TransNav
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 8
Number 4
December 2014
DOI: 10.12716/1001.08.04.09

Ship Route Design for Avoiding Heavy Weather and Sea Conditions

Y. Cai & Y. Wen
School of Navigation, Wuhan University of Technology, Wuhan, China
Hubei Inland Shipping Technology Key Laboratory, Wuhan, China

L. Wu
School of Navigation, Wuhan University of Technology, Wuhan, China
Hubei Inland Shipping Technology Key Laboratory, Wuhan, China
Department of Earth Science, Uppsala University, Uppsala, Sweden

ABSTRACT: This paper covers the current state of maritime oil transportation in the Baltic Sea and the development of oil transportation in the 2000s, as well as estimations of transported oil volumes in 2020 and 2030 in the Gulf of Finland. The scenarios were formulated on the basis of a current state analysis, energy and transportation strategies and scenarios and expert assessments. The study showed that the volumes of oil transportation in the Gulf of Finland will increase only moderately compared to the current status: 9.5-33.8 %, depending on the scenario. Green energy policy favours renewable energy sources, which can be seen in the smaller volumes of transported oil in the 2030 scenarios compared to the 2020 scenarios. In the Slow development 2020 scenario, oil transport volumes for 2020 are expected to be 170.6 Mt (million tonnes), in the Average development 2020 187.1 Mt and in the Strong development 2020 201.5 Mt. The corresponding oil volumes for the 2030 scenarios were 165 Mt for the Stagnating development 2030 scenario, 177.5 Mt for the Towards a greener society 2030 scenario and 169.5 Mt in the Decarbonising society 2030 scenario.

1 INTRODUCTION

Almost 90% of the world’s trades are carried by ships, and for the vast majority of these trades, there are few or no alternatives to transporting by ships. This resulted in the increased capacities of the ships. Besides, the schedules are also tightened. At the same time, the requirements for ship routing become more strict and the weather forecasts become more significant in the weather routing.

Ship routing determines a route to sail between a starting place and a destination. The great circle sailing should be the shortest voyage if the ocean is =calm=. However, the navigational environment is far more complex, the strong wind, waves and ocean currents may severely affect ships' safety, speed, fuel consumption in bad conditions. Thus the problem of how to design a safe-economic route is a key consideration in weather routing.

The problem is that how to apply the results of the weather forecast and marine forecast into ship routing is kernel in weather routing. One of the most important processes of weather routing is the calculation of environmental factors. So this paper focuses on summarizing the research progress in calculation of environmental factors.

Firstly, the paper introduces the effects of environmental factors (wind, waves, currents), and secondly mainly describes the dangerous phenomena in the bad sea conditions. Finally, it summarizes the research progress in calculating the environmental factors and points out the direction of developments in the future.

2 EFFECTS OF ENVIRONMENTAL FACTORS

Important environmental factors in ship routing are those elements such as the atmosphere and ocean which may produce a change in the status of a ship transit. In ship routing, wind, waves, fogs, ice, and ocean currents should be considered. Their effects on ship navigation are analyzed in detail in this section.

2.1 *Effects of wind*

The effect of wind speed on ship performance is difficult to determine. In light winds (less than 20-knots), ship loss speed in headwinds and gain speed slightly in following winds. For higher wind speeds, ship speed is reduced in both head and following winds. This is due to the increased wave actions, which even results in increased drag from steering corrections in following seas, and indicates the importance of sea conditions in determining ship performance.

2.2 *Effects of wave*

Wave height is the major factor that affects ship performance. Wave action is responsible for ship motions which reduce propeller thrust and cause increased drag from steering corrections. The relationship of ship speeds to wave direction and height is similar to that of wind. In heavy waves, exact performance may be difficult to predict because of the adjustments to course and speed for ship handling and comfort. Although the effect of wind wave and swell is much greater for large commercial vessel than that of wind speed and direction, it is difficult to separate the two in ship routing.

2.3 *Effects of current*

Ocean currents do not present a significant routing problem, but they can be a determining factor in route selection and diversion. This is especially true when the points of departure and destination are at relatively low latitudes. The important considerations to be evaluated are the difference in distance between a great-circle route and a route selected for optimum current, with the expected increase in SOA from the following current, and the decreased probability of a diversion for weather and seas at the lower latitude.

Direction and speed of ocean currents are more predictable than wind and seas, but some variability can be unexpected. Major ocean currents can be disrupted for several days by very intense weather systems such as hurricanes and by global phenomena such as El Nino.

2.4 *Forecast of the environmental factors*

The weather forecast is vital to the weather routing. There are many numerical forecast model have been applied into the research of weather routing, including MM5, WRF, SWAN, WW3, POM. The models are commonly used in practice.

MM5 and WRF are atmosphere models, the model results mainly include surface winds, pressure, and temperature (Grell, 1995; Skamarock, 2005). SWAN and WW3 are wave models, and the model results are significant in terms of wave height, wave length, wave period, wave direction, frequency, and so on (SWAN team,2009; Tolman, 2002). POM is the ocean model, which is a three-dimensional primitive equation model. The model calculates these components of current velocity, salinity, temperature, turbulence kinetic energy, turbulence length scale, and free surface elevation as prognostic variables (Mellor, 1998). Besides, there is a distributed coupled atmosphere-wave-ocean model which had been firstly developed by Wuhan University of Technology in China (Huang, 2005; Zhang, 2006). The coupled model can simulate and forecast the wind field, the wave field and the current field at the same time, which is implemented by three independent models: atmosphere model (MM5), wave model (WW3), ocean Model (POM).

3 HAZARDS TO SHIPS IN HEAVY WEATHER AND SEA CONDITION

When sailing in adverse weather conditions, a ship is likely to encounter various kinds of dangerous phenomena, which may lead to capsizing or severe roll motions causing damage to cargo, equipment and persons on board. In following section the individual hazards due to ship motions are explained together with the relevant physical phenomena.

3.1 *Large angles of roll*

It's hard to quantize large angles of roll which depends on ship characteristic, type and size. In general, a large roll angle is defined as a roll angle which leads to one of the following events: capsizing; cargo shift or loss of cargo; failure of important ship systems; any situation which leads to an even large roll angle.

The occurrence of large roll angles is therefore an even which causes high financial losses up to the total loss of the ship. The reasons for the occurrence of large roll angles may be following: parametric roll motions; synchronous roll motion; reduction of intact stability when riding a wave crest amidships.

In a natural seaway, all effects do always appear in any possible combination. It is possible that the combination of these effects leads to an amplification of roll motion. These effects are described in the following.

3.1.1 *Parametric roll motion*

Parametric roll motion with large and dangerous roll amplitudes in waves are due to the variation of stability between the position on the wave crest and position in the wave trough. Parametric roll may occur in two different situations:

1 The stability varies with an encounter period T_E that is about equal to the roll period T_R of the ship (1:1 resonance). This situation is only possible

in following seas at relatively high speeds. As the roll damping is normally high at that speeds, it is only at very low values of stability possible that critical roll angles occur. Due to the tendency of retarded up-righting from the large amplitude, the roll period T_R may adapt to the encounter period to a certain extent, so that this kind of parametric rolling may occur with a wide bandwidth of encounter periods. In quartering waves a transition to harmonic resonance may become noticeable.

2 The stability varies with an encounter period T_E that is approximately equal to half the roll period T_R of the ship (2:1 resonance). This situation is met when two pitch cycles coincide with one roll cycle, and it is the most dangerous situation, because the wave crest is always amidships when the ship is in an upright position. In this situation, the ship may heel to one side.

If the ship travels in following seas, 2:1 resonance can only be met at relatively low values of stability in low ship speeds. Due to the low stability, the transversal accelerations may not be that large, but large roll angles may occur, which can lead to capsizing. Ship's natural roll period may strongly vary if the ship travels in following seas. Because the natural roll period depends on the stability of the ship, and the stability alterations become larger.

If the ship travels in head seas, 2:1 resonance is met at relatively large values of stability at small ship speeds. Due to the large stability and the short times on the wave crest, large roll angles are hardly possible, but large accelerations can be found quite often. Because the roll period of ship does not vary as much as in following seas, the resonant situation is more pronounced and it is more difficult to actually meet a 2:1 resonance situation in head seas.

3.1.2 *Synchronous roll motion*

Large rolling motions may be excited when the natural rolling period of a ship coincides with the encounter wave period. In case of navigation in following and quartering seas this may happen when the transverse stability of the ship is marginal and therefore the natural roll period becomes longer.

3.1.3 *Reduction of intact stability when riding a wave crest amidships*

When a ship is riding on the wave crest, the intact stability can be decreased substantially according to the changes of the submerged hull form. This stability reduction may become critical for wave lengths within range of 0.6L up to 2.3L, where L is the ship's length in meters. Within this range the amount of stability reduction is nearly proportional to the wave height. This situation may occur either in head or in following seas. The latter situation is particularly dangerous, because the duration of riding on the wave crest, which corresponds to the time interval of reduces stability, becomes longer.

The master shall avoid situations where the encounter period equals one time or two times the natural roll period of the vessel. As counter measures the guidelines propose to reduce the ship speed or to alter course and speed in such a way that resonant situations for the given period of the sea state can be avoided.

3.2 *Large accelerations*

Large accelerations are defined as accelerations which lead to the following events: massive cargo loss or cargo damages; heavy damages at machinery systems or vital safety systems; structural overload of safety relevant structural members; injuries to the crew. It is obvious that large acceleration lead to heavy damages to the ship and potentially to crew, but not necessarily to the total loss of the ship.

It must be pointed out that large accelerations do not necessarily coincide with large roll angles and vice versa. Even at relatively small roll angles, large accelerations can occur if the stability is large enough or if a 2:1resonance in head seas is met.

3.3 *Surf-riding and broaching-to*

Surf-riding and broaching-to occurs in following seas if ship travels on a steep wave crest. Typically the speed of a wave equaling ship length is larger than the ship speed, and the wave overtakes the ship. In such a situation it is possible that the overtaking wave accelerates the ship in such a way that it starts to ride on that wave (surf-riding). If this situation is combined with insufficient stability on the wave crest, the ship may capsize or experience large roll angles. Surf-riding also increases the time interval when the ship remains in the crest position.

On the other hand the danger exists that the ship broaches after surf-riding. The main root of that failure mode is yawing moment introduced into the ship (by the waves) or insufficient course keeping ability. Due to the wave induced velocities, the relative flow speed to the ship's rudder is significantly decreased, which decrease the manoeuvrability of the ship further. The large yawing motion connected to broaching-to cause large centrifugal forces, which can lead to the capsizing of the ship.

Broaching-to problems are not really problems connected to intact stability failures, because broaching-to cannot be avoided by moderating alterations of the stability. It is more a manoeuvring problem in waves.

3.4 *Combination of various dangerous phenomena*

The dynamic behavior of a ship in following and quartering seas is very complex. Ship motion is three-dimensional and various detrimental factors or dangerous phenomena like additional heeling moments due to deck-edge submerging, water shipping and trapping on deck or cargo shift due to large roll motions may occur in combination with the above mentioned phenomena, simultaneously or consecutively. This may create extremely dangerous combinations, which may cause ship capsize.

4 SHIP ROUTE DESIGN FOR AVOIDING THE HEAVY WEATHER AND WAVE CONDITIONS

When sailing in heavy weather and sea conditions where there are rough seas and strong wind, ship may encounters several hazards. So how to design ship route for avoiding the heavy weather and sea conditions is very significant to guarantee the safety of crew and ship. One of the most important processes of weather routing is the calculation of environmental factors, so the calculation of environmental factors is our key consideration. But even careful weather routing cannot avoid the fact that the ship may sometimes experience rough weather and sea conditions. Therefore, in this section, we also focus on how to avoid the hazardous phenomena in the heavy weather and sea conditions except the calculation of environmental factors.

4.1 *The calculation of environmental factors*

In the present research, the calculations of environmental factors mainly focus on added resistance and ship speed loss. The first section summarize the methods to calculate added resistance, in the second section the speed loss is discussed.

4.1.1 *The calculation of added resistance*

4.1.1.1 Added resistance/force due to wind

The earliest method to calculate wind force is suggested by Hughes in 1930, the expression as follow:

$$F_a = q \cdot C_a \cdot (\mathrm{A}_T \cdot \cos^2\theta + \mathrm{A}_L \cdot \sin^2\theta)$$

where F_a is wind force, q is wind pressure, C_a is the coefficients of wind force, A_T is orthographic projection area of the ship above water, θ is relative bearing of wind, A_L is lateral projection area of the ship above water.

$$X_{WF} = C_{WX}(\gamma_R)\frac{1}{2}\rho_a A_f V_{rel}^2$$

$$Y_{WF} = C_{WY}(\gamma_R)\frac{1}{2}\rho_a A_S V_{rel}^2$$

$$N_{WF} = C_{WN}(\gamma_R)\frac{1}{2}\rho_a A_S L V_{rel}^2$$

where X_{WF}, Y_{WF} and N_{WF} are the ahead force, the side force and the yaw moment, respectively. C_{WX}, C_{WY} and C_{WN} are the drag coefficients of the wind forces. γ_R is the coefficient of the relative wind incident angle. The longitudinal and the lateral projected areas of the ship on the wetted area are denoted as A_f and A_S, respectively. ρ_a is the air density and L is the ship length. It is noted that V_{rel} is the relative velocity between the wind and the ship.

4.1.1.2 Added resistance due to wave

The mean added resistance in an irregular wave field is given by twice the area under the spectrum,

$$R_{AW} = 2\sqrt{m_0}, \quad m_0 = \int_0^\infty S_R^{AW}(\omega_e)d\omega_e .$$

The appropriate relation to determine the response spectrum can be modified as (Panigrahj,2012):

$$S_R^{AW}(\omega_e) = \frac{R_{AW}}{\zeta_W^2} S_W(\omega_e) .$$

where R_{AW} is added resistance in monochromatic waves, ω_e is the frequency of encounter, S_R^{AW} is the added resistance spectrum, S_W is clam water resistance, ζ_W is wave amplitude.

Furthermore, a simplified formulation for added resistance suggested by Bhattacharya can be plugged into the calculations,

$$R_{AW} = \frac{\omega_e^3}{2g}(\mathrm{b}_z \mathrm{z}_a^2 + \mathrm{b}_\theta \theta_a^2)$$

$$\omega_e = \omega(1 - \frac{V\omega}{g}\cos\beta)$$

where z_a and θ_a are heave and pitch displacements for corresponding heave (b_z) and pitch (b_θ) damping, V is the ship speed, ω is the absolute wave frequency, β is the ship heading with respect to the waves.

4.1.1.3 Added resistance due to current

The equations of the relative velocities between a ship in the body-fixed coordinate system and ocean surface currents in the inertial coordinate system is briefly defined as follows (Yu-Hsien,2013):

$$\frac{dx}{dt} = v\sin\theta + \mu\sin q_c$$

$$\frac{dy}{dt} = v\cos\theta + \mu\sin q_c$$

where V_c is the current speed, α_c is the attack angle between the current incidence and the body-fixed coordinate system.

Subsequently, the current forces for a ship can be represented as the following formulae:

$$F_{cx} = \frac{1}{2}\rho(\mathrm{V}_{cx}^2 + \mathrm{V}_{cy}^2)\,\mathrm{BdC}_{cx}(\alpha_{cr})$$

$$F_{cy} = \frac{1}{2}\rho(\mathrm{V}_{cx}^2 + \mathrm{V}_{cy}^2)\,\mathrm{LdC}_{cy}(\alpha_{cr})$$

$$N_c = \frac{1}{2}\rho(\mathrm{V}_{cx}^2 + \mathrm{V}_{cy}^2)\,\mathrm{LdC}_{cn}(\alpha_{cr})$$

where $\alpha_{cr} = \arctan(\frac{V_{cy}}{V_{cx}}) - \psi$ C_{cx}, C_{cy} and C_{cn} are the drag coefficients of ocean currents, which are determined by the coefficient of the relative current incidence, α_{cr}. ψ is the ship heading angle in the inertial coordinate system. B is the width of a ship on the wetted surface.

4.1.2 *The calculation of speed loss*

4.1.2.1 Speed loss due to wind

High winds will have a greater adverse effect on a large, fully loaded container ship or car carrier than a fully loaded tanker of similar length. This effect is most noticeable when docking, but the effect of beam winds over several days at sea can also be considerable (Bowditch, 2002). The effect of wind speed on ship performance can be calculated as follows (Chiang, 2004):

$$V_w = V\sqrt{\frac{C_a \bullet \gamma_a \bullet A}{C_w \bullet \gamma_w \bullet B}}$$

where V_w is the increment or decrement of ship speed due to the wind force, V is the wind speed, C_a is the air drag coefficients, γ_a is the air specific gravity, C_w is the sea water resistance coefficient, γ_w is the sea water specific gravity, A is the side projection area of the hull on the waterline, B is the side projection area of the hull under the waterline.

4.1.2.2 Speed loss due to wave

When the ship is travelling in the ocean, she experiences the wave with variable height and direction hindering the ship's speed. The effective speed on the ship is estimated using the relationship between ship's speed and wave characteristic by James (Panigrahj, 2008).

$$V = V_0 - [\alpha_1 + \alpha_2 \cos(\beta - \alpha)]\mathrm{H}$$

where V is the effective speed, α is the ship's course, β is the direction from which the waves are coming. α_1 and α_2 are constants taken from James (1959), V_0 versus H curve.

Some researchers also propose new formula, according to their research results. The formula is expressed as follows (Tsou,2013):

$$V = V_0 - (0.745\mathrm{h} - 0.257qh)(1.0 - 1.35\times10^{-6}\,\mathrm{DV}_0)$$

where V is the actual speed in the sea, V_0 is the speed in calm water, h is the wave height, q is the angle between ship heading and wave direction, D is the actual displacement of the ship (tons).

Both of the two methods mentioned above mainly consider wave height and wave direction. There are also some methods consider other characteristic of wave expect wave height and wave direction, when calculating the speed loss. The formula is expressed as follows (Chiang, 2004):

$$V_v = \gamma_h \bullet h \bullet \mu_h$$

$$\gamma_h = \lambda / L$$

$$\mu_h = \omega / \lambda$$

where V_v is the increment or decrement of ship speed due to the wave, γ_h is the coefficient of significant wave height, λ the wave length, L is the ship's length over all, h is the significant wave height, μ_h is the multiple coefficient, ω is the frequency.

4.1.2.3 Speed loss considering various factors

There are also some methods to calculate the speed loss considering various factors in the present research. One of these methods considering the effects of wave and current is described as follow (Chen, 1978):

$$\frac{dx}{dt} = v\sin\theta + \mu\sin q_c$$

$$\frac{dy}{dt} = v\cos\theta + \mu\sin q_c$$

where $(\mathrm{x}_1, \mathrm{x}_2)$ are rectangular coordinates, μ is the speed of current, θ is ship heading, q_c is current direction, q_w is wave direction, v is ship speed which can be obtained by following formula:

$$v = v_0 - (ah + bh^2) + kq_w$$

where v_0 is still water speed, h is wave height, a, b, k are practical coefficients.

Other methods to calculate speed loss considering wave and current are quite similar to the one shown above and are therefore omitted.

However, these are a method to calculate speed according to total resistance which caused by environmental factors, including clam water resistance and added resistance. The formula expressed as follows (Yu-Hsien,2013):

$$V_r = (\mathrm{V}^3 - 2\frac{F_A(\mathrm{V})\mathrm{V}}{\rho S C_R})^{1/3}$$

V_r is reduce speed , V is clam water speed, $F_A(\mathrm{V})$ is the total resistance, ρ is the water density, S is the wetted surface of the hull, C_R is the coefficient of clam-water wave resistance.

4.2 *How to avoid dangerous conditions*

4.2.1 *For surf-riding and broaching-to*

Surf-riding and broaching-to may occur when the angle of encounter is in the range 135°<α<225° and the ship speed is higher than $(1.8\sqrt{L})/\cos(180-\alpha)$ (knots). To avoid surf riding and possible broaching-to, the ship speed, the course or both should be taken outside the dangerous region.

4.2.2 *For successive high-wave attack*

When the average wave length is larger than 0.8 L and the significant wave height is larger than 0.04 L, and at the same time some indices of dangerous behaviour of the ship can be clearly seen, the master should pay attention not to enter into the dangerous zone. When the ship is situated in this dangerous zone, the ship speed should be reduced or the ship course should be changed to prevent successive attack of high waves, which could induce the danger due to the reduction of intact stability, synchronous rolling motions, parametric rolling motions or combination of various phenomena.

4.2.3 *For rolling motions*

The master should prevent a synchronous rolling motion which will occur when the encounter wave period is nearly equal to the natural rolling period of ship. For avoiding parametric rolling in following, quartering, head, bow or beam seas ,the course and speed of the ship should be selected in a way to avoid conditions for which the encounter period is close to the ship roll period or the encounter period is close to one half of the ship roll period. The period of encounter may be determined by entering with the ship speed in knots, the encounter angle and the wave period.

5 CONCLUSION AND DISCUSSION

In the present researches of weather routing, researchers almost considered the effects of single environmental factors. There are few methods that consider the couple-effect of environmental factors. But the environment of ship sailing is very complex, the single factor or accumulation of several environmental factors cannot reflect the effect of environmental factors on the ship performance. Although Kobe university have done some research on numerical ship navigation based on numerical forecast models (Shigeaki, 2008, 2010; T. Soda, 2012; Chen, 2013), they didn’t give a formula about calculating added resistance or/and ship loss. In the future research of weather routing, the couple-effects of environmental factors on ship performance will be one of the hot topics.

REFERENCE

[1] Böttner, C. U. (2007). Weather routing for ships in degraded conditions. In International Symposium on Safety, Security and Environmental Protection. National Technical University of Athens, Athens.

[2] Bowditch, N. (2002). “The American Practical Navigator (Pub. No. 9).” National Imagery and Mapping Agency, 539-550.

[3] Chen, H. H. (1978). A dynamic program for minimum cost ship routing under uncertainty (No. PhD Thesis).

[4] Chiang, G. D. (2004). “The analysis on sailing routes of liner vessels from West Coast of North America to Taiwan.” Technical Note, Chinese Taiwan.

[5] Grell, G. A., Dudhia, J., Stauffer, D. R. (1995). “A description of the fifth-generation Penn State/NCAR mesoscale model (MM5).” NCAR Technical Note, National Center for Atmospheric Research.

[6] IMO(2007). Revised Guidance to the Master for Avoiding Dangerous Situations in Adverse Weather and Sea Conditions. MSC.1/Circ.1228.

[7] James, R. W. (1957). Application of wave forecasts to marine navigation.

[8] Krata, P., & Szlapczynska, J. (2011). 21. Weather Hazard Avoidance in Modeling Safety of Motor-driven Ship for Multicriteria Weather Routing. Methods and Algorithms in Navigation: Marine Navigation and Safety of Sea Transportation, 165.

[9] Lin, Y. H., & Fang, M. C. (2013, June). The Ship-Routing Optimization Based on the Three-Dimensional Modified Isochrone Method. In ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (pp. V005T06A067-V005T06A067). American Society of Mechanical Engineers.

[10] Mellor, G. L. (1998). “Users guide for a three-dimensional, primitive equation, numerical ocean model.” Technical Note, Princeton University.

[11] Moiseenko, S., Meyler, L., & Faustova, O. (2013). Prognostic Estimation of Ship Stability in Extreme Navigation. Marine Navigation and Safety of Sea Transportation: Maritime Transport & Shipping, 271.

[12] Padhy, C. P., Sen, D., & Bhaskaran, P. K. (2008). Application of wave model for weather routing of ships in the North Indian Ocean. Natural Hazards, 44(3), 373-385.

[13] Panigrahi, J. K., Padhy, C. P., Sen, D., Swain, J., & Larsen, O. (2012). Optimal ship tracking on a navigation route between two ports: a hydrodynamics approach. Journal of marine science and technology, 17(1), 59-67.

[14] Perez Arribas, F. (2007). Some methods to obtain the added resistance of a ship advancing in waves. Ocean Engineering, 34(7), 946-955.

[15] Shiotani, S. (2008). Navigational Simulation Using Tidal Simulation and Tidal Effects on Sailing Ship.

[16] Shiotani, S., Sasa, K., & Tarada, D. (2010, January). Numerical Navigation for a Ship in Simulation of Waves. In Proc. of the International Offshore and Polar Engineering Conference. Beijing, China:[sn] (pp. 663-670).

[17] Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W., & Powers, J. G. (2005). A description of the advanced research WRF version 2 (No. NCAR/TN-468+ STR). National Center For Atmospheric Research Boulder Co Mesoscale and Microscale Meteorology Div.

[18] The SWAN Team (2009).SWAN, Scientific and Technical Documentation, SWAN Cycle III version 40.72ABC,http://www.swan.tudelft.nl, Delft University of Technology.

[19] Tsou, M. C., & Cheng, H. C. (2013). An Ant Colony Algorithm for efficient ship routing. Polish Maritime Research, 20(3), 28-38.

[20] Tolman, H. L. (2002). “User manual and system documentation of WAVEWATCH-IIIversion 2.22.” Technical Note, National Centers for Environmental Prediction.

[21] Zhang, J. F., Huang, L. W., Wen, Y. Q., Deng, J. (2006). “Implementation of a Distributed Atmosphere-Wave-Ocean Coupling Model: Typhoon Wave Simulation in the China Seas.” 2006 International Symposium on Distributed Computing and Applications for Business, Engineering, and Sciences, 141-143.

[22] Zhang, J., & Huang, L. (2007). Optimal Ship Weather Routing Using Isochrone Method on the Basis of Weather Changes. In International Conference on Transportation Engineering 2007 (pp. 2650-2655). ASCE.