \quad \forall i \in N_0, s \in S \tag{11}
\]
\[
\sum_{j \in N} \sum_{v \in V} z_{ij s} = \sum_{v \in V} w_{is} v \quad \forall i \in N_0, s \in S \tag{12}
\]
\[
z_{ij s} v, w_{is} v \in \{0,1\} \quad \forall i, j \in N, v \in V, s \in S \tag{13}
\]
\[
t_{is} \geq 0 \quad \forall i \in N, s \in S \tag{14}
\]
\[
x_{ijs} \geq 0 \quad \forall i, j \in N, s \in S \tag{15}
\]

Objective function (1) aims to minimize the total transportation costs simultaneously maximizing the total benefit from shipping the shipments. Objective function (2) considers social part of ship transportation by maximizing the number of workers that work in each cargo-ship and objective function (3) minimizes total CO\(_2\) emissions in total trips. Equation (4) guarantees that each shipment are served by at most one ship. Equation (5) ensures that all ships leave the origin port. Equation (6) forces the ships to leave the ports until end of the trip. Equation (7) ensures that each ship finishes the trip at its destination. Equation (8) calculates the total time span. If \(x_{ijs} v = 1\) equation (9) calculates that the time span of ships from arriving at the loading port of shipment \(i\) to arriving at the loading port of shipment \(j\). \(M\) is respective for large number. Equation (10) calculates the time window. If a Shipment is served by a ship it can only be transported by one speed (Equation (11)). Equation (12) ensures the balance between \(x_{ijs} v\) and \(y_{is} v\). Equation (13) - (15) represent the binary and non-negative variables.

5. Mixed possibilistic-flexible formulation
In real word, some required data are unclear and vague, so they are assumed to be fuzzy in nature. The triangular fuzzy numbers are commonly used for modeling such imprecise parameters. The possibility distribution of the parameters is represented in Figure 3. The imprecise parameters are described in Table 2.

{Please insert Figure 3 about here}

{Please insert Table 2 about here}

CO₂ emission rate is a fuzzy parameter because data for this parameter are considered optimistically. Therefore, it can be increase or decrease by over flow or under flow loading. A port service time strongly depends on the number of personal and their ability. Because of some reasons such as shift changing or hourly workers it is not fix. The time of traveling one distance unit at speed \( v \in V \) it is not a fixed parameter due to some unpredictable variables like climate change, a sudden problem on the sea or ETC. As such, in model formulation constraint (10) needs to be flexible and violation from the time window must have a penalty cost. So we rewrite it as equation (16).

\[
a_i \leq t_{is} \leq b_i \quad \forall i \in N, s \in S
\]

Fuzzy form of the model formulation is as bellow:

\[
\begin{align*}
\text{Min} & \quad \sum_{(i,j) \in A} \sum_{s \in S} \sum_{v \in V} z_{ij}^s CO_{2s}^v d_{ij} + \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} w_{is}^v h_i \\
\text{Subject to} & \quad \tilde{p}_i + \sum_{v \in V} l_i \tilde{g}_v w_{is}^v + \sum_{v \in V} d_{ij} \tilde{g}_v x_{ij} = x_{ij} \quad \forall (i,j) \in A, s \in S \\
& \quad a_i \leq t_{is} \leq b_i \quad \forall i \in N, s \in S
\end{align*}
\]

And constraints (1), (4), (5), (6), (7), (9) and (10) - (15).

5.1. Crisp equivalent of the formulation

Robust fuzzy mathematical programming methods are discussed widely as in [46], so we use suggested robust programming method in [49]. The proposed mixed possibilistic-flexible formulation is formulated as follow:

\[
\begin{align*}
\text{Min} & \quad \sum_{(i,j) \in A} \sum_{s \in S} \sum_{v \in V} z_{ij}^s \left( \frac{CO_{2s}^1 + 4CO_{2s}^2 + CO_{2s}^3}{6} \right) d_{ij} + \sum_{i \in N} \sum_{s \in S} \sum_{v \in V} w_{is}^v h_i \\
\end{align*}
\]
\[
\min \left( \sum \sum \sum z_{ij}^v \cdot CO_2_{sv} \cdot d_{ij} \right) - \\
\sum \sum \sum z_{ij}^v \left( \frac{CO_2_{sv1} + 4CO_2_{sv2} + CO_2_{sv3}}{6} \right) d_{ij} \right) + \\
\omega \left[ (t_2 + \frac{t_1 + t_3}{3})(1 - \alpha) \right] + \beta \left[ (r_2 + \frac{r_1 + r_3}{3})(1 - \varepsilon) \right]
\]

Subject to:
\[
\frac{\left(p_{i1} + 4p_{i2} + p_{i3}\right)}{6} + \sum \sum \sum \frac{\left(g_{v1} + 4g_{v2} + g_{v3}\right)}{6} w_{is} \quad \forall (i,j) \in A, s \in S (23)
\]
\[
+ \sum \sum \sum \frac{\left(g_{v1} + 4g_{v2} + g_{v3}\right)}{6} z_{ij}^v = x_{ij} \quad \forall (i,j) \in A, s \in S (24)
\]
\[
t_{is} \geq a_i - (t_2 + \frac{t_1 + t_3}{3})(1 - \alpha) \quad \forall i \in N, s \in S (25)
\]
\[
t_{is} \leq b_i + (r_2 + \frac{r_1 + r_3}{3})(1 - \varepsilon) \quad \forall i \in N, s \in S (26)
\]

And constraint (1), (4), (5), (6), (7), (9) and (10) - (15).

The first two term of objective function (20), is about the CO$_2$ emissions, and it is crisped by the average of CO$_2$. The other terms calculating total penalty cost of possible violation of the soft constraints. The penalty costs are considered for violation of the time window via parameters $\omega$ and $\beta$ in proposed model. Notice that the $\alpha$ and $\varepsilon$ are the satisfaction level and model optimizes these variables.

6. Solution methodology

In this section methodology to solve presented problem is demonstrated. Figure 4 describes this paper framework as a flowchart. Proposed formulation contains three individual objective functions. We solve our formulation with these three objectives, separately and obtained results show the conflict between objectives as described in Figures 5-7. So in this problem we do not have a single optimal solution and we must explore Pareto-optimal solutions (set of efficient solutions) in our multi objective problem (MOP). In popular methods decision maker (DM) should determine the priority or weight for the objective functions before or after the solution process or interactively. It is important to choose a method that be capable to choose efficient solutions rather that weakly efficient solutions [50].

{Please insert Figure 4 about here}

One of the most used methods to achieve efficient Pareto-optimal solutions in MOP is the $\varepsilon$ -constraint method. In $\varepsilon$ -constraint method DM should determine the most desirable Pareto
solutions after the solution process (posteriori method). Indeed, the Pareto-optimal solutions are determined by the \( \varepsilon \) -constraint method, with different \( \varepsilon \) values at the right hand side (RHS) of the objective functions that considered as additional constraint, until the DM be satisfied (Effective implementation of the e-constraint method in Multi-Objective Mathematical Programming problems). It is proved that the \( \varepsilon \) -constraint method explores efficient solutions but it also may generate infeasible solutions [51]. So the \( \varepsilon \) -constraint method, is extended by an improved version of the augmented e-constraint method (AUGMECON2) for finding the exact Pareto set in multi-objective integer programming problems. In Augmented \( \varepsilon \) -constraint (AUGMECON) method, we explore only efficient solution. To solve the ship-routing multi objective optimization problem we propose a two-stage approach.

In the first stage, uncertainty of parameters at the objective functions and constraints and flexibility of the constraint were recognized and crisp equivalent counterpart of the model formulation is provided by mixed flexible-posibilistic approach as an aforementioned. In the second stage, lexicographic and augmented \( \varepsilon \) -constraint method are applied to explore efficient Pareto-optimal solutions.

Consider the problem of minimizing \( P \) conflict objective functions. The AGMECON optimizes the main objective function (usually cost objective considered as a main objective) as equation (27) subject to other objectives constrained as equation (28) and feasible decision space.

\[
\min \{ f_i(x) - \left( r_1 \times \sum_{i=2}^{p} \frac{s_i}{r_i} \right) \} \tag{27}
\]

S.T.
\[
x \in X \land f_i(x) + s_i = \varepsilon_i \land s_i \in R^+, \ i = 2, ..., p \} \tag{28}
\]

where the \( f_1(x) \) is the main objective, \( f_i(x) \) is the \( i \)-th objective function , \( x \) denotes the decision variable , \( s_i \) denotes the \( i \)-th slack or surplus variable and \( r_i \) represents the range of \( i \)-th objective function which is calculated from pay-off table. Pay-off table is a square table of \( p \) rows and columns to find the positive ideal solutions of the objective functions \( (f^{PIS}) \) and negative ideal solutions of the objective functions \( (f^{NIS}) \). Then the range of each objective simply is calculated by equation (29).

\[
r_i = f_i^{NIS} - f_i^{PIS} \tag{29}
\]

This study applies lexicographic method as equation (30) - (38) to calculate \( f^{PIS} \) and \( f^{NIS} \) from the pay-off table.

<table>
<thead>
<tr>
<th>( i )</th>
<th>type</th>
<th>Model ((i=1,2,\ldots,p))</th>
<th>Optimum solution</th>
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<tbody>
<tr>
<td>( i=1 )</td>
<td>minimization</td>
<td>( \min Z_1 )</td>
<td>( Z_1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.T. ( x \in X )</td>
<td></td>
</tr>
<tr>
<td>( i=2 )</td>
<td>maximization</td>
<td>( \max Z_2 )</td>
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</table>
\[ \text{S.T. } x \in X \]
\[ Z_1 = \dot{Z}_1 \]  
\[ i = 3 \text{ minimization } \]
\[ \min Z_3 \]
\[ Z_2 = \dot{Z}_2 \]

Then \( \varepsilon \)-vector can be calculated by equation (39). With \( m \) grid points or \((m-1)\) equal intervals.

\[ \varepsilon_i = f_i^{\text{NIS}} - \left( \frac{f_i^{\text{NIS}} - f_i^{\text{PIS}}}{m} \right) \times n = 0, 1, 2, \ldots, m \]  

More number of grid point generates more efficient solutions. The problem can be solved by different grid points to achieve more efficient solutions until the DM be satisfied. Proposed solution for the sustainable ship routing and scheduling problem is summarized as follow:

**Step 1:** Determine the uncertain parameters  
**Step 2:** Convert the model into mixed flexible-possibilistic equivalent  
**Step 3:** Apply the lexicographic method to build payoff table  
**Step 4:** Calculate the range of each objective function according to obtained payoff table from step3 by equation (29).  
**Step 5:** Construct the \( \varepsilon \)-vectors according to the ranges obtained in step4 for each objective function.  
**Step 6:** Solve the augmented \( \varepsilon \)-constraint method to find the efficient solutions from the Pareto-optimal set. If the DM is satisfied with the acquired efficient solutions, then stop otherwise go to step5 to find more efficient solutions.

**7. Numerical results**

In this section computational results of this paper are presented in which mathematical model is validated by applying several test problems, and conflict between three objectives of the model is checked. Then, sensitivity analyses is applied for different values of decision maker’s satisfaction degree on both parameters of solution method and proposed crisp equivalent counterpart of the model.

**7.1. Model validation**

In order to validate the proposed mathematical model, several random small examples are solved with GAMS software in a Core i5 ASUSE laptop computer. Each objective is solved by GAMS software separately with model constraints, to show conflict of objectives. Range of parameters with their common module which are used to solve sample problems are in Table3. It should be noted that knots is a common module for measuring speed in ship
(1knots=1.852 km/h). A uniform parameter is a number between its specific ranges, with a same possibility for occurrence of each number in the range. For example, it is common that in small ship transportation companies 1, 2 or 3 ships can be available. In addition, Fuel cost of traveling a ship in about one kilometer at speed 1.852 km/h, is usually between (130,170).

7.2. Objective conflict

Proposed problem is defined by a multi-objective sustainable mathematical model. This model contains three aspect of sustainability (i.e., economic, Social and environment). The first objective is minimizing cost of ship operation due to its optimal routing and scheduling. This objective contains ship fuel cost, ship travel taxes, cost of renting each ships, cost of hiring ship and port workers and reward of transporting shipments. The second objective considers social aspect of sustainability by maximizing job creation. Number of workers in ports and ships are considered in social objective to be maximized. The third objective is minimizing CO$_2$ and considering penalty cost or transporting hazardous shipments like gas, oil and so forth. Table 4 shows conflict between cost and social objective, since cost is a minimizing objective and social is a maximizing one, it is demonstrated that by unfavorable increasing cost, job creation is maximizing positively. Figures 5 –7 shows the optimum solution by considering the cost, social and environmental objective function. According to these figures different results have been obtained regarding to different objective functions. Therefore, it can be say that there is a conflict between three objective functions.

7.3. Sensitivity analysis

In this section, several test problems are solved, with different value of stated parameters. We apply sensitivity analysis on the parameters which affect the obtained routes and objective functions, significantly. The model is solved with different number of workers. Figure 8 and Figure 9 show the number of workers influence on cost objective and social objective, respectively. According to test problems, (as we could predict it before) by increasing the number of workers, social objective will possessively increase and cost objective will increase adversely. It shows there is an evident conflict between these objectives. As shown in Figure 10, purpose of the paper is to find solutions to balance between cost and social objectives.
Each ship serves the shipments with different speeds. Higher speeds, transport the shipments with lower times but it increases the amount of CO\textsubscript{2} emissions and since higher speeds consume more fuel, transporting with higher speeds are costlier (see Figure 11). Environmental objective function changes by increasing in CO\textsubscript{2} emissions as shown in Figure 12. We solve test problems with proposed solution method. Table 5 shows the pay-off table for the objective functions. Moreover, different Pareto-optimal solutions for a test problem are shown in Figure 10. Different value of speed, CO\textsubscript{2} emission and fuel consumption which are used to solve test problems and our case study problem are shown in Table 6.

8. Case study

A company which has some related activities to maritime transportation has been selected as a real case study to this paper. Stated company is a big oil company which is located in Iran, and it has several departments in different field related to oil industry. Its logistic department regularly services to some oil platforms which are located in Persian Gulf. This services are being provided with average twelve anchor handling tug supply (AHTS) ships which are usually rented by the stated company. Although AHTS can travel with four different speed levels (10,12,14,16 knots), stated company ships only travels with minimum speed (10 knots). All ships are the same kind and have certain capacity. Moreover, this problem is a full-shipload shipping. There are ten major nodes for this company shipping problem which are five oil platform in Persian Gulf, and five of Iran's port located in the south of Iran and one of United Arab Emirate major port named Sharjah. Schematic view of this nodes are shown in Figure 13 and Table 7 are shown nodes names in details.
Number of labor which are working in each ships are between 12 and 14. All other related information that is used as inputs in this paper like fuel cost of full and empty ships, transit time, distance between nodes and ships technical specifications like variable speeds and CO$_2$ emission used from case study data base.

8.1. Case study computational result

In this section, performance of AUGMENTED epsilon constraint method is evaluated by the proposed ship routing and scheduling model. We model the problem of a maritime transportation company to show the applicability of the proposed model in real situations.

To solve proposed model, we used real data from the stated company, 5 oil platforms, 5 ports and 12 ships with four speed levels (10, 12, 14, 16 KNOTS) are considered. Each port has a time window in which the shipment should start being loaded. Sustainable problem considers three objectives simultaneously. The problem is aimed to minimizing total costs, maximizing the social effect by maximizing job opportunity and minimizing total environmental damages caused by CO$_2$ emissions from ships and decreasing utility of serving hazardous materials like oil and gas. Uncertainty is considered for some of model parameters in order to deal with lack of data and changing some parameters in different time periods. Mixed flexible-possibilistic method is used to convert model with uncertain parameters to its crisp equivalent. Mathematical model is solved by Augmented epsilon constraint method. Result of ships routing and scheduling are shown in Table 8. Number 1 to 12 are assigned to each ships as its name, and time windows show the start time of ships travels (time unit is day) and routes in each time windows are available in Table 8. Longest ship travel ends by 3 routes at 31 days.

{Please insert Table 8 about here}

8.2. Managerial insights for the case study

In this section we extend the proposed mathematical model in order to achieve managerial insights. For this, we consider $n_s$ as a variable which determines the number of ships. Notably in the stated case there are predetermined number of ships. However, this model suggests the stated company to hire the optimum number of ships. In the following model, we are going to determine optimum the number of available ships.

$$
\text{Min} \sum_{seS} \sum_{veV} h^v_s n_s \quad \text{(40)}
$$

$$
\text{Max} \sum_{seS} n_s \quad \text{(41)}
$$

$$
\text{Min} \sum_{seS} \sum_{veV} CO2_{sv} n_s \quad \text{(42)}
$$
Subject to:
\[
\begin{align*}
& \min_s n_s \leq n_s \leq \max_s \quad \forall \ v \in V, s \in S \quad (43) \\
& n_{s,v} \geq 0 \ , \text{integer} \quad \forall \ v \in V, s \in S \quad (44)
\end{align*}
\]

Where \( \min_{s,v} \) is the minimum number of ships which decision maker thinks is necessary (can be zero), and \( \max_{s,v} \) is the maximum number of ships which the company can afford to rent each year due to company capital, \( h_s^v \) indicates the hiring cost of ship \( s \) with speed \( v \). The first objective minimizes the hiring cost of ships and second objective maximizes the number of available ships (it maximizes the social effect by hiring more workers). The third objective minimizes the total \( \text{CO}_2 \) produced by ships. Results of resolving the model by adding the objectives in to their corresponding i.e. Equations (1-3) and adding equations (43) and (44) are shown in Table 9. It is important to say that adding these equations are constant in to the first model so we did not consider them in the model.

{Please insert Table 9 about here}

9. Conclusion

In this study, a fuzzy multi-objective ship routing and scheduling was presented to satisfy three sustainable objectives. The proposed problem was aimed to find the best route and schedule for each ship while minimizing cost and \( \text{CO}_2 \) emission, and maximizing job creation at the same time. Variable speeds levels were considered to find the optimal speed for each ship considering speed correlation to ship's emission and fuel consumption. Uncertainty was added to the model by converting it to mixed flexible-possiblisic robust programming. Several test problems were conducted in order to validate mathematical model by GAMS software, and different parameters’ effect on objectives are evaluated by applying sensitivity analysis. Augmented \( \varepsilon \) -constraint was used as a solution methodology to solve the proposed problem. Also, real input data is considered from a case study to solve the model in large sized problems. We extend the proposed mathematical model to achieve the optimal number of ships and optimum speed of each ships. Computational results showed considerable positive influence (about 13%) of this study contributions. Maritime transportation managers and decision makers can use this paper numerical results, sensitivity analysis and managerial insights in their decisions. Moreover, considering different kinds of maritime risk in routes and considering variable speeds in continues form is a possible extent to this paper.

References


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**Figures caption:**

Fig.1. schematic view of sustainability aspects considered in this study
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Fig.3. Triangular possibility distribution of parameters generated to solve a sample problem
Fig.4. paper framework
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Fig.6. Optimal solution by considering social objective function
Fig.7. Optimal solution by considering environmental objective function
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Fig. 9. Social objective function versus the number of workers
Fig. 10. Environmental objective function versus CO₂ emissions
Fig. 11. Pareto-optimal solutions for a test problem
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Table 6. Value of different speed levels vs. CO₂ emission vs. fuel consumption
Table 7. Case study nodes name
Table 8. Results of case study
Table 9. Different results by considering number of Ships as a parameter and number of Ships as variable.

Figures:

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Fig. 2. Three ports of network, which ships travel between them.

Fig. 3. Triangular possibility distribution of parameters generated to solve a sample problem.
Step 1: Review paper related to ship routing and scheduling in literature

Step 2: Find literature gap

Step 3: Describe problem with limitations and assumptions

Step 4: Present mathematical modeling

Step 5: Validate model by GAMS software

Step 6: Determine uncertain parameters

Step 7: Rewrite mathematical model in mixed flexible-possibilistic

Step 8: Find lexico pay-off table

Step 9: Apply augmented $\varepsilon$-constraint

Step 10: Evaluate pareto solutions

Step 11: Report best solutions

Step 12: Managerial insight

Step 13: Apply sensitivity analysis

Fig.4. paper framework
Fig. 5. Optimal solution by considering cost objective function

Fig. 6. Optimal solution by considering social objective function

Fig. 7. Optimal solution by considering environmental objective function
Fig. 8. Cost objective function versus the number of workers

Fig. 9. Social objective function versus the number of workers
Fig. 10. Pareto-optimal solutions for a test problem

Fig. 11. Cost and environmental objective functions versus the different speed

Fig. 12. Environmental objective function versus CO$_2$ emissions
Fig. 13. Schematic form of case study ports and platforms in map
Tables:

Table 1. Summary of related literature.

<table>
<thead>
<tr>
<th>Articles</th>
<th>Scheduling</th>
<th>Routing</th>
<th>Tramp ship</th>
<th>Speed</th>
<th>Job creation</th>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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Table 2. The imprecise parameters.

<table>
<thead>
<tr>
<th>g_v</th>
<th>the time of traveling one distance unit at speed v€V</th>
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<tr>
<td>p_i</td>
<td>a port service time</td>
</tr>
<tr>
<td>CO2_sp</td>
<td>CO_2 emission from each ship in each speed</td>
</tr>
<tr>
<td></td>
<td>(g_1, g_2, g_3) (h/km)</td>
</tr>
<tr>
<td></td>
<td>(p_1, p_2, p_3) (day)</td>
</tr>
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<td>(CO2_1, CO2_2, CO2_3)</td>
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Table 3. Range of parameters value of sample problems

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<th>Values</th>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>n_s</td>
<td>~Uniform(1,3)</td>
<td>[a, b]</td>
<td>~Uniform(0.5, 10, 20)</td>
</tr>
<tr>
<td>c_s (dollar/km)</td>
<td>~Uniform(130,170)</td>
<td>Speeds(knots)</td>
<td>Rnd(10,12,14,16)</td>
</tr>
<tr>
<td>g_v (h/km)</td>
<td>~Uniform(0.1, 0.9)</td>
<td>p_i</td>
<td>~Uniform(1,3)</td>
</tr>
<tr>
<td>f_i (Binary)</td>
<td>wSi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b_i (dollar)</td>
<td>~Uniform(4500,7000)</td>
<td>M_i (dollar)</td>
<td>30 per day</td>
</tr>
<tr>
<td>e_i (dollar)</td>
<td>4500 per day</td>
<td>CO2_sp (g)</td>
<td>~Uniform(10, 40)</td>
</tr>
<tr>
<td>d_ij (km)</td>
<td>~Uniform(20,300)</td>
<td>h_i</td>
<td>0 or ~Uniform(2500,5000)</td>
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Table 4. Conflict between cost and social objective

<table>
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<th>Number of Worker</th>
<th>OFV1 (Cost)</th>
<th>OFV2 (Social)</th>
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<tbody>
<tr>
<td>13</td>
<td>853080</td>
<td>260</td>
</tr>
<tr>
<td>14</td>
<td>853100</td>
<td>280</td>
</tr>
<tr>
<td>15</td>
<td>853120</td>
<td>300</td>
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<td>16</td>
<td>853150</td>
<td>320</td>
</tr>
<tr>
<td>17</td>
<td>853170</td>
<td>340</td>
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Table 5. Payoff table for three objectives of sample problems

<table>
<thead>
<tr>
<th></th>
<th>Z₁</th>
<th>Z₂</th>
<th>Z₃</th>
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<tbody>
<tr>
<td>Min Z₁</td>
<td>934000*</td>
<td>250</td>
<td>180</td>
</tr>
<tr>
<td>Max Z₂</td>
<td>1660000</td>
<td>310*</td>
<td>155</td>
</tr>
<tr>
<td>Min Z₃</td>
<td>87400</td>
<td>100</td>
<td>160*</td>
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Table 6. Value of different speed levels vs. CO₂ emission vs. fuel consumption

<table>
<thead>
<tr>
<th>Speed (knots)</th>
<th>CO₂ emission (g)</th>
<th>Fuel consumption (t)</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>25</td>
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<td>14</td>
<td>30</td>
<td>38</td>
</tr>
<tr>
<td>16</td>
<td>40</td>
<td>51</td>
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</table>

Table 7. Case study nodes name

<table>
<thead>
<tr>
<th>Ports number</th>
<th>Name</th>
<th>Platforms number</th>
<th>Name</th>
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<tbody>
<tr>
<td>1</td>
<td>Kish Island, Iran</td>
<td>6</td>
<td>Oil platform A</td>
</tr>
<tr>
<td>2</td>
<td>Bandar Charak, Iran</td>
<td>7</td>
<td>Oil platform B</td>
</tr>
<tr>
<td>3</td>
<td>Bandar Lengeh, Iran</td>
<td>8</td>
<td>Oil platform C</td>
</tr>
<tr>
<td>4</td>
<td>Qeshm Island, Iran</td>
<td>9</td>
<td>Oil platform D</td>
</tr>
<tr>
<td>5</td>
<td>Sharjah, United Arab Emirates</td>
<td>10</td>
<td>Oil platform F</td>
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Table 8. Results of case study

<table>
<thead>
<tr>
<th>Ship number</th>
<th>route</th>
<th>Served ports</th>
<th>Travel time</th>
<th>CO₂ emission</th>
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<tr>
<td>S1</td>
<td>2 → 10 → 8 → 1</td>
<td>10-8</td>
<td>33</td>
<td>396</td>
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<tr>
<td>S2</td>
<td>1 → 7 → 9 → 2</td>
<td>7-9</td>
<td>34</td>
<td>408</td>
</tr>
<tr>
<td>S3</td>
<td>2 → 9 → 7 → 3</td>
<td>2-9-7</td>
<td>34</td>
<td>408</td>
</tr>
<tr>
<td>S4</td>
<td>2 → 10 → 3</td>
<td>2-10</td>
<td>30</td>
<td>360</td>
</tr>
<tr>
<td>S5</td>
<td>5 → 3</td>
<td>9</td>
<td>12</td>
<td>144</td>
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<td>S6</td>
<td>5 → 6 → 8 → 7 → 4</td>
<td>8-7</td>
<td>39</td>
<td>468</td>
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<tr>
<td>S7</td>
<td>1 → 2 → 9 → 6 → 3</td>
<td>2-9-6</td>
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<td>S8</td>
<td>5 → 8 → 4</td>
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<td>S9</td>
<td>4 → 8 → 5</td>
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<td>S10</td>
<td>1 → 9 → 2 → 7 → 3</td>
<td>9-2-7</td>
<td>33</td>
<td>396</td>
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<td>S11</td>
<td>5 → 2</td>
<td>7</td>
<td>14</td>
<td>168</td>
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<tr>
<td>S12</td>
<td>4 → 5</td>
<td>8</td>
<td>28</td>
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Table 9. Different results by considering number of Ships as a parameter and number of Ships as variable.

<table>
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<th>Number of Ships as a parameter</th>
<th>Number of Ships as variable</th>
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<td></td>
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<td>2</td>
<td>12</td>
<td>34454</td>
</tr>
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<td>12</td>
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