TRANSNAV International Journal on Marine Navigation and Safety of Sea Transportation
Volume 5 Number 3 September 2011

On the Method of Ship's Transoceanic Route Planning

O. D. Pipchenko
Odessa National Maritime Academy, Odessa, Ukraine

ABSTRACT: In this article control of ship on a transoceanic route is represented as multicriteria optimization problem. Optimal route can be found by minimizing the objective function expressed as ship integral work for a voyage, taking into account ship's schedule, weather conditions, engine loads and risks connected with ship dynamics in waves. The risk level is represented as non-linear function with heterogeneous input variables which estimated by means of multi-input fuzzy inference system on the basis of pre-calculated or measured ship motion parameters. As the result of this research the optimal transoceanic route planning algorithm is obtained.

1 INTRODUCTION

Ship routing is one of traditional navigational tasks directly related to her safe and efficient exploitation. Rising fuel prices and overcapacity spurring owners to implement on more of their ships the slow steaming policy that obviously makes ocean passage stage of the voyage longer and consequentially increases risks connected with ship operation in heavy weather conditions. Hence, the problem of optimal compromise between safety and economy become even more crucial. At the present time series of routing methods exist, such as isochrones (James 1959, Bijlsma 2004, Szlapczynska, Smierzchalski 2007), graph (Vagushchenko 2004, Padhy et al. 2008), expert (Oses, Castells 2008) and intelligence methods (Nechayev et al. 2009). All of them allow to perform route optimization by number of preset criteria. However the main problem, connected to optimization process, that's still remaining, is to obtain the objective function based on formalized relationship between ship motion parameters, power inputs, needed for environmental disturbances compensation, and route economical efficiency. One of the possible solutions of this problem is given below.

2 OPTIMIZATION TASK & OBJECTIVE FUNCTION

The solution of the above mentioned problem is based on the next hypothesis (Pipchenko 2009): *optimal route in prescribed weather conditions is such combination of route legs and corresponding engine loads, on which expended ship power inputs are closest to minimum and predicted voyage time does not exceed scheduled one, with regard to the safety limits*.

To assess the economical efficiency of the route, one can divide overall ship costs in two categories: minimal-unavoidable costs, needed for the voyage in ideal conditions that can be expressed by minimal-unavoidable work A_{min}, and additional work ΔA. Therefore, total work, performed during the voyage can be given as:

$$A = A_{\min} + \Delta A , \qquad (1)$$

or as voyage time integral of variable engine power:

$$A = \int_T P(t)\, dt , \qquad (2)$$

where P = main engine power.

Minimal-unavoidable work can be defined from the condition of minimum work performed during specified time with constant engine power on the shortest distance between ports:

$$A_{\min} = \int_{T_v} P_{const} dt, \text{ with } S_v = \min\left(S\left(\Re\right)\right), \qquad (3)$$

where S_v = the shortest route length; T_v = scheduled voyage time; $S(\Re)$ = length depending on route $\Re$ configuration.

Thus, the main voyage optimality criterion, without risks consideration, is the minimum of additionally performed work, appeared due to weather, time and distance limitations. This work can be given as voyage length integral of additional resistance R_W arisen due to environmental disturbances:

$$\Delta A = \int_S R_W ds \tag{4}$$

From equations (2), (3) the additional work can be obtained as:

$$\Delta A = \int_T P(t)\,dt - A_{\min} \tag{5}$$

Therefore, the objective function representing the specified route optimality can be expressed as:

$$Z = \int_{T \le T_v} P(t)\,dt,\ Z \to A_{\min} \tag{6}$$

For the full-valued solution of the problem, it is also necessary to take into account corresponding limitations. For this purpose the risk assessment concept was used and next was formulated: *the optimal route is found if the total work for the voyage is closest to minimal, voyage time does not exceed the scheduled one, and the risk level on each route leg is less then specified limit*. Thus, the objective function will be given as:

$$Z = \int_{T \le T_p} \min\left\{ P_{\max}, \begin{bmatrix} \boldsymbol{P}\left(U_{safe}(\mathrm{R}), t\right) \\ +\Delta\boldsymbol{P}\left(R_W\left(U_{safe}(\mathrm{R})\right), t\right) \end{bmatrix} \right\} dt, \tag{7}$$

where U_{safe} = maximum safe speed, at which the specified hazardous occurrence risk R is below the critical limit; P_{max} = maximum engine power; P = engine power needed to keep defined calm water speed; $\Delta P(R_W)$ = additional power needed to compensate the resistance due to environmental disturbances R_W; $\mathrm{R} \in (0,1)$ = risk level on the specified route leg.

3 RISK EVALUATION

3.1 *Problem definition*

According to the route optimality definition, given above, the risk level conducted with ship activity in prescribed weather conditions shall be determined for each route leg. Therefore, we define the leg as the part of the route on which ship control regime (speed and heading) and weather conditions remain constant. As opposed to classical definition two or more different route legs may be situated on one line between the waypoints, depending on weather grid density.

Mathematically the risk level can be defined as product of likelihood of hazardous occurrence and its consequence. In our case we define likelihood as probability of reaching defined dynamical motion parameters that may lead to the series of negative consequences, conducted with ship's operation in storm.

Assessing the risks of ship operation in heavy weather conditions one can define the situations connected with damages to hull structure, ship's systems and machinery and the situations arising due to violations of cargo handling technology.

For instance, the achievement of defined high amplitudes of roll may lead to the series of situations with different levels of consequences, such as shifting or loss of cargo, flooding of ship's compartments, capsizing. Therefore, next risk levels can be highlighted: *insignificant, low, practically allowable and not allowable*. The risk management should cover such measures which allow to vary the probability of definite event or to reduce the degree of its consequence. When solving the problem of safe ship control regime selection in heavy seas we assume the degree of consequence as constant. From the other hand by altering ship control settings operator can affect the probability of reaching such ship motion parameters that lay beyond the limits of practically allowable risk. In this case the risk level can be given as

$$\mathrm{R} = f\left(p_1, p_2, ..., p_n\right), \tag{8}$$

where $p_1, p_2, ..., p_n$ = probabilities of reaching the ship motion parameters, that may lead to definite hazardous occurrence.

3.2 *Seaworthiness criteria*

To perform the risk assessment and to find a safe control regime in given weather conditions it's necessary to define appropriate criteria, thereupon following factors should be taken into account:

- frequency and force of slamming;
- frequency of green water;
- motion amplitudes;
- hull stresses;
- propeller racing;
- accelerations in various ship points;
- forced and controlled speed redaction.

Table 1. General operability limiting criteria for ships.

Criterion	Cruikshank & Landsberg (USA)	Tasaki et al. (Japan)	NORDFORSK, 87 (Europe)	NATO STANAG 4154 (USA)
RMS of vertical accelerations on forward perpendicular	0.25 g	0.8 g / p = 10^{-3}	0.275g (L_{pp} < 100 m) 0.05g (L_{pp} > 300 m)	-
RMS of vertical accelerations on the bridge	0.2 g	-	0.15g	0.2g
RMS of transverse accelerations on the bridge	-	0.6 g / p = 10^{-3}	0.12g	0.1g
RMS of roll motions	15°	25°/ p = 10^{-3}	6°	4°
RMS of pitch motions	-	-	-	1.5°
Probability of slamming	0.06	0.01	0.03 (L_{pp} < 100 m) 0.01 (L_{pp} > 300 m)	-
Probability of deck wetness	0.07	0.01	0.05	-
Probability of propeller racing	0.25	0.1	-	-

*The significant motion amplitudes ($X_{1/3}$) can be obtained by doubling the corresponding RMS (root mean square value).

Table 2. Management level navigators inquiry results.

	Roll motion amplitude, °	Slamming, intensity per hour	Deck wetness, intensity per hour	Speed reduction, %	Deviation from course, °
Small	< 7	< 5	< 5	< 13	< 20
Not dangerous	< 14	< 11	< 10	< 24	< 38
Substantial	< 23	< 19	< 20	< 46	> 40
Dangerous	> 26	> 23	> 23	> 58	-

*The average values of inquiry data are given.
** Example: slamming probability with period of pitching 5 sec and intensity 20 times/hour: **0.028.**

The comparative table of general operability limiting criteria for wide variety of ships in waves combined from data of Lipis (1982) & Stevens (2002) is given in table 1. However criteria of NORDFORSK and NATO STANAG appear to be too strict, and in series cases, when ship proceeds through a heavy storm, the motion parameters may exceed these criteria.

According to inquiry of management level navigators (captains and chief mates) passing the Ship Handling course in Training & Certifying Centre of Seafarers of Odessa National Maritime Academy (TCCS ONMA) empirical values of ship operability criteria were obtained (table 2).

Usage of last gives possibility to perform more detailed, supported by personal seagoing experience of navigators, assessment of ship state in waves.

It should be noted that risk assessment by only threshold values, defined for the series of criteria is ineffective. Therefore, we suggest to apply not two-valued state assessment function, but numerical or linguistic function, defined in range between two extreme values: «0» - «1», «best» - «not allowable» (minimal – maximal risk level).

4 FUZZY LOGIC ASSESSMENT

4.1 *Assessment algorithm*

To implement above mentioned suggestion seaworthiness assessment system consisting of two fuzzy inference subsystems (FIS) was built (fig. 1) on the basis of more complex model given in (Pipchenko, Zhukov 2010).

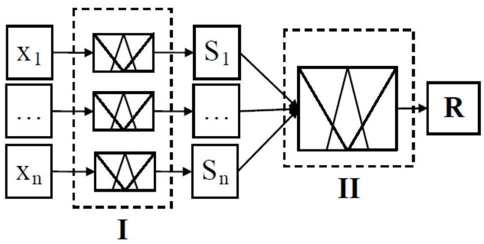

Figure 1. Multicriteria seaworthiness assessment system

$x_1 \ldots x_n$ = motion parameters, $S_1 \ldots S_n$ = corresponding rates, R = risk level.

Following algorithm was adopted in the system to define the generalized risk level from several motion parameters. Ship motion parameters, taken as the system input, pass the FIS structure of the 1st level. As the result series of rates on each criterion in form of numerical or linguistic variables (for instance, slamming impact: “small”, “substantial” or “dangerous”) received on its output.

In course of definition system’s membership functions (MF) it is suggested to form boundary conditions on the basis of existing international operability criteria, and MF's intermediate values – by approximation of preliminary transformed expert inquiry data.

After that obtained rates pass the FIS of the 2nd level, on the output of which the general assessment on the set of conditions is obtained in the form of risk level. For defuzzification Mamdani algorithm was used in both subsystems.

4.2 *Membership functions evaluation*

Let's describe the FIS membership functions (MF) definition process on example of roll amplitude.

Maximum allowable roll amplitude can be determined from condition:

$$\varphi_{1/3}^{\text{limit}} = \min\left\{\varphi_{shift}, \varphi_{flood}, \varphi_{capsize}, \varphi_{operator}\right\}, \quad (9)$$

where φ_{shift} = cargo critical angle; φ_{flood} = flooding angle; $\varphi_{capsize}$ = capsize angle; $\varphi_{operator}$ = operator defined maximum roll amplitude. For general case the maximum angle of 30° was chosen.

For each linguistic term a numerical interval, on which a membership function is defined, can be found from condition:

$$\varphi \in \left(0, \max\left\{\varphi_T^*\right\}\right), \varphi = 0,1,2..., \max\left\{\varphi_T^*\right\} \in N, \quad (10)$$

where φ_T^* = values declared by respondents as limits for specified terms. For roll amplitude these terms are: "Non Significant" – NS, "Not Dangerous" – ND, "Significant" – S, "Dangerous" – D.

The principal variable on which the computation of experimental membership function made in the work is *relative term repetition frequency* $\tilde{\nu}_T = \nu_T / \nu_T^{\max}$, ν_T = quantity of respondents, declared specific value (i.e. roll amplitude is "non significant", if φ < 5°), $\nu_T^{\max}$ = maximum number of value repetitions for specified term.

Basing on relative term repetition frequency experimental data for membership functions μ_T^* obtained in the way given below.

For "Non Significant" amplitude term μ_{NS}^*:

$$\left.\begin{aligned} &\mu_{NS}^*(\varphi) = 1 - \tilde{\nu}_{NS}(\varphi), \text{for } \varphi < \varphi\left(\max\left(\tilde{\nu}_{NS}\right)\right) \\ &\mu_{NS}^*(\varphi) = \tilde{\nu}_{NS}(\varphi)/2, \text{for } \varphi \geq \varphi\left(\max\left(\tilde{\nu}_{NS}\right)\right) \end{aligned}\right\} \quad (11)$$

For "Not Dangerous" amplitude term μ_{ND}^*:

$$\left.\begin{aligned} &\mu_{ND}^*(\varphi) = \tilde{\nu}_{NS}(\varphi)/2, \text{for } \varphi < \varphi\left(\max\left(\tilde{\nu}_{NS}\right)\right) \\ &\mu_{ND}^*(\varphi) = 1 - \tilde{\nu}_{ND}(\varphi), \text{for} \\ &\varphi\left(\max\left(\tilde{\nu}_{NS}\right)\right) \leq \varphi < \varphi\left(\max\left(\tilde{\nu}_{ND}\right)\right) \\ &\mu_{ND}^*(\varphi) = \tilde{\nu}_{ND}(\varphi)/2, \text{for } \varphi \geq \varphi\left(\max\left(\tilde{\nu}_{ND}\right)\right) \end{aligned}\right\} \quad (12)$$

For "Significant" amplitude term μ_S^*:

$$\left.\begin{aligned} &\mu_S^*(\varphi) = \tilde{\nu}_{ND}(\varphi)/2, \text{for } \varphi < \varphi\left(\max\left(\tilde{\nu}_{ND}\right)\right) \\ &\mu_S^*(\varphi) = 1 - \tilde{\nu}_S(\varphi), \text{for} \\ &\varphi\left(\max\left(\tilde{\nu}_{ND}\right)\right) \leq \varphi < \varphi\left(\max\left(\tilde{\nu}_S\right)\right) \\ &\mu_S^*(\varphi) = \tilde{\nu}_S(\varphi)/2, \text{for } \varphi \geq \varphi\left(\max\left(\tilde{\nu}_S\right)\right) \end{aligned}\right\} \quad (13)$$

From table 2 it can be seen that limit values for terms NS, ND & S roll amplitudes were defined from condition $\varphi < \varphi_{\max}^*$. At the same time term "Dangerous" amplitude was defined from condition $\varphi > \varphi_{\max}^*$, therefore:

$$\mu_D^*(\varphi) = \tilde{\nu}_D(\varphi) \quad (14)$$

On the basis of experimental membership functions values, following function can be approximated for application in fuzzy inference algorithm:

$$\left.\begin{aligned} &\mu(\varphi) = e^{\frac{-(\varphi/\varphi_{\max} - c)^2}{2\sigma^2}}, \varphi < \varphi_{\max} \\ &\mu(\varphi) = 1, \varphi \geq \varphi_{\max} \end{aligned}\right\} \quad (15)$$

where σ, c = function parameters.

As result of approximation four MF's were obtained (fig. 2.).

4.3 *Rules set definition*

To make an inference or to get a determined ship state assessment applying fuzzy logic it is necessary to construct corresponding set of rules.

As input parameters roll amplitude and "maximum probability" coefficient were applied in suggested system. "Maximum probability" coefficient $K_{SGR} \in (0,1)$ can be determined as:

$$K_{SGR} = \min\left(1, \max\left(\frac{p_S}{p_S^{\max}}, \frac{p_{GW}}{p_{GW}^{\max}}, \frac{p_R}{p_R^{\max}}\right)\right) \quad (16)$$

$$K_{SGR} \in (0,1),$$

where p_S, p_{GW}, p_R = slamming, green water and propeller racing probabilities, superscript *max* means maximum allowable criterial value.

The output risk level R is divided in four linguistic terms: «non significant», «low», «allowable» and «not allowable».

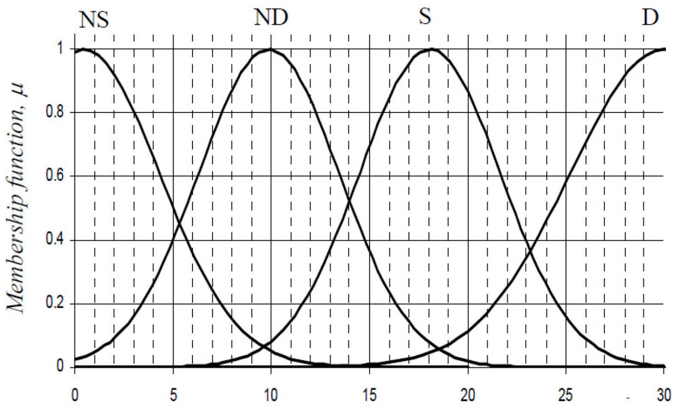

Figure 2. Roll amplitude assessment membership functions

The corresponding set of rules is given in table 3.

Table. 3. Risk evaluation rules set.

№		Roll amplitude, φ		Probability coefficient, K_{SGR}	**Conclusion** Risk level, R
1	**IF**	Non significant	**AND**	Low	Non significant
2	**IF**	Non significant	**AND**	Moderate	Low
3	**IF**	Not dangerous	**AND**	Low	Non significant
4	**IF**	Not dangerous	**AND**	Moderate	Low
5	**IF**	Significant	**AND**	Low	Allowable
6	**IF**	Significant	**AND**	Moderate	Allowable
7	**IF**	Dangerous	**OR**	High	Not allowable

Thus, the risk level for each route leg can be assessed on the basis of weather prognosis data and measured or predicted ship motion parameters. Such prediction can be made by ship dynamic model either linear or non-linear which satisfies accuracy and computational costs criteria. To meet these requirements the combination of linear and non-linear ship motion models were used for calculations in (Pipchenko 2009).

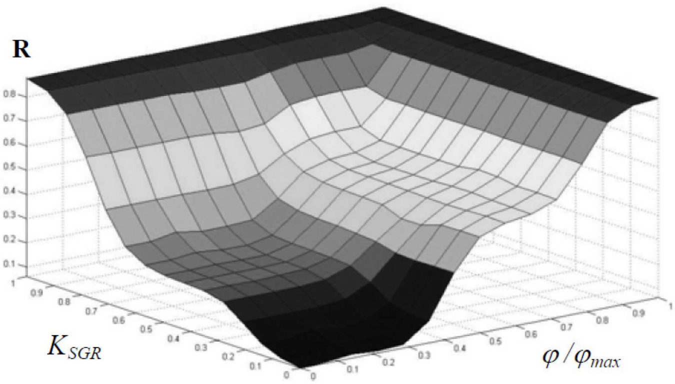

Figure 3. Function surface **R**$(\varphi_{1/3}, K_{SGR})$.

5 ENGINE LOADS ESTIMATION

To estimate engine power required to keep preset safe speed the functional relationship between speed, power and additional resistance in waves shall be determined.

Ship speed with regard to environmental disturbances, basing on equality condition of propeller thrust to water resistance in calm water can be found as follows:

$$U_W = f\left(T_e - R_W\right); \tag{17}$$

where T_e = propeller thrust in calm water; R_W = average additional resistance due to wind and waves, calculated in this work using methods of Boese (1970) and Isherwood (1973).

Engine load, required to keep specified speed undergoing the wind and waves influence can be determined as:

$$\begin{aligned} T_w &= f\left(U\right) + R_W\left(U\right) \\ &= c_1 \cdot U^2 + c_2 \cdot U + c_3 + R_W\left(U\right), \end{aligned} \tag{18}$$

$$P_w = \frac{T_w \cdot U}{\eta}, \tag{19}$$

where P_w = engine power; c = approximation coefficients, determined from experimental data.

Additional resistance in constant weather conditions can be represented as function of ship speed. Therefore if required speed cannot be reached due to lack of engine power and wave impacts, maximum possible speed can be found applying next recursive procedure:

$E(0) = U'(0)$, $U'(0) = U_{max}$;

WHILE $E > \varepsilon$, $\varepsilon \to 0$

$$T'_w = c_1 \cdot U'^2 + c_2 \cdot U' + c_3 - R_W\left(U'\right);$$

$$U'' = \max\left\{0, \min\left\{U_{\max}, c'_1 \cdot e^{c'_2 \cdot T'_w} + c'_3 \cdot e^{c'_4 \cdot T'_w}\right\}\right\};$$

$$E = \left|U'' - U'\right|;\; U'' = U'.$$

END OF CYCLE

Where U' = calm water speed; U'' = predicted maximum speed in waves, defined as inverse function of T_w; c' = approximation coefficients, determined from experimental data.

6 ROUTE OPTIMIZATION ALGORITHM

The route optimization is performed by following algorithm.

- Ship motion parameters in specified load condition are calculated for defined range of speeds and courses in wave frequency domain. The result of such calculation is a group of four-dimensional arrays $X = f(U, \mu, \omega)$, where X – specified motion parameter.
- Initial transoceanic route is given as great circle line, on which the optimal engine load and corresponding minimal work A_{min} needed to perform the voyage in calm water are estimated.
- Weather prognosis for the voyage is given as multidimensional array with discrecity 1-2° φ x λ.
- After indexing of cells containing weather data, correspondence between route legs and chart grid shall be defined.
- On each route leg (1:N): ship motion parameters for specified wind and wave conditions are recalculated using spectral analysis techniques; risk level and corresponding safe speed are determined.
- If the safe speed on any route leg is less then specified minimum threshold, algorithm switches to route variation stage, if no – engine power inputs and additional work are calculated.
- Optimization task is reached if the minimum additional work in given weather conditions is found, and the maximum risk level on the route is less then specified threshold.

In isochrones method proposed by James (1959) the engine power is considered as constant, where speed is only changed due to wind and waves effect. Thus it's not applicable with the objective function (7). From the other hand directed graph method (Vagushchenko 2004) allows to control the ship by both speed & course. But to get the accurate solution the dense waypoint matrix shall be built that leads to high computational costs. Therefore we suggest to make generation of alternative routes by setting additional waypoints – "poles". In this case, pole it is intermediate point inserted for avoidance of adverse weather conditions. Positions of poles may be changed either manually or by optimization algorithm.

Poles shall be set as:

$$\begin{bmatrix} Pole_1 \\ Pole_2 \\ \dots \\ Pole_m \end{bmatrix} = \begin{bmatrix} \varphi_1 & \lambda_1 \\ \varphi_2 & \lambda_2 \\ \dots & \dots \\ \varphi_m & \lambda_m \end{bmatrix}, m = 1,2,\dots,M \quad (20)$$

Position of each pole shall satisfy following conditions (fig. 4.):

1 Length of perpendicular, dropped to the orthodromy line between start and destination points must not exceed specified threshold:

$$d(m) \le d_{\text{margin}} \quad (21)$$

$$d(m) = \arctan \frac{\cos\left(\arctan \dfrac{\cos l_{AP}}{\cot(\Psi - \Psi_A)}\right)}{\cot l_{AP}} \quad (22)$$

2 Absolute difference between courses put from pole to start and destination points must exceed 90°. It provides that pole stays in the space between start and destination points:

$$\Psi_P(m) \ge 90^o \quad (23)$$

3 Distance from start point to each next pole shall increase:

$$l_{AP}(m) > l_{AP}(m-1) \quad (24)$$

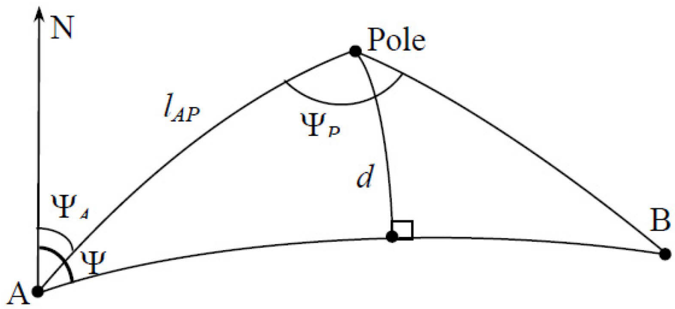

Figure 4. Pole position in relation to the route.

Route legs are rebuilt depending on poles positions. Quantity of waypoints is determined proportionally to the distances between poles. Route legs before or after poles normally built as great circles.

If M≤4, optimization is carried out by Nelder-Mead method. If M>4, optimization is carried out by Genetic Algorithm method, because of Nelder-Meads coefficient quantity limitations.

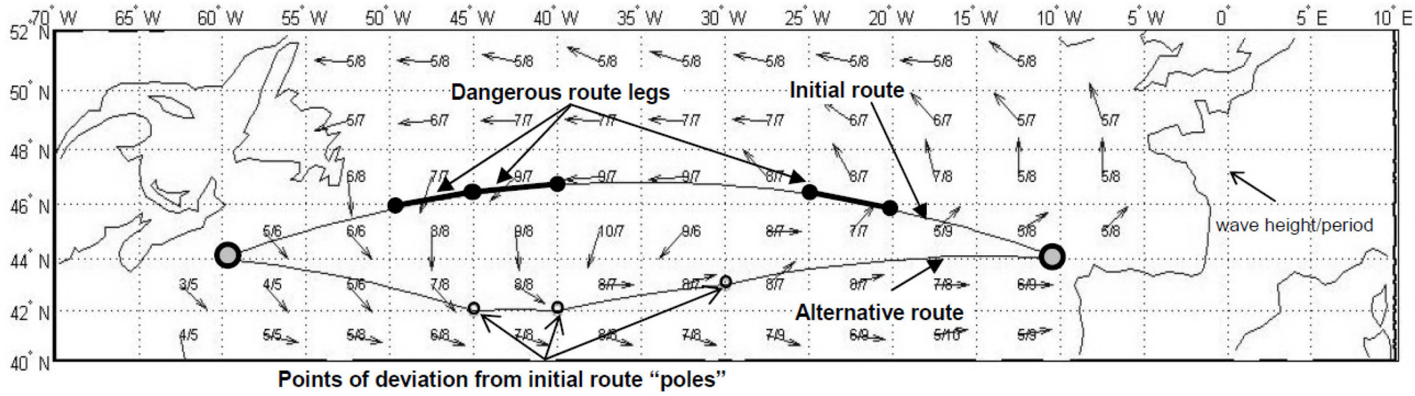

Figure 5. Example of imitated transatlantic route optimization.

7 EXAMPLE

As an implementation example of the given route optimization method planning of imitated transatlantic route for handymax container vessel (L = 200 m, B = 30 m, GM = 1.0 m) is illustrated on figure 5. The comparison of initial great circle and alternative routes is given in table 4.

Table. 4. Initial and alternative routes comparison.

Parameter	Great circle		Alternative route	
	Min	Max	Min	Max
Distance, nm	2125		2212	
Poles positions	42.0 N 45.0 W // 42.0 N 40.0 W // 43.0 N 30.0 W			
Specified voyage time, hours	106			
Voyage speed, knots	20		20.8	
ΔA, % from A_{min}	14.9		11.2	
Risk level, %	7	88	6	56
Engine load, %	61	95	67	67
Rolling amplitude, deg	0	18	1	22
Slamming intensity, times/hour	0	3	0	0
Green water intensity, times/hour	0	103	0	0

As can be seen from this data, optimization leads to quite good results both for safety and efficiency of the route. Thereupon the time of the voyage remains the same, with even less total engine loads (and obviously less fuel consumption). From the other hand on alternative route slamming and green water probabilities reduced to a minimum. However the rolling amplitude remains high on separate parts of alternative route, but it should be taken into account that there are not many good choices to make as the imitated weather conditions are almost everywhere adverse.

8 CONCLUSION

To optimize the transoceanic route objective function which represents ship work expended for the voyage was suggested. The work in that case represented as time integral of main engine power-inputs needed to keep specified speed and to compensate the additional resistance arisen due to environmental disturbances with regard to ship's safety.

To perform the safety assessment a fuzzy logic system which represents relation between ship motion parameters and corresponding risks was developed. That allowed to perform the general risk level value evaluation on the basis of multi input data.

Both these results give the opportunity to perform effective transoceanic route planning on the basis of formalized safety and efficiency assessment with regard to specified weather conditions.

REFERENCES

Bijlsma, S. J. 2004. A computational method in ship routing using the concept of limited maneuverability. *The Journal of Navigation.* Vol.57, No3: 357-370.

Isherwood, R.M. 1973. *Wind resistance of merchant ships.* Transactions of Royal Institution of Naval. Architects, Vol. 115: 327-338.

James, R.W. 1959 Application of wave forecasts to Marine Navigation. U.S. Navy Hydrographic office.

Boese, P. 1970. Eine Einfache Methode zur Berechnung der Wiederstandserhöhung eines Schi¤es in Seegang. *Technical Report 258, Institüt für Schi¤bau der Universität Hamburg, BRD.*

Lipis, V. & Remez, Yu. 1982. Safe ship control regimes in storm. M.: Transport.

Nechaev, Yu., Pipchenko, O. & Sizov, V. 2009. Selection of optimal course in adverse weather conditions. *Navigation: ONMA scientific journal, Issue 16.* Odessa: Izdatinform: 105-118.

Oses, F. & Castells, M. 2008. Heavy Weather in European Short Sea Shipping: It's Influence on Selected Routes. *The Journal of Navigation. Vol.61, No1, Jan 2008*: 165-176.

Padhy, C. P., Sen, D. & Bhaskaran, P. K. 2008. Application of wave model for weather routing of ships in the North Indian Ocean. *Nat Hazards 44*: 373–385.

Pipchenko, O. D. & Zhukov, D. S. 2010. Ship control optimization in heavy weather conditions. *Proceedings of the 11th AGA, IAMU*, *Busan*: 91-95.

Pipchenko, O. D. 2009. Method for optimal ship routing in adverse weather conditions. *Proceedings of scientific and technical conference «Modern problems of navigation safety enhancement»*. Odessa, Ukraine: ONMA: 85-87.

Stevens, S. & Parsons, M. 2002. Effects of Motion at Sea on Crew Performance: A Survey. *Marine Technology, Vol. 39, N1, Jan 2002*: 29-47.

Szlapczynska, J. & Smierzchalski, R. 2007. Adopted Isochrones Method Improving Ship Safety in Weather Routing with Evolutionary Approach. *International Journal of Reliability and Safety Engineering. Vol 14; # 6, 2007*: 635 – 646.

Vagushchenko, O. L. 2004. Method for transoceanic routing. *Navigation: ONMA scientific journal, Issue 8*. Odessa: Latstar: 12-21