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Effects of slow steaming strategies on a ship fleet

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Abstract Currently, container ships operators have implemented slow steaming (SS) strategies in their fleets to improve the profit margins by reducing operational costs. However, some ship owners are not yet convinced of this practice because the navigation time is increasing that cause a reduction of the number of travel per year of the ship. The use of speed reduction by liner shipping has been widely discussed in the literature. Nevertheless, this effect has not been studied in bulk carriers because they are navigating slower than container ships. This paper proposes a simulation model of a bulk carrier's fleet composed by 13 ships from a unique ship owner in three conditions: the actual condition of navigation, the SS and the ultra-slow steaming. A discrete-event simulation model has been developed considering historical data of a bulk carrier fleet. The results obtained are the total fuel consumption, emissions and the cargo transported per year. These values are showing that the fleet can be operated with higher efficiency when the SS strategy is used. Indeed, the saving in fuel cost and emissions are balancing the reduction of the cargo transported per year.

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1 Introduction

In the last decade, the world merchant fleet dedicated to international trade has increased. In January 2016, the ship world fleet grew by 3.5% and reached 1.8 billion DWT that consisted of 90,917 vessels including bulk carriers, oil tankers and container carriers. The sea shipping industry is responsible for about 90% of world trade (in tons) that is representing a total international cargo over 9841 millions of tons [26].

Consequently, it produces a growth of fuel consumption and Green House Gas (GHG) emissions at sea. The GHG emission of ship engines have raised the concern of International Maritime Organization (IMO) on the consequences for environment and human health.

In addition, IMO first adopted MARPOL Annex VI in 1997. It limits the main air pollutants in ships exhaust gas, including sulphur oxides SO_X.

Following entry into force of MARPOL Annex VI, the main changes are a progressive reduction in emissions of SO_X, NO_X and particulate matter (PM), as well as the introduction of emission control areas (ECAs). ECAs are created to further reduce emissions of those air pollutants in designated coastal areas.

Nevertheless, the shipping industry is facing huge challenges. First, main concern of ship owners is to reduce operating cost and maximize incomes, whereas the fuel price has increased significantly over the years. Second, customers such as shippers and freight forwarders are increasingly demanding on-time delivery [12]. Third, ships must fulfil the rules regarding environmental restrictions implemented by the IMO (emissions limitations).

In the case of fuel cost, the fuel consumption of sea vessels depends heavily on the steaming speed. The practice of slow steaming (SS) (speed reduction denoted in this paper as SS) has become more common in cargo fleets especially in liner shipping [2].

The study of SS practice in liner shipping became more frequent in the last years [2, 23, 27]. There are classic studies [19], which deal with the use of SS. Moreover, in the solid bulk and oil market the freight formation model (supply curve) presented by several authors, such as [21], provides for SS to reduce supply and reduce costs. In these cases unlike liner services (container ships), the lines are not regular, and there is no scheduled service, where the number of ships and the frequency set define the speed [17].

There are studies linking emissions reduction and/or SS, on other types of ships other than container ships, but there are indeed many more publications analyzing the problem in container ships [1, 5, 14].

SS is also a market practice in the bulk carriers trading. However, only few recent studies are studying the economic impact of speed reduction and emissions in this specific case.

In addition, delivering on time is a difficult challenge due to port congestion, inefficient port operations, extreme weather conditions, machine breakdowns and other factors [12]. Besides, some industries criticize the SS because it is necessary to build more ships to transport the same quantity of product and achieve targets of delivery time.

Lastly, one positive effect of SS is that it reduces GHG emissions that are proportional to the amount of fuel burned [2].

Recently, they have been significant advances in SS approach not only in the study of economic aspects [7, 15, 16, 18], but also in others areas as resistance [24], shipping time, bunker cost, ability to deliver on time [12] and environmental advantages [2, 6].

In this paper, the influence of SS on one fleet of 13 bulk carrier ships is analysed through simulation. This model uses criteria based on speed, fuel oil consumption, distance travelled, cargo and emissions quantity (CO_2 and SO_X). Then, the results of a simulation model suggest that SS implementation is a possible solution to turn navigation more profitable in economic and environmental aspects for bulk carriers.

2 Methodology

This section presents the developments of the model including the explanation of the methodology, the database (DB) used in the analysis as well as the criteria selection. Thereafter, the definition and implementation of the
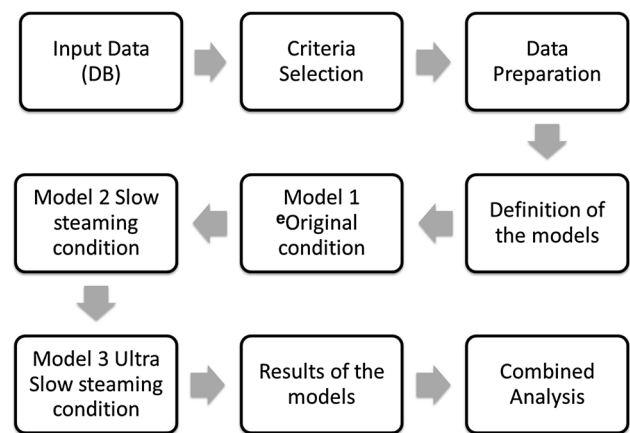

Fig. 1 Flowchart of the methodology

models are presented. The main steps of the proposed methodology are shown in Fig. 1.

The goal of this work is to evaluate the potential economic and environmental benefits of new navigation condition: SS and ultra-slow steaming (USS).

The proposed framework consists of a discrete-event simulation (DES) model to represent the voyage process. Both economic and environmental parameters were considered to assess the influence of SS and USS in a fleet of bulk carrier ships. The design of the alternatives is based on the review literature and expertise.

This approach is similar to previous studies proposed by [4]. The previous mentioned study analyses the influence of the SS and USS on one fleet of 15 bulk carriers considering only the fuel consumption, distance, and cargo. In addition to these variables, the present model consider the emissions that is a critical parameter to fulfil current regulations.

Several alternatives were designed for different variable settings. DES was then used to evaluate key performance improvements.

A DES model can reproduce an existing complex system using a sequence of events and provide to the decision-maker a vision on how that system might perform [22].

The model is developed to balance and evaluate the operational decision on speed reduction with the factors on bunker cost, fuel oil consumption, distance travelled, cargo quantity, carbon dioxide emission and sulphur oxide.

2.1 Database and input analysis

The simulation stage was based on a valid process model. The main steps of the proposed methodology are shown in Fig. 1.

In this study, 13 bulk carrier vessels from a ship fleet of a unique ship owner are considered. Table 1 gives a highlight on ship main features.

Table 1 Ship fleet parameters (13 vessels)

Description	Mean	Standard deviation
Total length (m)	289.5	16.7
Breadth (m)	46.7	3.6
Draft (m)	18	0.7
Design speed (knots)	14.22	0.77
Max. displacement (tons)	202,052	36,274
DWT (tons)	179,438	33,351

Table 3 Fuel mass to CO_2 mass conversion factors C_F in [kg-CO_2/t-fuel] [10]

Type of fuel	Carbon content	C_F
Diesel/gas oil	0.875	3.206
LFO—light fuel oil	0.86	3.151
HFO—heavy fuel oil	0.85	3.114
LPG—liquefied petroleum gas—propane	0.819	3.000
LPG—liquefied petroleum gas—butane	0.827	3.030
LNG—liquefied natural gas	0.75	2.750

The DB represents a period of 2.5 years. That means 6844 records corresponding to 223 voyages (one-way travels).

The information available is obtained in laden and ballast conditions. The simulation was developed to split the ship fleet in three ship categories based on maximum displacement of each one.

Ship category 1 is composed by vessels that have a maximum displacement between 167,963 and 191,668 tons. It represents 54% of the whole fleet. Ship category 2 is composed by vessels that have a maximum displacement between 201,550 and 224,978 tons. It represents 31% of the whole fleet. Finally, the ship category 3 is composed by vessels that have a maximum displacement between 259,711 and 280,313 tons. It represents the 15% of the entire fleet.

The model simulates one-way voyages of the vessels using ARENA software for both ballast and laden conditions. For each sub-model (original, SS or USS), inputs and outputs are detailed in the Table 2.

The present study includes the CO_2 and SO_X emissions in the model. IMO defined the Energy Efficiency Operational Indicator (EEOI). It is an expression of emission efficiency in the form of CO_2 emitted per unit of transport work [9]. The ECO_2 is given by Eq. 1, ECO_2 represents the amount of CO_2 emission released into the atmosphere, where j is the fuel type, FC is the mass of consumed fuel in kg, C_F is the fuel mass to CO_2 mass conversion factor in kg-CO_2/t-fuel, see Table 3. M is the cargo carried in tons and D is the travel distance in nautical miles. A higher value of this indicator denotes a lower efficiency

$$ECO_2 = \frac{\sum_j FC_j \times C_{Fj}}{M \times D}. \tag{1}$$

Today there is commercial software's used to estimate the EEOI value before the trip. Even though the indicator EEOI is not enough to measure the overall efficiency of ships, it indicates the amount of CO_2 released into the atmosphere.

The ESO_X is given by Eq. 2, ESO_X represents the amount of SO_X emission released into the atmosphere per unit of transport work, where j is the fuel type, FC is the mass of consumed fuel in kg, C_S is the fuel mass to SO_X mass conversion factor in kg-SO_X/t-fuel, see Eq. 3. M is the cargo carried in tons and D is the travel distance in nautical miles

$$ESO_X = \frac{\sum_j FC_j \times C_{Sj}}{M \times D}, \tag{2}$$

$$C_S = SF \times 20 \times VB, \tag{3}$$

where SF is the percentage of sulphur present in the fuel and VB is the volume of bunker in Tons of Fuel.

The ESO_X is in kg-SO_X/t-fuel and it depends on the type and sulphur content of the fuel used by the ship [13]. It has to multiply total bunker consumption by the percentage of sulphur present in the fuel and subsequently by a factor of 20 to compute SO_2 emissions. The 20 SO_X factor is exact and comes from the chemical reaction of sulphur and oxygen to produce SO_2. A higher value of this indicator denotes a lower efficiency.

The SF is calculated based on the actual sulphur content in the fuel, see Eq. 5. The dilution factor is calculated by the average quantity of sulphur content that depends on the type of bunker fuel (IFO or MDO) on-board and the quantity of the fuel in this operation in the port of refuel.

Table 2 Input and output values for laden and ballast conditions

Inputs	Outputs
Average daily speed (knots)	Total of cargo transported (tons)
Total consumption of fuel (IFO) (tons)	Total of fuel consumed (IFO) (tons)
Distance (nautical miles)	Total of emission (tons)
Cargo (tons)	
Average daily emissions (tons)	

The fuel quality can be altered depending on the refuelling port, which influences the quality of the bunker.

It is assumed that the average sulphur content (SF) for IFO and MDO are 2.5 and 0.25%, respectively, if the information about quality of fuel (sulphur content) is not available [3].

$$SF = ABQ \times ASC + RBQ \times RSC, \qquad (4)$$

where ABQ is the actual quantity of bunker on-board in tons, ASC is the percentage of concentration of SO_X of the bunker on-board, RBQ is the quantity of bunker to be refuelled in tons, RSC is the percentage of the average concentration of SO_X of bunker to be refuelled.

The models represent 360 days (1 year), and it is running for 200 iterations to verify the model convergence. Semi-random numbers have been altered between each iteration.

Currently in shipping market, the ships frequently sails in part-load condition and in different speed compared with design speed and not always with an efficient speed [8].

Model 1 represents the original (ORI) condition of the system and others models SS strategies. The main parameter to define the model is the speed. Model 2 represents the SS condition of the system where speed is decreased by 2 knots compared with the ORI model. Model 3 represents the USS condition of the system where speed is decreased by 4 knots compared with the ORI model.

The speed reduction values used in this paper are an outcome of the European Research project entitled *ULYSSES* of the 7th Framework Programme for Research and Technological Development [6]. The objective of this project that has been conduced between 2011 and 2013 was to demonstrate that the efficiency of the world fleet can be increased to a point where the following CO_2 targets are met, through a combination of USS and complementary technologies:

- Before 2020, reducing greenhouse gas emissions by 30% compared to 1990 levels;
- Beyond 2050, reducing greenhouse gas emissions by 80% compared to 1990 levels.

The *ULYSSES* project focused on bulk carriers and tankers, as these ship types produce 60% of the CO_2 from ocean-going vessels. The main results defined the requirements for USS, including technical, economic, safety and environmental factors.

In this study, the inputs parameters are fixed for laden (LC) and ballast (BC) conditions as well as for original, SS and USS strategies. Total consumption of fuel and average daily emissions parameters are modified due to speed effect. The simulation work flow used is the same for Original, SS and USS as shown in Fig. 2.
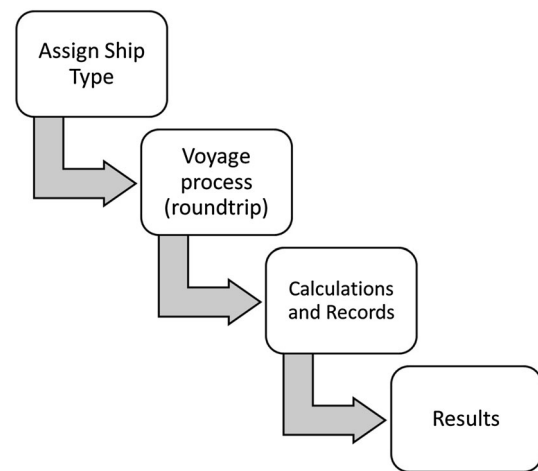

Fig. 2 Workflow of the voyage simulation of the bulk carrier fleet

In the simulation, the ships are created and initialized according to specific rules. It has been calculated based on the average travel time per year of whole ship fleet and the number of ships.

The average time between arrivals is about one every four days. Three sub-processes have been created to map the three ship categories defined before. Each of them is respecting the assignments sequence shown in Fig. 2.

As an illustration, Table 4 shows the distributions used to define the input parameters of ORI model of ship category 1.

The voyages implemented in each sub-process correspond to Eq. 5 where T_V is the voyage time distribution in days, D is the distance distribution in nautical miles, and S is the average daily speed distribution in nautical miles per day.

$$T_V = \frac{D}{S} \qquad (5)$$

The model estimate the information above mentioned as results, the total of cargo transported, the total of fuel consumed, the total CO_2 emission, and the total SO_X emission.

The following variables are evaluated for each ship and each iterations: L_T is the cargo transported, T_{FC} is the total fuel consumed, T_{CO_2} is the total CO_2 emission and T_{SO_X} is the total SO_X emission.

3 Results and discussion

The influence of SS and USS on the fleet of 13 bulk carrier ships is shown in this section.

The result for the three models is given in Table 5. We observe the amount of cargo transported (in tons) in each of the proposed alternatives (ORI, SS and USS), total

Table 4 Input distributions for ship category 1 ORI model for laden (LC) and ballast (BC) conditions

Parameter	Distribution	Mean	Standard deviation
Distance (nautical miles)	Log-normal	4934.76	4148.39
Total consumption of fuel (IFO) in BC (tons)	Log-normal	664.41	567.96
Total consumption of fuel (IFO) in LC (tons)	Log-normal	897.72	790.72
Average daily speed in BC (knots)	Normal	12.9	1.33
Average daily speed in LC (Knots)	Normal	11.56	1.11
Cargo in BC (tons)	Normal	72,344	14,130
Cargo in LC (tons)	Normal	169,614	10,578
Average daily emissions of CO_2 in BC (tons)	Normal	4.88	0.85
Average daily emissions of CO_2 in LC (tons)	Normal	2.82	0.75
Average daily emissions of SO_X in BC (tons)	Normal	7.61	1.56
Average daily emissions of SO_X in LC (tons)	Normal	4.3	1.31

Table 5 Result descriptions in tons for ORI, SS and USS models

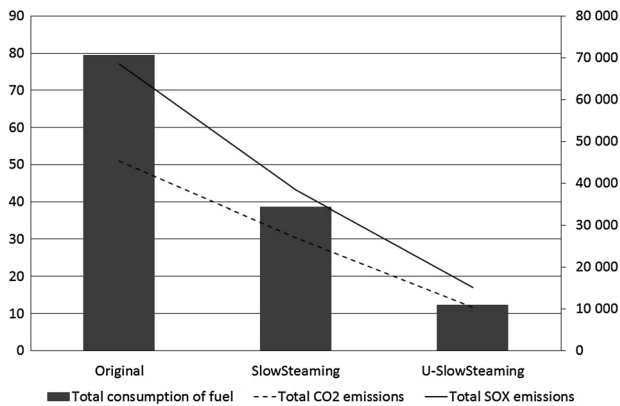| Results	ORI	SS	USS
Cargo transported	7,852,017	7,844,856	7,311,822
Total consumption of fuel	70,562	34,356	10,908
Total CO_2 emissions	51	30	12
Total SO_X emissions	82	43	17

Fig. 3 Total consumption of fuel in tons right y-axis and total consumption of emissions in tons left y-axis for ORI, SS and USS models

Fig. 4 Examples of average of fuel consumption (tons) reduction for ship category 1, 2 and 3, including the quantity of ships that are necessary to complete this simulation

consumption of fuel of the fleet (in tons), and the total of emissions (CO_2 and SO_X) in tons for a fixed period of 1 year.

The results show that the values of consumption decrease by 49 and 15% in SS and USS, respectively. The values of CO_2 emissions decrease by 60 and 23% in SS and USS, respectively. Finally, the values of SO_X emissions decrease by 43 and 13% in SS and USS, respectively, see Fig. 3.

Figure 4 shows the average of fuel consumption for each ship and the number of ships that leave the round trip in the simulation. The round trip represents a laden voyage
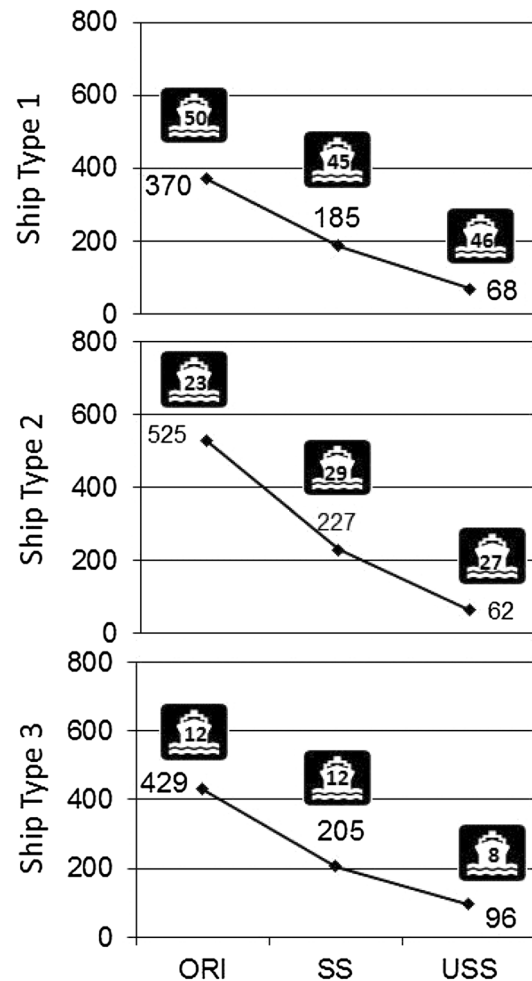
followed by a ballast voyage. That is important to analyse the advantage of SS and USS to each ship category. In all cases, USS strategy is the most advantageous.

Table 6 Cargo transported by the fleet and the percentage of cargo in the three navigation strategies

Model	Cargo transported (ton)	Percentage of cargo
ORI	7,852,017	100
SS	7,844,856	99.91
USS	7,311,822	93.12

The major disadvantage of SS strategy for shippers is the longer shipping times. This factor is associated with the cargo transported. In the model proposed the total cargo transported by each ship in SS and USS strategies is compared with the total cargo transported in original model. Consequently, to move the same amount of cargo (in same number of days), it would be necessary to use a larger number of vessels in the fleet.

The difference of the cargo transported between the models shows that the fleet needs one more ship to transport the same quantity of cargo in both proposed strategies (SS and USS), see Table 6. It is worth to mention that the extra waiting time that may suffer the freight owners due to the longer shipping time is not considered in this study. Moreover, the cargo considered in the study is only composed by minerals whereas cargo quality is not affected by extra shipping time. In the case of grains, beans, corns and cereals, this concern might be an issue that should be carefully examined.

This analysis is general, it considers the increase of ship in a global way. In future works, the economic analysis can be improved including the increment of ships with a separate analysis for each ship category to transport the same quantity of cargo in SS and USS strategies.

According to [2], to determine the sustainability of SS and USS strategies, the cost of added vessels to a service under this strategy as well as the increase in costs for shippers must be considered. Capital and Operational costs vary according to the number of vessels added and their characteristics.

Assuming the fuel price about 257 USD for a metric ton (Ship-Bunker, 2016), cost savings by fuel consumption of SS and USS are assessed, respectively, to 9.3 and 15.3 millions of USD annually as shown in Table 7.

Sea costs in shipping are composed of: Capital expenditure (CAPEX), Operational expenditure (OPEX) and Travel cost at sea. In this study, OPEX costs are based on Moore Stephens reports on ship operating costs, see Table 8 [20]. The CAPEX depends heavily on the ship price, which suffered large fluctuations in recent years. The CAPEX estimate (US$/day) considered three price scenarios for the 2006/2016 period, based on Clarksons data: Highest annual average, lower average annual and average for the period, see Table 9. The CAPEX estimate considers a 10% year of discount rate, a 2.62% year of Commercial Interest Reference Rates (CIRR)- 2016 average, 15 years of use-life.

Here, the Travel cost at sea (TCS) or running cost varies for ORI, SS and USS strategies. The TCS is composed by: fuel cost, port charges, channel crossing rates, commissions, cleaning holds and tanks, and other relate expenses. Considering that the ships take the same routes with the three ship categories, only fuel costs could be considered variables [11]. Therefore, the variations of fuel consumption are enough to take into account the variation of TCS.

Considering that the CAPEX price of a new bulk carrier vessel (see Table 9) is in average about $17,339 $USD/day,

Table 7 Annual costs and fuel consumption saving in USD and projection to the next 10 years

Description	ORI	SS	USS
Total annual fuel consumption (ton * 1000)	70.6	34.4	10.9
Annual cost of total fuel consumption ($mUSD)	$18.1	$8.8	$2.8
Annual saving of fuel consumption (ton * 1000)	–	36.2	59.7
Annual saving of fuel consumption ($mUSD)	–	$9.3	$15.3
Total saving of fuel consumption in 10 years ($mUSD)	$0	$93.0	$153.3
Total fuel consumption in 10 years (ton * 1000)	705.6	343.6	109.1
Total saving of fuel consumption in 10 years (ton * 1000)	–	362.1	596.5
Quantity extra of ships to fulfil the total cargo	0	1	1
Extra cost of extra ships—CAPEX ($mUSD)	$0.0	$63.3	$63.3
Extra cost of extra ships—OPEX ($mUSD)	$0.0	$27.5	$27.5
Extra annual of fuel consumption of extra ships ($mUSD)	$0.0	$0.11	$0.04
Extra fuel consumption of extra ships in 10 years ($mUSD)	$0.0	$1.06	$0.36
Total costs in 10 years ($mUSD)	$181.3	$180.2	$119.2
Total saving—costs in 10 years ($mUSD)	$0.0	$1.2	$62.1
Percentage of total costs in 10 years	100	99	66

Table 8 OPEX estimation, based on [20]

Description	Medium size	Highest size	Lowest size
OPEX estimation daily price ($USD/day)	$7303	$7507	$7650

Table 9 CAPEX estimation price, based on Clarksons database

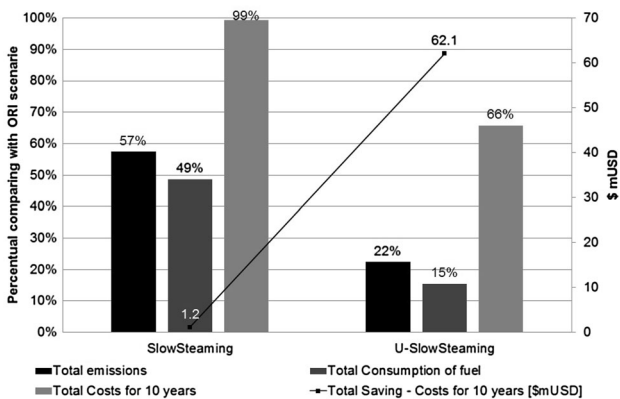| Description of CAPEX prices	Medium size	Highest size	Lowest size
Price ($mUSD)	59.7	97.0	43.0
CAPEX daily price ($USD/day)	$17,339	$28,173	$12,489

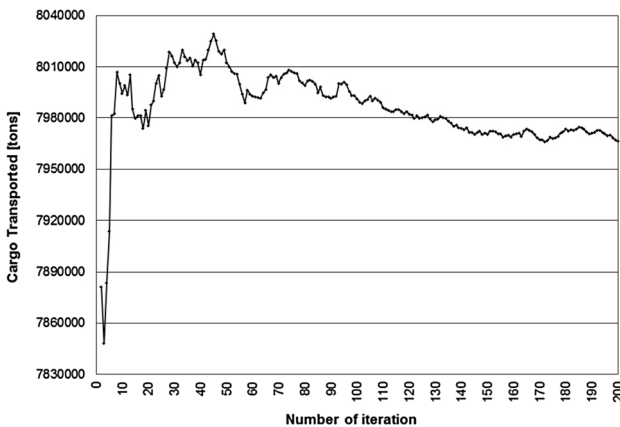**Fig. 5** Effectiveness analysis of SS and USS simulation

Fig. 6 Convergence of cargo transported in tons for the SS model

Table 10 Sensitivity analysis comparing the total cost for 10 years prediction by CAPEX variation

Cost of extra ships—CAPEX ($mUSD)	Total cost SS strategy (%)	Total cost USS strategy (%)
50.6	92	59
53.8	94	61
57.0	96	62
60.1	98	64
63.3	99	66
66.5	101	67
69.6	103	69
72.8	105	71
75.9	106	73

Table 11 Sensitivity analysis comparing the total cost for 10 years prediction by fuel price variation

Fuel price ($USD/ton)	Total cost SS strategy (%)	Total cost USS strategy (%)
206	112	78
218	108	75
231	105	71
244	102	68
257	99	66
270	97	63
283	95	61
296	93	59
308	91	57

the projection of CAPEX cost in 10 years is about $63.3 $mUSD. The annual costs and consumption saving can be assessed and projected on 10 years. Then, profitability of SS and USS can be evaluated, see Table 7 [25].

Figure 5 shows the effectiveness analysis of SS and USS simulation, in SS strategy. The emissions are reduced to 57 and 22%, the consumption of fuel is reduced to 49 and 15%, and the total cost in the next 10 year is reduced to 99 and 66%, respectively, in comparison with the ORI model.

The convergence is verified for each model, e.g. cargo transported convergence after 200 iterations is shown in Fig. 6. Semi-random numbers have been altered between

each iteration. Figure 6 presents in x-axis the number of iteration and in y-axis the value calculated in the simulation of cargo transported in tons. The three strategies are evaluated in 200 iterations each one with semi-random numbers automatically generated by the ARENA software.

This study considers a sensitivity analysis to show how the CAPEX and bunker value are affecting the total cost of the different strategies. Tables 10 and 11 show the results of a sensitivity analysis comparing the total cost for 10 years prediction by bunker price and CAPEX variation. This results indicate that the use of USS is more

profitable than SS and ORI. It is noticed that when the fuel price is low or the CAPEX is high the SS strategy may not be any more an efficient decision.

4 Conclusions

Main results evidenced the reduction of transported cargo by less than 8% for two conditions (SS and USS), while the total fuel consumption decreased by almost 51 and 85%, respectively.

This study prove that the speed reduction in USS strategy through just-in-time-arrival is possible without reducing the capacity of the maritime transport systems, with the increment of one ship unit. This paper shows that SS has reduced emissions by around 22% over 1 year; it fulfil the target of IMO.

Savings in operational costs, considering fuel consumption and emissions (CO_2 and SO_X) invites us to reflect on the number of extra vessels required to fulfil the cargo transport objective. Due to the need to increase the number of ships to move the same amount of cargo transported in the same time, USS is more profitable than ORI and SS conditions.

An important consideration for USS strategy is the fact that at this slow speed the engine might be not any more efficient. Therefore, it require additional investigations to confirm the viability of this scenario.

The findings of this study bring useful insights about different simulation approaches used as decision support systems in the field of navigation strategies. This study increment the literature about the use of DES focused on SS and USS for bulk carrier ships.

The models provide helpful insights for ship owners and tactical transportation planners.

This simulation contribute to the limited literature that uses SS with DES. This paper explores the use of DES as modelling tools used to support decision-making.

The use of DES can help to simulate scenarios with real historical data, assisting ship owners in making decisions about the number of ships in their fleet and establishing best operating strategies.

It is suggested that further research investigate the acquisition of new ships in the fleet to evaluate if it is necessary to buy one ship of each type or several of smaller ones. It would improve the economic evaluation in a future research.

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