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***Abstract* —Maritime accidents and incidents, such as ship to ship collision or ship grounding, most often occur near ports due to the intensive water traffic and shallow water depth. The occurrence of those accidents place a port in a very dangerous situation, since the port could suffer from a high risk of blockage of port entry, and the consequent economic loss can be substantial. In the case of maritime accidents, it is of great significance for sea-going ships outside of the accident zone to determine a safe and smooth sailing route and efficient speeds at a busy port, thus to reduce the risk of blockage and the economic loss of the port, whilst not disturbing the current emergency logistic response system. In this regard, a decision-making method for safe and smooth sailing route and efficient speeds for sea-going ships encountering an accident can be very valuable. Because of the high nonlinearity of these decisions, PSO algorithm is used to search the safe and smooth sailing route and efficient speeds. The study results show that the proposed method can effectively achieve the safe and smooth sailing route and efficient speeds for ships encountering an accident, thus to be more economic and reduce the risky chance of blockage of the port entry.**

Keywords—maritime accident; emergency response; route and speed optimization; PSO; busy port

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I. INTRODUCTION

Maritime transport is one of the most important players in facilitating international trade and maintaining global economy. Due to increasing demands and supplies, maritime transport has witnessed a huge increase in maritime traffic. According to a yearly report by United Nations Conference on Trade and Development (UNCTAD), there was an increase of 3.4% in the volume of world seaborne shipments in 2014, which resulted in a total trade volume of 9.84 billion tons constituting about 80% of the global sea trade volume [1-2].

With such growing traffic, it is imperative to study the marine traffic risk and develop technology to make marine transport safer and more efficient. Between 2011 and 2014, 9180 occurrences have been reported by the EU Member States [3]. According to EMSA, there have been 3025 reported accidents that involved 3,399 ships in 2014. In these accidents, 51 ships were lost, 1,075 people were injured and 136 fatalities were reported [3]. For some ports, maritime safety has become a major concern because of increasing traffic and lack of traffic management technology [4].

With the increasing maritime traffic and international trade over the years, many researches have been carried out to make maritime transport safer, less risky and more efficient. Major developments have been carried out in processes ranging from designing of ship, production methods and improved operational techniques which have reduced loss of vessels and life in the event of an accident [5]. In 2000, IMO introduced a regulation requiring all ships to carry automatic identification system (AIS) to provide information that may be used for navigation of ships. The AIS provides static, dynamic and voyage related data about the ship such as the dimension of ship, dynamic position of the ship, course and other information [6]. In the same year, IMO introduced the guidelines for Formal Safety Assessment (FSA). It is a structured and systematic methodology which uses risk analysis and cost benefit assessment to achieve the above goals. In their research on review of safety level and risk analysis of ship accidents, Eleftheria et al. show a schematic of the various steps involved in application of FSA [7].

Siljander et al. [8] have explored the use of Geographic Information (GIS) based methodology to determine a cost-distance model which can be used to strategically plan a Search and Rescue (SAR) operation. This methodology also helps in allocating proper SAR resource unit by determining the response time for each type of vessel during a particular wave height and wind condition. Ai et al. [9] addresses the location-allocation problem of emergency resources and configuration of salvage vessels in the event of maritime emergency. Their model coupled with Maximal Coverage Location Problem (MCLP) can be used to strategically locate emergency resources and achieve complete coverage of the emergency area with minimum cost and minimum facilities. Besides, Zheng et al. [10-11] studied the collision avoidance strategies for cooperative Waterborne AGVs and gave advanced model predictive control and predictive path following method on this topic, which is meaningful for the accidental avoidance.

The occurrence of maritime accidents would place the port in a very dangerous situation, since the port could suffer from a high risk of blockage of port entry, and the consequent economic loss can be substantial. Therefore, in addition to the above-mentioned emergency response and resource allocation for the ships in distress, avoiding the risks of maritime accidents for the sailing ship encountering an accident and determining the optimal sailing route and speeds of these ships should also be one of the important contents of ship navigation safety and port logistics emergency response. The determined optimal sailing route and speeds, can not only avoid maritime risks and the influence to the current emergency response units, but also reduce the losses due to the decline in throughput of the port.

II. Problem and Method

A. Problem

When an accident occurs at a busy port, there will be a high risk of blockage of port entry since the ship in the accident zone should get away from the accidental area and the patrol vessels and other emergency response units will come to deal with the accident. In this regard, it is of highly significance for sea-going ships to find a safe, smooth and cost-effective route, but not the straight route between position A and B although it is the shortest way. As is shown in Fig. 1, when a sea-going ship encounters a maritime accident, she could get the information from the data center or management institution, including the environment and waterway information, location of the accident zone and the location of the other ships. Then she should search the safe, smooth and cost-effective sailing route and speeds, so as to be safe and reduce the risk of delay and the loss of the throughput of the port, whilst not disturbing the emergency response system. In this process, the information acquisition and transmission based on Internet of Things technology are much important.

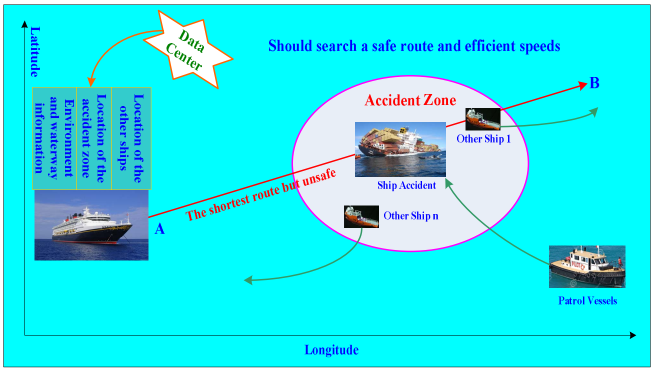

Fig. 1. Problem description of the safe and smooth sailing route and efficient speeds decision

B. Method

The whole area of the port can be divided into different sections by drawing the grids according to the longitudinal and altitudinal values. In this regard, the optimization problem can be transferred to search the sailing position of the grids between position A and B and decide the optimal sailing speed between the two adjacent grids, as illustrated in Fig. 2. The optimization target is to minimize the total fuel consumption under the sailing time limitation between position A and B, meanwhile, avoiding the accident zone and not disturbing the emergency logistic response system by excluding their positions when searching the safe sailing route.

In Fig. 2, the area can be divided into M grids according to the distance. In this case, the decision of the safe sailing route and efficient speeds will contain 2M-3 optimization variables, with the first M-1 variables ‘N’ as the optimal sailing speed between the two adjacent grids and the last M-2 variables ‘P’ as the sailing position of these grids. The constraints include the sailing time, position, engine speed and so on. The sailing time and fuel consumption are the nonlinear function of the variables ‘N’ and ‘P’. Therefore, it is a multi-constraints and variables nonlinear optimization problem.

The nonlinear optimization problem is very common in practical applications [12], but actual problems are complicated due to the lack of effective analysis solutions. Recently, many scholars have proposed various solutions for the nonlinear optimization problems from different standing points, such as the genetic algorithm, simulating the process of biological evolution of Darwin's genetic selection and natural selection [13], and the particle swarm optimization algorithm

(PSO). PSO algorithm is a kind of optimized computing technology based on iterative process. Recently, PSO has been applied in a wide range of optimization problems, such as berth allocation [14] and vehicle routing optimization [15], and displays very efficient performance. Compared with the genetic algorithm, PSO is easy to implement and there are few control parameters to be adjusted. Based on these facts, the PSO algorithm is adopted to solve the multi-constraints and multi-variables nonlinear optimization problem on the decision of safe and smooth sailing route and efficient speeds for the sea-going ship encountering an accident at busy port.

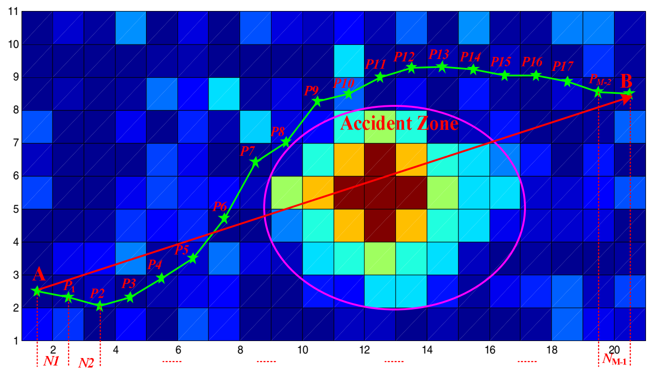

Fig. 2. Description of this optimization problem

PSO algorithm is initialized with a population of random solutions and potential solutions, which are called as "particles". Each particle is allocated with a random velocity initially, and its location is adjusted according to its own previous best (p_{best}) and the global best (g_{best}). Velocity change is weighted by random terms, with separate random numbers generated for acceleration toward two best solutions, p_{best} and g_{best}. The general procedures of PSO are described as follows:

1) Initialization. Generate a population of particles, and allocate a velocity to each particle randomly.

2) Evaluation. Compute the optimization fitness function and update the best locations of particles.

3) Velocity and location update. The location of each particle is changed by updating its own velocity, and the velocity update of a particle is dynamically changed. The updates of velocity and location of each particle can be realized through (1) and (2).

$$V^{k+1} = w\cdot V^k + c_1\cdot r_1({p_{best}}^k - X^k) + c_2\cdot r_2({g_{best}}^k - X^k) \quad (1)$$

$$X^{k+1} = X^k + V^{k+1} \quad (2)$$

where k denotes the number of iterations of the current; w denotes the inertia weight; p_{best} denotes the previous best; g_{best} denotes the global best; X denotes the location of the particle; V denotes the velocity of the particle; c_1 and c_2 denote the learning factors; and r_1 and r_2 denote the random numbers between 0 and 1.

In order to improve the accuracy of the algorithm, Equation (3) is used to obtain the w. At the beginning of iteration, the larger inertia weight can ensure the strong global search ability of the algorithm, and in later iterations, the lower inertia weight can guarantee the accurate local search of the algorithm [16].

$$w = w_{max} - (w_{max} - w_{min})\cdot it_{current} / it_{max} \quad (3)$$

where w_{max} denotes the maximum inertia factor; w_{min} denotes the minimum inertia factor; $it_{current}$ denotes the current iteration times; and it_{max} denotes the maximum iteration times.

4) Termination. Stop the algorithm if the stopping criterion is met; otherwise the algorithm loops back to step 2.

III. Model Establishment

Considering the fact that the ship fuel consumption is different under different navigation environment, we also should determine the optimal sailing speeds under different environment factors during the decided route, thus to reduce fuel consumption and meet the constraint of sailing time.

A. Fuel consumption

The energy consumption of the ship main engine is mainly used for the overcoming of the ship sailing resistance. When the ship is sailing at a certain speed, the main engine should output enough power to drive the propeller in order to push the ship forward and overcome the resistance [17]. The propeller thrust can be shown as (4).

$$T_{prop} = \frac{T_{eff}}{(1-t)\cdot k} = \frac{R_{ship}}{(1-t)\cdot k} = K_T \times \rho n^2 D^4 \quad (4)$$

where, T_{prop} is propeller thrust; T_{eff} is the effective thrust of the propeller, which is equal to the resistance exerted on the hull; t is thrust deduction coefficient; k is the number of propellers; R_{ship} denotes the total ship resistance; K_T is the thrust coefficient of propeller; ρ is the density of the water; n is the propeller speed; D is diameter of the propeller.

Then, the main engine power P_b can be expressed by (5) [17].

$$P_b = \frac{R_{ship}\cdot V_S}{k\cdot\eta_S\eta_G\eta_O\eta_H\eta_R} = \frac{R_{ship}\cdot V_S\cdot K_Q\cdot 2\pi\cdot(1-w)}{k\cdot\eta_S\eta_G\eta_R\cdot K_T\cdot J\cdot(1-t)} = \frac{2\pi\cdot\rho\cdot n^3\cdot D^5\cdot K_Q}{\eta_S\eta_G\eta_R} \quad (5)$$

where, V_s is ship sailing speed; η_S is transmission efficiency of the shaft; η_G is the efficiency of the gearbox; η_O is open water efficiency of the propeller; η_H is the hull efficiency; η_R is relative rotating efficiency; w is wake coefficient; J is the propeller advance coefficient; K_Q is the torque coefficient.

Above all, we can get the fuel consumption of the main engine per unit distance, as showed in (6).

$$q_{main} = \frac{2\pi\cdot\rho\cdot n^3\cdot D^5\cdot K_Q}{\eta_S\eta_G\eta_R Vs}\cdot g_{main} = \frac{2\pi\cdot\rho\cdot n^2\cdot D^4\cdot K_Q\cdot(1-w)}{\eta_S\eta_G\eta_R\cdot J}\cdot g_{main} \quad (6)$$

where, q_{main} is the fuel consumption of the main engine per unit distance; g_{main} is the specific fuel consumption rate of the main engine.

In addition, the energy consumption of the ship also includes fuel consumption of auxiliary equipment and the cost of ship sailing due to the prolonged sailing time. Therefore, the total fuel consumption per unit distance can be shown as (7), in which the fuel consumption of the auxiliary equipment can be obtained by (8).

$$Q = q_{main} + q_{auxi} + q_{other} \tag{7}$$

$$q_{auxi} = P_{auxi} \cdot g_{auxi} \tag{8}$$

where, q_{auxi} is the fuel consumption of the auxiliary equipment; q_{other} denotes the fuel consumption per unit distance transformed from the additional cost brought by the prolonged sailing time; P_{auxi} is the output power of the auxiliary equipment; g_{auxi} is the specific fuel consumption rate of the auxiliary equipment.

All in all, the total fuel consumption between position A and B can be obtained by (9).

$$Q_{total} = \sum_{i=0}^{m}(Q_{i,i+1} \cdot S_{i,i+1}) = \sum_{i=0}^{m}\left(g(n_{i,i+1}) \cdot \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2} \cdot S_0\right) \tag{9}$$

where, Q_{total} denotes the total fuel consumption between position A and B; $Q_{i,i+1}$ denotes the fuel consumption between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}); $S_{i,i+1}$ denotes the sailing distance between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}); $g(\cdot)$ is another expression of (7), which is the function of the engine speed $n_{i,i+1}$ between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}); S_0 is the length and width of one grid, 900 m in this paper.

B. Sailing time

The total sailing time can be obtained by adding the time spent on each sections between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}), which is shown in (10).

$$T_{total} = \sum_{i=0}^{m} T_{i,i+1} = \sum_{i=0}^{m} (S_{i,i+1} / V_{i,i+1}) = \sum_{i=0}^{m} \left(S_{i,i+1} / f(n_{i,i+1})\right) \tag{10}$$

where, T_{total} denotes the total time between position A and B; $T_{i,i+1}$ denotes the sailing time between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}); $V_{i,i+1}$ denotes the sailing speed between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}), which can be expressed by $f(\cdot)$, which is also the function of the engine speed $n_{i,i+1}$ between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}).

C. Optimization model

Therefore, the problem of determining a safe and smooth sailing route and optimal speeds for the sea-going ships outside of the accident zone can be described by the established optimization model, as showed in (11).

$$\begin{cases} \min \; Q_{total} = \sum_{i=0}^{18}(Q_{i,i+1} \cdot S_{i,i+1}) = \sum_{i=0}^{18}\left(g(n_{i,i+1}) \cdot \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2}\right) \\ s.t \quad \sum_{i=0}^{18}\left(S_{i,i+1} / f(n_{i,i+1})\right) < T_{\text{limit}} \\ \quad 300 < n_{i,i+1} < 700 \\ \quad g(n_{i,\,i+1}) > 0 \\ \quad f(n_{i,\,i+1}) > 0 \\ \quad P_i(x_i,\, y_i) \neq P_{i0}(x_{i0},\, y_{i0}) + \omega_0 \end{cases} \tag{11}$$

where, T_{limit} denotes the sailing time limitation between position A and B; $n_{\min}$ denotes the minimal engine speed and $n_{\max}$ denotes the maximal engine speed; P_{i0} (x_{i0}, y_{i0}) denotes the positions in the accident zone or the positions of other ships and ω_0 means the margin of the accident zone considering the inertia of the hull when ship is sailing.

IV. Optimization Implement Based on the PSO Algorithm

A. Encoding and initialization of particles

In this paper, 50 particles are totally initialized, and each particle is of 2M-3-dimensional. The first M-1-dimensional of the particles correspond to the sailing speeds, and the last M-2-dimensional of the particles correspond to the ship's positions during each sailing section, as is shown in (12).

$$\begin{aligned} &\text{Paticle 1:} \; (N_1, N_2, N_3, \cdots\cdots, N_{M\text{-}1}, P_1, P_2, \cdots\cdots, P_{M\text{-}2}) \\ &\text{Paticle 2:} \; (N_1, N_2, N_3, \cdots\cdots, N_{M\text{-}1}, P_1, P_2, \cdots\cdots, P_{M\text{-}2}) \\ &\qquad \cdots\cdots \qquad\qquad \cdots\cdots \\ &\text{Paticle 49:} \; (N_1, N_2, N_3, \cdots\cdots, N_{M\text{-}1}, P_1, P_2, \cdots\cdots, P_{M\text{-}2}) \\ &\text{Paticle 50:} \; (N_1, N_2, N_3, \cdots\cdots, N_{M\text{-}1}, P_1, P_2, \cdots\cdots, P_{M\text{-}2}) \end{aligned} \tag{12}$$

B. Numerical simulation of fuel consumption and sailing time

Due to the complexity of calculation of the fuel consumption and sailing time, an numerical simulation model of fuel consumption and sailing time is established based on 'Simulink', including the model of main engine, propeller, transmission system, ship resistance and fuel consumption and sailing time, as showed in Fig. 3.

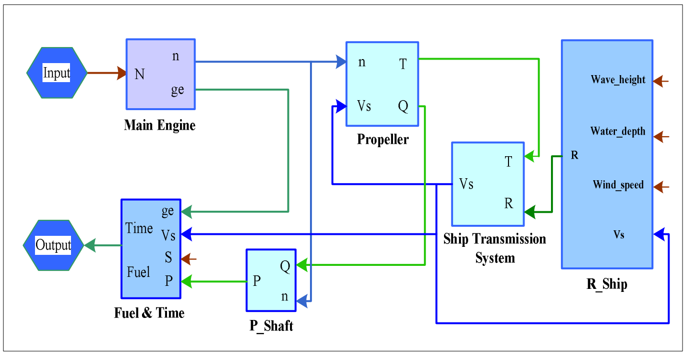

Fig. 3. Numerical simulation model of fuel consumption and sailing time

C. *Optimization process*

The optimization process of the ship's optimal speed and route based on PSO is shown in Fig. 4, described as follows:

1) Initialize particles and calculate fitness value of each particle by calling the numerical model in Fig. 3, namely, the total fuel consumption sailing from position A to position B. And determine the individual optimal and group optimal value.

2) Update positions of the particles, recalculate the fitness values of each particle and calculate the navigation time and other constraints. If the constraints are not satisfied, the update is invalid and it will be re-updated. If satisfied, then update the individual optimal value and population optimal value.

3) The iterative process is repeated until the algorithm converges or reaches the pre-set maximum number of iterations. When the algorithm ends, the optimal individual can be obtained. That is to say, the optimal sailing speeds and route are obtained.

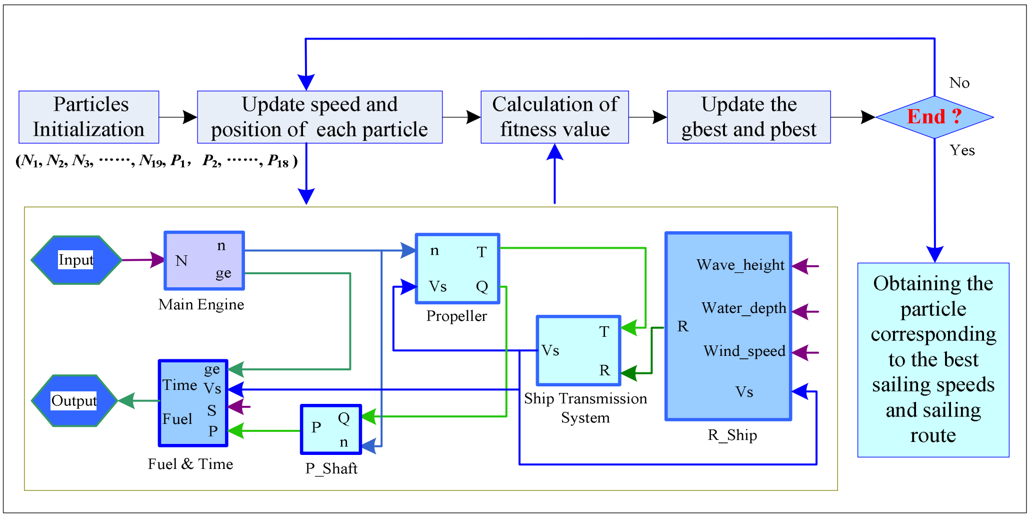

Fig. 4. Optimization process for ship sailing speeds and route based on PSO

V. NUMERICAL STUDY

A. *Study case*

This study focuses on the decision of safe sailing route and efficient speeds for sea-going ships encountering accidents, especially at the busy ports like 'Rotterdam Port', which has a lot of ship entries and therefore has more possibility to occur accidents like ship collision and sinking. In addition, the blockage in these ports will certainly cause substantial economic loss. The parameters of the PSO-based method for safe sailing route and efficient speeds decision are shown in Table 1.

TABLE I. PARAMETERS OF THE PSO ALGORITHM

c_1	c_2	w_{max}	w_{min}	it_{max}	M	m
2	2	0.9	0.4	800	20	18

B. *Optimization results*

After iteration of 459 steps, the algorithm converges, as showed in Fig. 5. As a result, the obtained optimal sailing route is illustrated in Fig. 6; Fig. 7 gives the obtained optimal engine speeds of each sections; Fig. 8 shows the corresponding fuel consumption and sailing time of each section; In this case, the total fuel consumption of the ship sailing from position A to position B is 198.82 Kg.

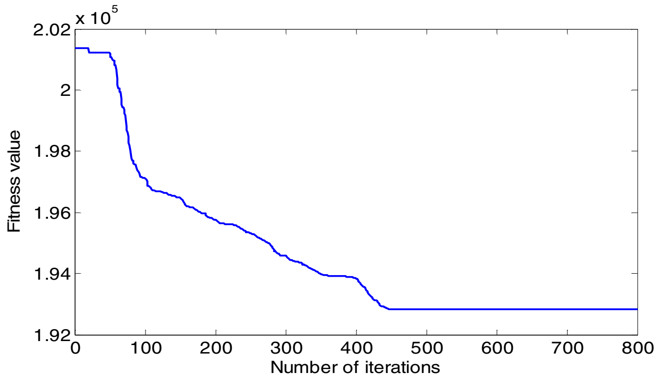

Fig. 5. The iterative values of each step

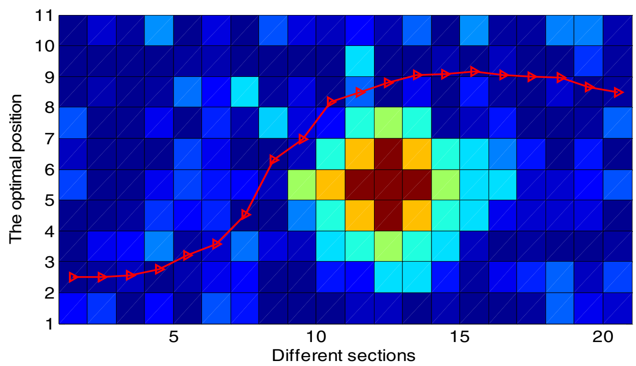

Fig. 6. The obtained optimal sailing route

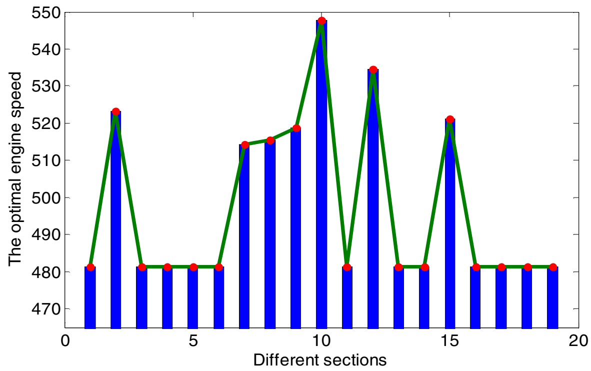

Fig. 7. The optimal speeds in different sections

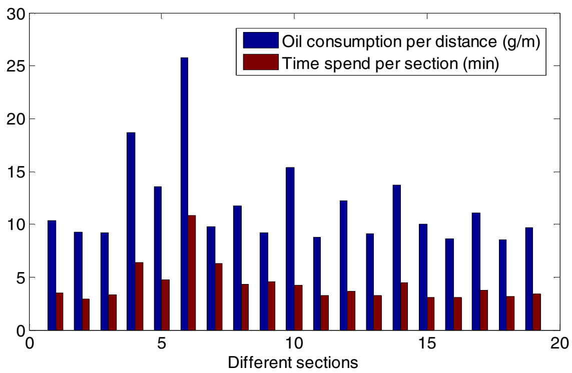

Fig. 8. The oil consumption and sailing time in different sections

VI. Conclusions

In the case of maritime accidents, it is of great significance for the sea-going ships outside of the accident zone to determine a safe and smooth sailing route and efficient speeds at a busy port. In this paper, from the point of view of the safety and energy consumption of ships encountering an accident, the optimization method based on the PSO algorithm is proposed to optimize the sailing route and reduce the loss of the ship and the harbor, in which the environmental factors, the position of other ships and the accident area are considered synthetically. Through the established model and the PSO algorithm, the optimal route of the ship in the port and the optimal speeds of each section can be obtained. The results show that this method can ensure the ship to enter and leave the port within the stipulated time and ensure the fuel consumption of the ship is the lowest, whilst not affecting the emergency response mechanism of the accident area. It can ensure the port's throughput and reduce other losses of the ship outside of the accidental area and the port.

Acknowledgement

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