A multi-objective approach to analyse the effect of fuel consumption on ship routing and scheduling problem

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Abstract: This paper investigates the impact of fuel consumption on ship routing and scheduling problem. In current trends, the anthropogenic emission due to excess fuel consumption is a topic of intense debate in the global world ship trading society. We have modelled a problem as a mixed integer nonlinear programming (MINLP), which encounters the issues related to routing, fuel consumption, and customer demand. A meta-heuristic approach *controlled elitist non-sorting genetic algorithm* (CENSGA) has been proposed to solve the bi-objective problem. Finally, the utility of the model is demonstrated by a case study.

Keywords: carbon emission; ship routing; mixed integer nonlinear programming; meta-heuristic.

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1 Introduction

In the recent trading system, shipping industries play a vital role in the growth of the economy of the country. The various modes of transportation have been introduced by the researchers, i.e., seaside, roadside and airside, among these, seaside is the cheapest mode of transportation for the bulk cargo, goods. The shipping industries are liable for nearly 3% anthropogenic carbon emission in the environment. Therefore, it become one of the major emitters of greenhouse gases (Hoffmann et al., 2012).

Most of the shipping companies focus on strengthening the shipping network while fulfilling the customer demand within promising time. However, due to the lack of proper route networking and scheduling of ships, tremendous delay in cargo handling is caused (Song et al., 2015; Pang and Liu, 2014). In De et al. (2017) ship routing problem, the cargo is transported from origin ports to destination ports within a certain promising time. The ship should cover the distance between the ports in a defined range of speed, which effects on the fuel consumption of the ship engine and CO_2 emission to global environment. The energy efficiency design index (EEDI) is introduced to measure energy efficiency for new ships/vessels and energy efficiency indicator (EEOI) for existing ships/vessels (IMO, 2009a, 2009b, 2009c). Several other indexes have been used to measure energy index, vessel speed optimisation and vessels/ships enlargement. Generally, there are three ways to control the anthropogenic greenhouse gas emission. Operational measure, which includes adoption of slow steaming policies such as vessel speed optimisation. Technological measures mainly involve the usage of alternative fuels such as using energy-saving engines, more efficient ship propulsions etc. Market based policies includes emission trading and carbon levy schemes, IMO has been working extensively on the introduction of the policies in the context of shipping operations. For this, we have developed a model to consider the ship routing, minimising the delay from an origin port to a destination port and minimising the fuel consumption rate with the optimal speed of the ship.

The rest of the paper is structured as follows: Section 2 describes the literature review based on ship routing and carbon emission. The problem description and mathematical formulation are described in Section 3. Section 4 shows that solution methodology and approach. In Section 4, we have discussed the results and the related scenarios. Finally, we conclude the work and future scope in Section 5.

2 Literature review

In the context of maritime/seaborne transportation, most of the researchers focused on the intricacies associated with ship routing and scheduling along with carbon emission.

2.1 Ship routing and scheduling

Sherali et al. (1999) explored the problem based on Kuwait Petroleum Corporation Limited and developed a mixed integer program model to optimise the operations cost of ship and demurrage cost due to delay in delivery. Agarwal and Ergun (2008) developed the ship scheduling and cargo routing network problem to maximise the revenue of the port. Korsvik and Fagerholt (2010) proposed a model of ship routing and scheduling problem and used the Tabu-search heuristic method to maximise the revenue associated with the port. A ship routing and berth assignment model is introduced (Li and Pang, 2011) in simultaneous manner. The proposed model describes the routing, berthing time and pick-up delivery decision in an integrated approach. Korsvik et al. (2011) introduced a neighbourhood search heuristic approach to solve the ship routing and scheduling problem with split cargo. The splitting of cargo is used to utilise the fleet capacity in an efficient manner and maximise the total fleet profit. Container stowage and ship routing model (Moura et al., 2013) is introduced for a short sea routing problem. The mathematical model is formulated to reduce the total routing and shifting cost with loading and unloading complex operations. Babu et al. (2015) investigated the ship scheduling and train scheduling problem to fulfil the customer demand and improve the port efficiency in an integrated manner. Stålhane et al. (2015) stated a ship routing and scheduling problem with cargo coupling to maximise the total profit associated with shipping operations. De Armas et al. (2015) proposed a greedy randomised adaptive search procedure and variable neighbourhood search algorithm to solve ship routing and scheduling problem in the discretised time window. Pratap et al. (2016) described the ship unloader allocation problem and determine the near optimal ship schedule to minimise the total operational time of berthed ship. Agra et al. (2016) addressed a ship routing and inventory management problem for a fishing company. A mixed integer linear programming (MILP) model is proposed to capture the transportation cost and cost associated with inventory level. Meng et al. (2014) studied a containership scheduling and routing problem at strategic, tactical and operational planning level.

2.2 Carbon emission

Many of the researchers carried out a study on ship routing with carbon emission. Eide et al. (2011) proposed a model for cost effective carbon gas emission for a shipping industries and project towards the effect of cost reduction model up to future 2030. Andersson et al. (2015) described an integrated model on ship routing and real deployment problem for RO RO shipping company. A piecewise linear approximation method is introduced to determine the relationship between fuel consumption and speed of vessel. Norlund and Gribkovskaia (2013) developed a speed optimisation strategies to reduce the vessel supply chain operations. Wang and Xu (2015) stated that sailing speed is a crucial factor for deciding the ship routing and ship operating cost. Liu et al. (2015) introduced a model to capture the carbon emission cap trade mechanism for stochastic demand and reduce the carbon emission and maximise the revenue cost. Passchyn et al. (2016) developed two model to minimise the carbon emission and minimise the ship passing time at the locking gate. Endresen et al. (2007) studied the fuel emission rate by cargo and passengers shipping activities. Bialystocki and Konovessis (2016) investigated the ship fuel consumption rate with ships' speed.

In this paper, we highlight the carbon emission issue that researchers usually consider, but in a holistic perception; specifically, the considered scenarios based on ship routing and travel time of ships. In fact, we consider into account the interdependences between these carbon emissions and travelling time between the origin and destination port with the focus to obtain a global optimal solution for ship routing network problem.

3 Problem description

The schematic view of ship routing network model is shown in Figure 1. Destination port companies intend to order the cargo containers from other ports (origin) to fulfil the customer demands. Origin ports (P_o, o = 1, 2, 3, 4 … O) have its own capacity and characteristics to supply the cargo to the destination port (P_d, $d = O + 1, ... O + D$). Ships arrive at the anchorage of the destination port (P_d) and according to the berth status, port operators allow the ships to berth at the port terminal.

In this model, we introduced a ship routing and scheduling problem with carbon emission as a multi-objective problem, which aims to minimise both the travelling time and fuel consumption of ships. The model is formulated as a mixed integer nonlinear programming (MINLP). The relation of fuel consumption and speed of the ship is nonlinear in nature (De et al., 2015) as shown in Figure 2.

The model assumptions are described as follows:

1 The estimated departure time of ship at origin port and quantity of ship are known in advance.

2 The ship must be completely unloaded after the arrival on the destination port.

3 Time travel to cover the distance between anchorage and berth at the destination port is negligible.

4 Demurrages cost should be paid, if the ship is unable to cover the distance within the time window.

5 There shall always be enough supply in origin ports whenever needed.

Figure 1 Shipping networking route from origin port to destination port (see online version for colours)

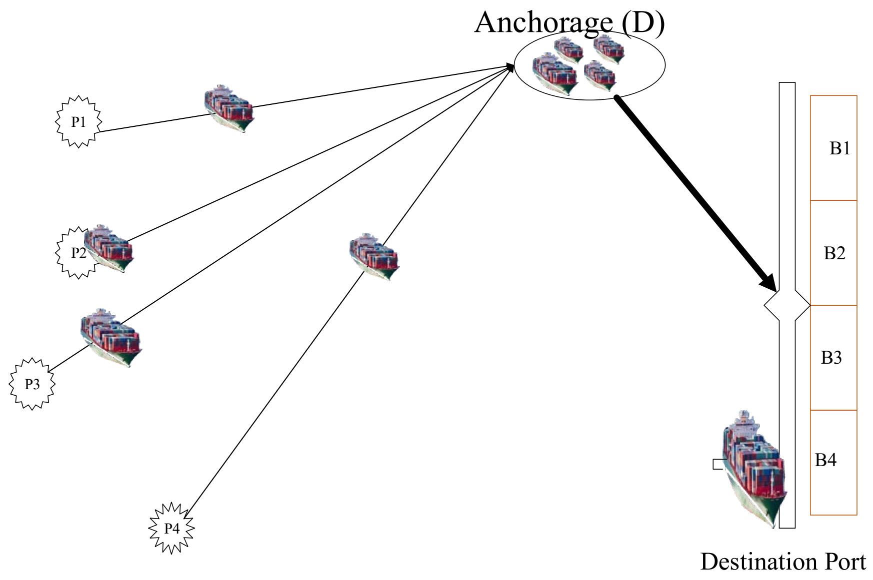
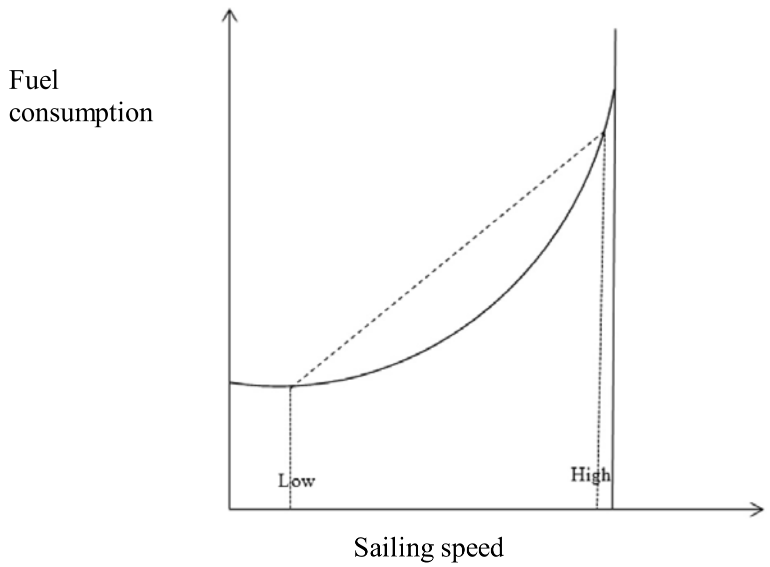


Figure 2 Relationship between the sailing speed and fuel consumption



3.1 Mathematical model

3.1.1 Indices

P_o Set of origin ports (o = 1, 2, 3, 4 … O)

P_d Set of destination ports ($d = O + 1, O + 2, O + 3, \dots O + D$)

I Set of vessels/Ships (i = 1, 2, 3 …… I)

C Set of customers (c = 1, 2, 3 …. C).

3.1.2 Parameters

t_{sio} Departure time of the vessel/ship i from the origin port o.

D_{od} Distance bertween source port p and destination d.

$v_{i(P_o \to P_d)}^{\max}$ Maximum speed of vessel/ship i along origin o to destination port d(*Knots*).

$v_{i(P_o \to P_d)}^{\min}$ Minimum speed of vessel/ship i along origin o to destination port d(*Knots*).

c Admirability constant (200 to 300)*10^6.

α Price of fuel per ton.

f_{ei} Fuel consumption of the vessel i engine (g/kWh).

$Q_{i(P_o P_d)}$ Number of cargo containers shift from port o to d through vessel/ship i.

U_I Unloading rate to unload the cargo containers per *hr*. from the vessel/ship i.

Q_{cd} Quantity of the cargo demand by the customer c at port d.

3.1.3 Decision variables

$$x_{i(P_p P_d)} \quad \begin{cases} 1 & \text{If ship } i \text{ covers origin } o \text{ to destination port } d \\ 0 & \text{Otherwise} \end{cases}$$

$v_{i(P_o \to P_d)}$ Speed of ship i along port o to port d.

t_{aid} Arrival time of ship i at the anchorage P_d.

Objective 1: objective 1 states to minimise the travel time from an origin port o to the final destination port d.

$$\min \sum_{i \in I} (t_{aid} - t_{sio}) x_{i(P_o P_d)} \tag{1}$$

Objective 2: objective 2 represent to minimise the fuel consumption to cover the distance from origin port o to destination port d. The fuel consumption is directly proportion to carbon emission.

$$\min\ 0.735\left(\alpha\sum_{i=1}^{I}\sum_{\substack{o=1\\o\neq d}}^{O}\frac{f_e D_{od}\mathrm{Q}_{i(P_oP_d)}{}^{2/3}v_{i(P_o\to P_d)}x_{i(P_oP_d)}}{c}\right) \tag{2}$$

3.2 Constraints

$$t_{aid} \geq t_{sip} \tag{3}$$

$$\sum_{i=1}^{I}\sum_{\substack{P_o=1\\P_o\neq P_d}}^{N} x_{i(P_oP_d)} \geq 1 \tag{4}$$

$$\mathrm{Q}_{i(P_oP_d)}x_{i(P_oP_d)} \leq Q_{cd} \tag{5}$$

$$\sum_{\substack{o=1\\o\neq d}}^{P}\sum_{i=1}^{I} t_{aid}.x_{i(\mathrm{P_oP_d})} \leq \left(t_{a(i+1)d} + \frac{Q_{i(P_oP_d)}}{U_I}\right) \tag{6}$$

$$v^{\max}_{(P_o\to P_d)} \geq v_{(P_o\to P_d)} \geq v^{\min}_{(P_o\to P_d)} \tag{7}$$

$$\left(\frac{D_{(od)}}{v_{(P_o\to P_d)}}\right)x_{i(P_oP_d)} \leq T_{P_oP_d} \tag{8}$$

$$v_{(P_o\to P_d)} \geq 0 \tag{9}$$

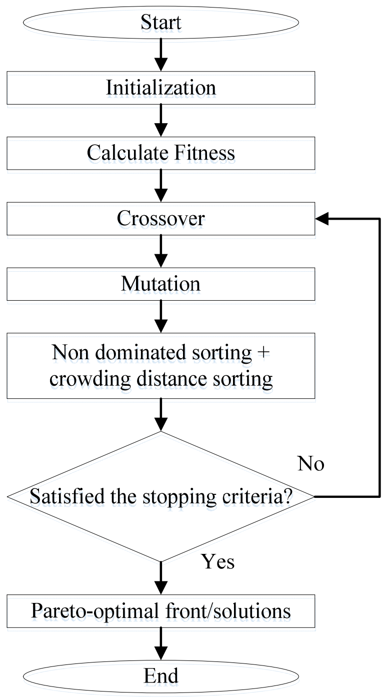
$$x_{i(P_oP_d)} = \begin{cases} 1, & \text{If ship } i \text{ covers origin } o \text{ to destination port } d \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

Constraint (3) reveals that the arrival time of ship *i* to port d should be greater than or equal to the departure time of ship *i*. Constraint (4) describes that at least one ship departs from origin port and arrives at port *d*. Constraint (5) introduces the supplied quantity of cargo must be greater than or equal to the demand of customer (i.e., load the cargo on the basis of customer demand). Constraint (6) states that the ship (*i* + 1) arrives after the arrival of the ship *i*. The speed range of the ship *i* is defined by the equation (7). Constraint (8) ensures that the ship *i* arrive at destination port d within the time window. Constraint (9) shows the non-negativity constraint. Constraint (10) represents the binary variable.

4 Solution methodology

The proposed model is formulated as multi-objective mixed integer nonlinear problem. Multi-objective optimisation problems (MOPs) can be considered as simultaneous optimisation problem for all the functions involved in the problem. The solution of problem may be global best or not with respect to all objectives and it encourages the non-dominated and non-inferior solutions. In this type of problem, we have to determine the set of Pareto solutions or non-dominated solutions, which should satisfy all the objectives and constraints. The control elitist non-sorting genetic algorithm (CENSGA) is a meta-heuristic algorithm to solve the multi-objective problem and generates the set of Pareto solutions (Mohapatra et al., 2015; Pratap et al., 2015, 2017) and selection criteria to select the best individual font is based on geometrical distribution as describes in equation (11)–(13). The flowchart of CENSGA is shown in Figure 3.

Figure 3 Flowchart of CENSGA



The implementation of the CENSGA is discussed:

4.1 Initialisation

Initially, generate the random number of feasible solution for ship routing and assigned the numbers in the range of [0–1] randomly to the solutions and sorted out as a sequence of the order.

4.2 Crossover

The crossover operator is used for convergence and get the local optima of the solution. It reproduces new offspring from the parent chromosomes and generate the random numbers in the range of [0–1] as a binary and sorted in such a way the same sequence of parent chromosome.

4.3 Mutation

To maintain the genetic diversity from one generation of a population of genetic algorithm chromosomes to the next, mutation is used and provide the global optimum solutions. The chromosomes mutate and form a new chromosome.

4.4 Selection (CENSGA)

The number of individuals to be selected as the new parent in the currently best non-dominated front is restricted. The restriction is done based on a predefined distribution of a number of individuals in each front. (Deb and Goel, 2001) proposed the geometric distribution to restrict the number of individuals in each front.

The number of individuals in each front is restricted to n_i, where geometric distribution is determined from equation (11), where n_i is the maximum number of allowed individuals in front *i*.

$$n_i = rn_{i-1} \tag{11}$$

Reduction rate = *r* (<1) and number of non-dominated fronts = *k*. n_i can be expressed as:

$$n_i = N\frac{1-r}{1-r^k}r^{i-1} \tag{12}$$

Let, from the front *i*, *n*(*i*) is the max allowed number of individuals.

$$n_i \le n^{(i)} \tag{13}$$

The crowded distance is used to select the number of individuals *n*(*i*) from front *i* and the number of solution is reduced exponentially by the proposed geometric distribution method. This selection mechanism provides the best optimal individual fonts to the solutions.

5 Result and discussion

In this paper, we have considered a real scenario of cargo handling port. The data collected 4 origin port and a 1 destination port, which can accommodate 27 ships in a month. We used the MATLAB 2015 on I7 processor in windows 10 platform to solve the considered scenario.

5.1 Determination of optimal ship routing sequences

5.1.1 Inputs data

In this case study, the origin port is 2 (P_1 and P_2) and destination ports are 4 (P_3, P_4, P_5, P_6). These ports deal with five leading customers. The departure time (t_sio) of vessels at the origin port is known in advance as shown in Table 1.

The maximum and minimum speed of vessel is 14 and 17 knots respectively from port *o* to *d*. The unloading rate of each quay cranes is 72 containers per hour and fuel price is 299 USD per metric tonnes. Table 2 describes the port distance between the origin and destination ports (2 origin ports i.e., 1 and 2 and 4 destination ports i.e., 3, 4, 5 and 6).

Table 1 Vessels departure information

Vessel N.	*Port* (*o*)	*Port* (*d*)	*Quant.*	*Dep_D*	*Month*	*t_sio*
1	1	3	12,300	5	10	11.14
2	1	5	10,020	5	10	13.45
3	1	6	8,560	5	10	14.20
4	2	4	9,540	5	10	14.20
5	1	3	10,800	5	10	16.20
6	2	6	12,050	5	10	16.30
7	1	4	10,010	6	10	10.80
8	1	5	7,850	6	10	12.15
9	2	3	11,200	6	10	13.25
10	2	5	12,500	6	10	16.24
11	2	6	5,600	7	10	11.18
12	1	6	4,528	7	10	11.35
13	1	3	10,540	7	10	13.30
14	1	4	11,001	7	10	15.15
15	2	4	8,475	7	10	15.45
16	1	5	10,800	8	10	11.00
17	2	4	10,020	8	10	11.05
18	1	3	12,010	8	10	12.57
19	2	5	8,452	8	10	15.70
20	2	6	12,540	9	10	13.10
21	1	3	10,547	9	10	13.45
22	1	5	8,759	9	10	15.27

Table 2 Distance matrix (miles)

	Singapore	*India*	*Australia*	*North Korea*
Hong Kong	1,460	3,895	3,594	1,444
Shanghai	2,237	4,672	3,919	802

5.1.2 Results and discussion

The optimal sequence of ship routing is determined in fitness selection process by the CENSGA II and non-sorting genetic algorithm II (NSGA II). The considered parameters adopted are: Population size is 50, crossover probability (pc) is equal to 0.60 and Mutation probability (pm) is equal to 0.1. Figure 4(a) and 4(b) reveals that nature of the solution with respect to the generation. After the convergence of solution, the Pareto front is obtained. The port manager has a wide option to select the near optimal solution from the front. The obtained result reveals that in each case the solution is converged at a generation and found that CENSGA II performs better than NSGA II. The solutions satisfy the both objectives and their associates constraints.

Figure 4 Pareto front generated through NSGA II and CENSGA (see online version for colours)

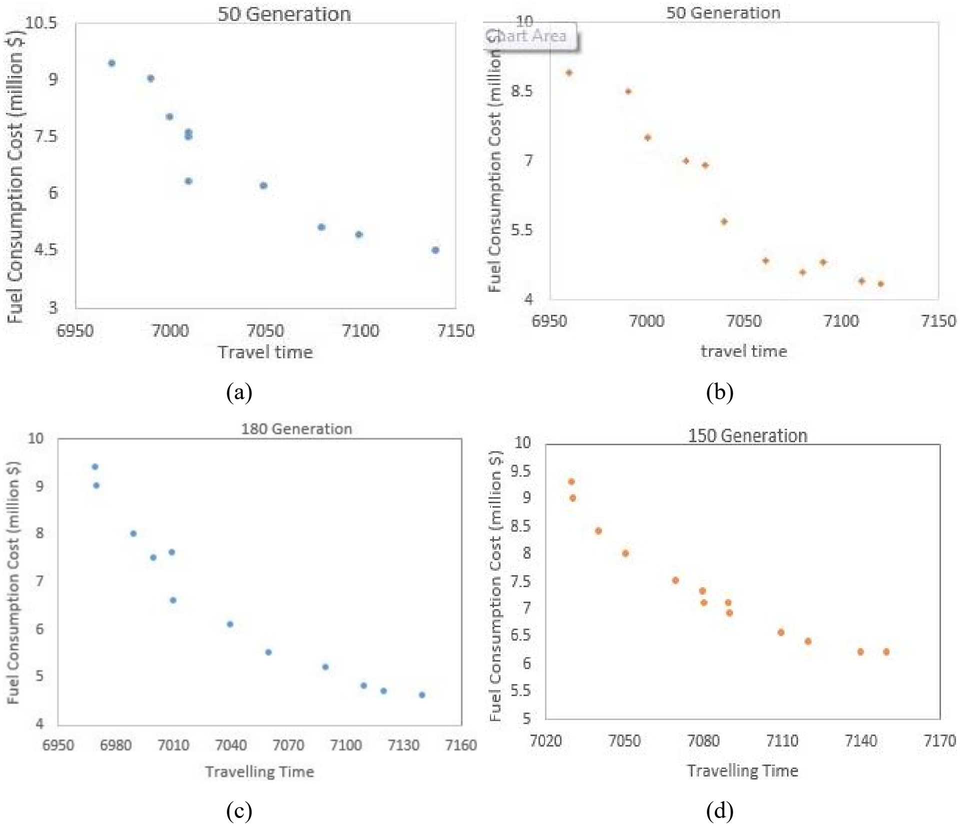


Table 3 Computational experiment

Instances	*NSGA II*		*CENSGA*	
	Total travelling by ships in a month (port o to d) hrs.	*Total fuel consumption cost (million $)*	*Total travelling by ships in a month (port o to d) hrs.*	*Total fuel consumption cost (million $)*
1 (18 Ships)	7,083.277	7.38	7,042.64	6.58
2 (22 Ships)	9,426	14.1	9,394	12.9
3 (28 ships)	9,529	23.7	9,506	22.9

Figure 4(a), 4(b), 4(c) and 4(d) represents the Pareto optimal front for NSGA II and CENSGA. The solution and convergence rate of CENSGA performs better than the NSGA II. Table 3 shows the computation result and reveals that the performance of CENSGA is better than NSGA II. The convergence of the Pareto front solutions in

CENSGA is obtained in a generation 150 and generation 180 in NSGA II for the instances 1.

5.2 Sensitivity analysis

In this case, we have considered the port cargo supply demand ratio set equal to 10,000 (10k). For the sensitivity analysis, we gradually increase the demand ratio from 10k to 30k. In this considered instance, the port supply capacity of the port is kept same with 4, 50,000. The origin port can satisfy the destination port demands. Under the setting, we generate the Pareto front between fuel consumption and travelling time and obtain the solutions for the port management decision maker. Figure 5 illustrates the Parteo-optimal frontier, which demonstrates the trade-off between fuel consumption and travel time for different supplier capacity ratio. We can analyse that slope of the curve decreases and became flat, when travelling time increases, which reveals the convex property of the model.

Figure 5 Pareto curve for various capacity ratio (see online version for colours)

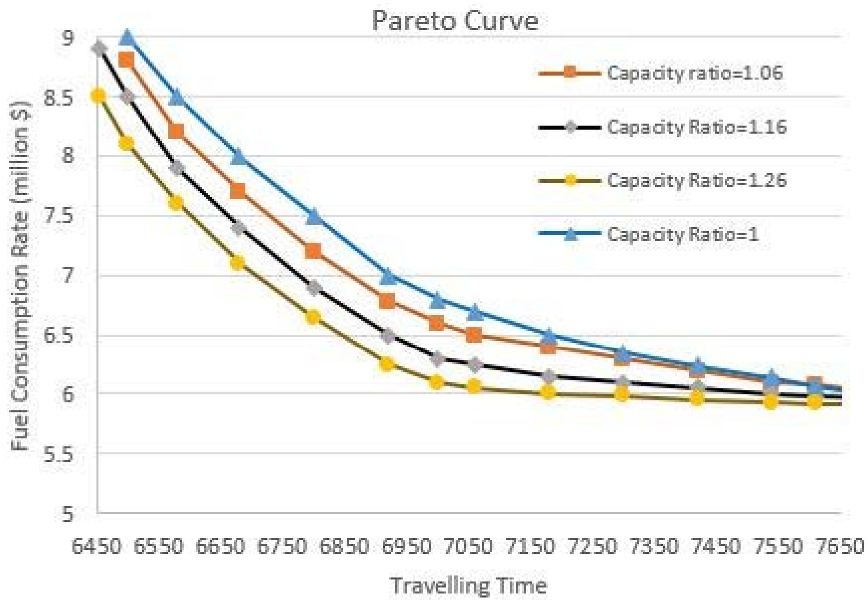


Table 4 Percentage gap of fuel consumption and travelling time

Demand ratio	*Min (fuel consumption)*	*Max (fuel consumption)*	*Gap (fuel consu.)*	*Min (total travelling time)*	*Max (total travelling time)*	*Gap (travelling time)*
10K	2.014	3.66	81.72%	4,720	5,520	16.94%
10.5K	2.800	5.12	82.85%	5,690	6,709	17.90
20K	3.850	7.03	82.59 %	6,321	7,,129	12.78
3K	5.351	9.80	83.14 %	7,421	8,229	10.88

Finally, we carried out a sensitivity analysis of the proposed model with different demands of port. The results are shown in Table 4. We found that minimum fuel consumption that is the lowest value in Pareto curve. The fuel consumption gap determined by the maximum and minimum measured by the percentage. In similar manner, determine for the travelling time. We analysed that for different value of cargo demands, the fuel consumptions are similar. However, it shows that travelling time is decreasing when cargo demand is increasing. When the cargo demand becomes more, then travelling time is less, while fuel consumption has smaller change.

6 Conclusions

In this paper, we studied the effect of fuel consumption on ship routing problem and formulated the model as multi-objective mixed integer nonlinear program. The nature inspired meta-heuristic algorithm (CENSGA and NSGA II) is proposed to solve the problem and determine the near-optimal ship routing with respect to the final destination port. The splendid qualities of the proposed algorithm used (CENSGA) aids to easily flee from local optima and strongly obtain near optimum solutions consistently which can be analysed from the outputs. The obtained result reveals that the performance of CENSGA is better than NSGA II. In future, work can be extended to integrate with multi-port destination and proper synchronisation of berth allocation.

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