A Systematic Study on Posing and Solving the Problem of Pareto Optimal Ship Routing

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Abstract

The paper proposes an optimization approach to selecting the most advantageous route on the basis of hydrodynamic simulations. An elaborated example is given for an intercontinental container service (CMS Hannover Express) between Europe (Le Havre) and North-America (New York). Different weather situations for the North Atlantic are taken into account. Time loss, fuel consumption, accelerations and slamming are minimized on the basis of several performance models – for instance response amplitude operators for the ship's motions. The routes in adverse weather conditions are established as perturbations to a parent route in calm weather which is assumed to be the concatenated great circles between way points. Utilizing a B-spline technique, the number of free variables for describing both the course and the velocity profile is kept low. For solving the multi-objective, non-linear and constrained optimization problem the commercial package modeFRONTIER has been successfully applied. Investigations utilizing various objective functions serve to adopt a Multi-Objective Genetic Algorithm (MOGA) to automatically fill up a solution space of feasible routes for the support of the decision-making process.

1. Introduction

Sophisticated routing of ships is increasingly recognized as an important contribution to safe, reliable and economic ship operations. The more accurate both weather forecasts and performance simulations of ships in a seaway become, the better they serve to identify the best possible route.

An optimum route complies with the desired time of arrival at minimum fuel consumption and maximum safety. Permissible and reasonable loads on the ship, the cargo and the crew are not allowed to be exceeded. This establishes a multi-objective, non-linear and constrained optimization problem in which a suitable compromise is to be found between opposing targets.

2. Wave data

While the estimated time of arrival (ETA) and fuel consumption (FUEL) depend on all environmental conditions, accelerations and slamming are primarily influenced by swell. Swell - i.e., long-crested waves - being the crucial factor, we decided to focus on this influence, leaving out wind-sea, current, wind, drift-ice, shallow-water etc. for later and more refined work. The objective therefore was to suggest a novel approach to routing and to investigate its merits without claiming completeness of the model. It will be shown, however, that an extension of the optimization scheme is rather straightforward, allowing to quickly incorporate refined analyses.

The wave data used were provided by the *European Centre of Medium-Range Weather Forecast* (*ECMWF*). They are a hind cast of the sea conditions in the North Atlantic in the periods from 6. to 16. of June 2001 (calm sea condition), 20. to 30. of January 2002 (rough sea condition) and 1. to 11. of January 2003 (intermediate sea condition) and are based on a reanalysis of buoy- and satellite measurements. The data for the significant wave height $H_{1/3}$, the peak period T_P and the wave angle β are given in time steps of 12 hours on a grid with 1.5° mesh size. Within the route optimization these data were treated as if they had been a wave forecast.

To obtain a continuous wave energy spectrum as a function of the wave frequency the data were associated with the description of a Bretschneider wave spectrum, cp. *Lewis (1998):*

$$S_\zeta(\omega) = \frac{172.8 \cdot H_{\frac{1}{3}}^{2}}{T_1^4} \cdot \omega^{-5} \cdot \exp\left\{ \frac{-691.2}{T_1^4} \cdot \omega^{-4} \right\} \tag{1}$$

$\omega_p = \frac{2\pi}{T_p}$, the modal frequency, $T_1 = 0.772 \cdot T_p$, transformation from mean to peak period, *Journée (2001).*

3. Ship responses in waves

Response amplitude operators (RAOs) and response functions for the added resistance due to waves (RFs) were employed for the evaluation of the ship performance in waves. Both have been calculated prior to the optimization by means of the strip theory code SEAWAY, *Journée (2001),* based on potential theory. Besides RAOs for the center of gravity motions for all six degrees of freedom and RAOs for the motions of selected points also relative to the free surface, two different methods are available to determine the added resistance due to waves: The radiated energy method of Gerritsma and Beukelman and the integrated pressure method of Boese, *Journée (2001).*The numerical results used within the optimization procedure are:

- The RAOs of the translatory motions on the bridge (calculation of the loading on the crew by means of accelerations).
- The RAOs of the motion relative to the free surface (calculation of the slamming probability).
- The RFs for the added resistance due to waves (preferably according to the integrated pressure method which displays a smoother distribution over the wave frequency ω than its radiated energy counterpart).

Fig.1 shows the RAOs of motion on the bridge, relative motion at the bow and the RFs of the added resistance due to waves as computed with SEAWAY. The plots serve to illustrate the input to the response simulations within the route optimization.

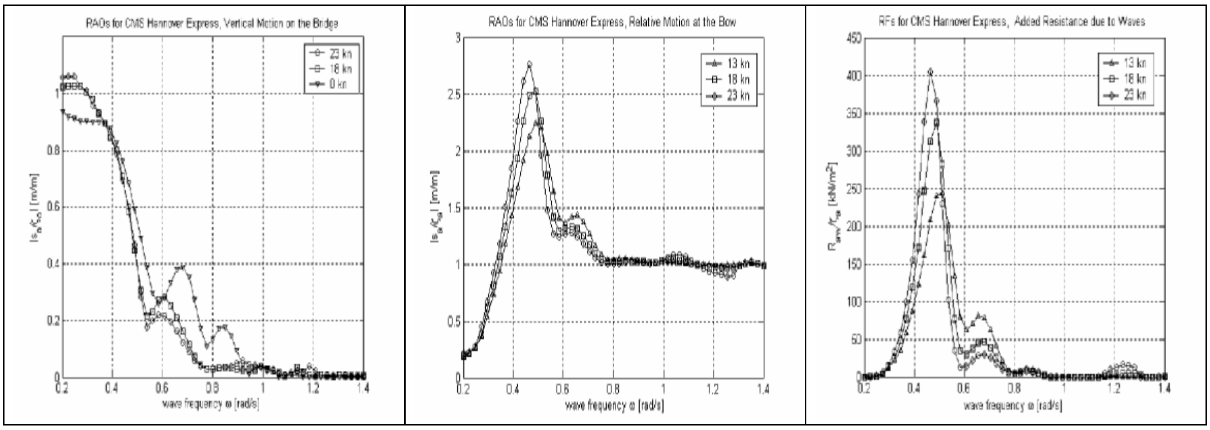

Fig.1: RAOs of motion on the bridge, relative motion at the bow
and the RFs of the added resistance due to waves

3.1. Ship motions

The product of the wave spectrum S_ζ and a squared RAO of the considered motion yields the response spectrum of the ship motion S_s:

$$S_s(\omega) = |RAO|^2 \cdot S_\zeta(\omega) \tag{2}$$

Taking into account the ship velocity, this operation has to be performed with all involved terms expressed as functions of the wave encounter frequency ω_e. Generally the nth moment of the response spectrum is built with:

$$m_{ns} = \int_0^\infty S_s(\omega_e) \cdot \omega_e{}^n d\omega_e = \int_0^\infty S_s(\omega) \cdot \omega_e{}^n d\omega \tag{3}$$

The significant amplitude of the acceleration is determined with the following approximate formula provided by probability calculations:

$$\ddot{s}_{a\frac{1}{3}} = 2.0 \cdot \sqrt{m_{4s}} \tag{4}$$

This can be applied to determine the acceleration on the bridge for instance.

3.2. Slamming

Slamming can be defined as the coincidence of two events: the emergence of the bow and its subsequent dunking above a critical velocity. The critical velocity according to Ochi, *Journée (2001),* is:

$$\dot{s}_{cr} = 0.0928 \cdot \sqrt{g \cdot L_{pp}} \tag{5}$$

Presuming statistical independence of these events the probability of slamming is calculated from:

$$P\{slam\} = \exp\left\{ \frac{-D^2}{2\,m_{0s\,rel}} + \frac{-\dot{s}_{cr}{}^2}{2\,m_{2srel}} \right\} \tag{6}$$

Where m_{0srel} and m_{2srel} are the 0th and 2nd moment, respectively, of the response spectrum for a point on the keel line 10% behind the forward perpendicular FP, D being the draught 10% behind FP.

3.3. Fuel consumption

The added resistance due to waves is calculated from:

$$R_{AW} = \int_0^\infty RF \cdot S_\zeta(\omega)\, d\omega \tag{7}$$

The determination of the calm water resistance is based on a regression analysis of model tests and full-scale data, following *Holtrop and Mennen (1984).*The operating point of the propeller was calculated according to the *ITTC (1978)* power prediction method, using the characteristic of a propeller with the same diameter, number of blades, similar pitch and blade area ratio as given in *Yasaki (1962).* In a final step the fuel consumption and the compliance with the permitted operating condition was determined in agreement with the project guide available from the producer of the ship's main engine, *MAN B&W (2000).*

4. Setting up of the optimization task

Simply put, automated optimization is the formal process of finding a good (the best) solution from a set of feasible alternatives. It requires a complete mathematical problem formulation in terms of objective functions (what is to be improved), free variables (what shall be consciously changed) and constraints (what restricts the feasibility).

4.1. Free Variables

To provide free variables for both the spatial and the temporal description of the route the path and the velocity profile were given as B-splines. Perturbations of a parent route in time and space were realized by superposing the appropriate parent spline with a Greville-spaced shift spline. The vertices of the shift splines are controlled by shift parameters that were taken as the free variables of the optimization task.

The velocity perturbation was performed as a reduction of the design speed of 23kn. The spatial perturbation provides a shift of maximum 10% of the arc length of the original parent route to either starboard or port.

Fig.2 presents example routes as realized with 5 parameters for the spatial shift. The optimization was focused on the open water part of the journey, pilot time and estuary traveling was deliberately left out of the investigation. The geographical feasibility was checked during the optimization process.

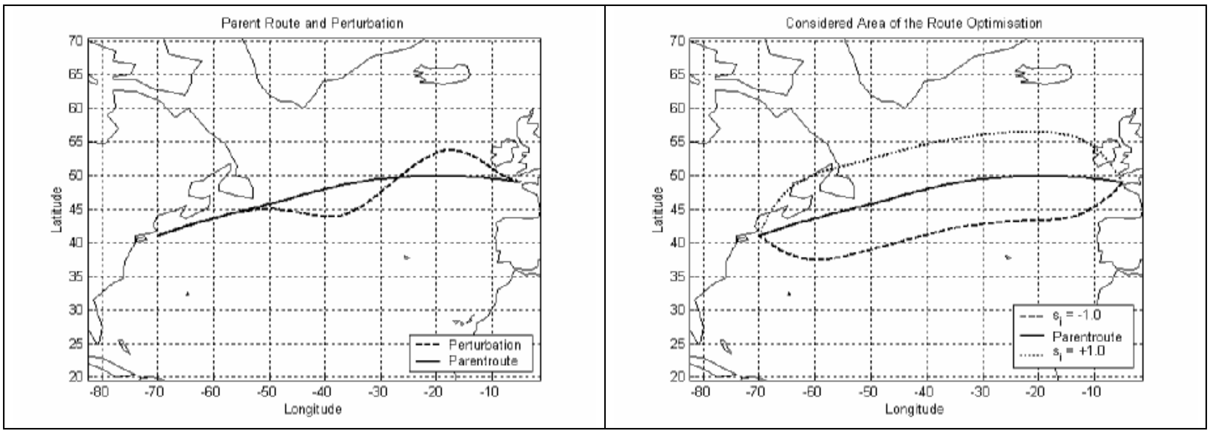

Fig.2: parent route, perturbation and investigated area

4.2. Constraints

Constraints were imposed by defining limiting values for the slamming probability (3%) and for the lateral and vertical accelerations (0.2 g, g = 9.807 m/s^2).

4.3. Objectives

Two major objectives, the estimated time of arrival (ETA) and the fuel consumption (FUEL), were taken into account both of which had to be minimized. Especially in rough weather conditions initial route variants need to be quiet slow to avoid infeasibility due to active constraints. The following objective functions were used to accelerate the propagation of the initial routes towards faster route variants in the multi-objective optimization:

$$Objective \quad ETA = \left(ETA - set\ value\ ETA\right)^2, \tag{8}$$

$$Objective \quad FUEL = weight \cdot \left(FUEL - FUEL \cdot \frac{ETA}{set\ value\ ETA} \right)^2. \tag{9}$$

The *set value* of ETA was derived from optimum results at calm water conditions (ETA = 114 hours after departure, the value matches the estimated duration of a journey as stated in the sailing lists of the ship operator; the weight assigned to the FUEL objective was 0.05, so as to produce objectives of an equal magnitude at the biggest deviants of the set value).

4.4. Optimization with modeFRONTIER

For the optimization task the generic optimization software modeFRONTIER was utilized, www.esteco.it. The process flow in Fig.3 can be read from left to right. Initially, the free variables used as input parameter of the optimization loop are collected in an input file (parameter.txt). Afterwards an application is started to build the new route by means of a perturbation of the parent route according to the actual input parameter (makeroute). Next, the route is evaluated (virtualShip) and results are given back to modeFRONTIER. Finally, the optimization routine observes the constraints, calculates the objectives and, if necessary, launches a new investigation. The optimization results presented in the following chapters belong to a westbound Atlantic crossing of the Hapag Lloyd panmax container vessel "CMS Hannover Express".

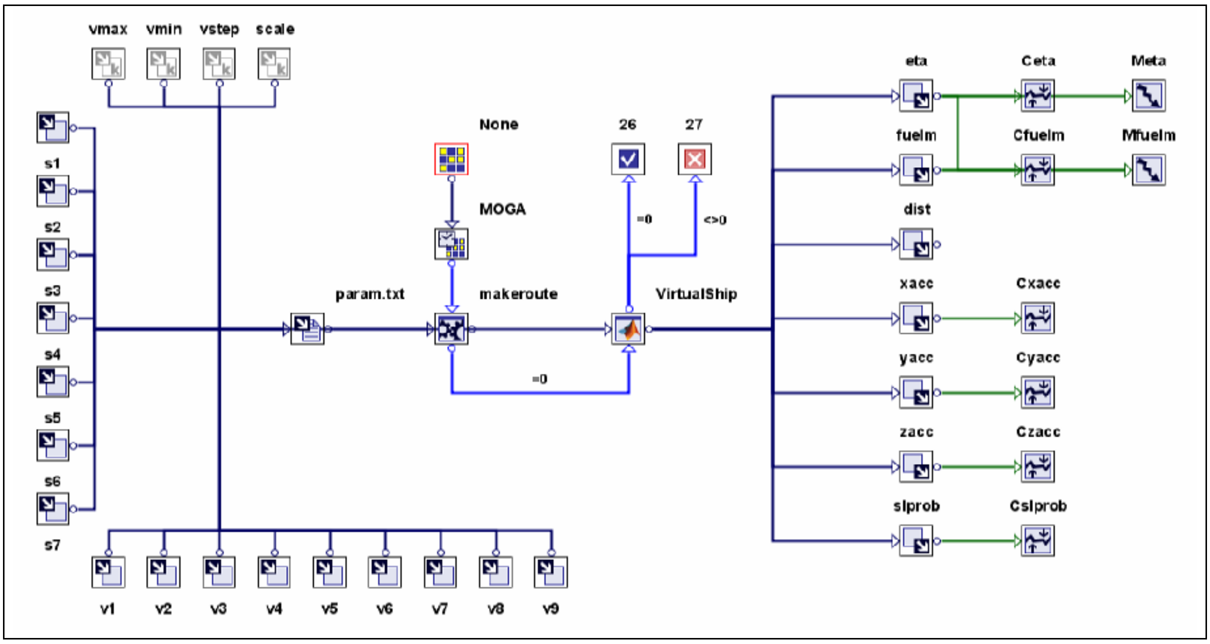

Fig.3: modeFRONTIER flow chart

5. Optimization results at different weather conditions

Two different search strategies, a SIMPLEX and a multi-objective genetic algorithm MOGA, were applied. Both, SIMPLEX and MOGA optimizations were conducted for a calm, a rough and an intermediate weather situation. Since the SIMPLEX algorithm can handle only one objective, optimizations were constricted to the minimization of ETA. Within MOGA the minimization of both ETA and FUEL was undertaken.

Fig.4 shows the result of a MOGA optimization in rough sea conditions. Each square represents a feasible route that can be taken into account for a route decision considering ETA and FUEL. The solution space is bordered by a Pareto frontier – the set of all solutions for which a single objective cannot be further improved without deteriorating any other objective. All routes lie above and to the right of the Pareto frontier. Those variants that are closest to the frontier display low passage time for reasonably low fuel consumption. Apparently, it is impossible to decrease ETA below certain limits without impairing FUEL.

Fig.5 illustrates the operation of a SIMPLEX optimization under rough sea condition. Starting from a set of initial designs at a low speed level the optimization converged to a local optimum. None of the routes touch the Pareto frontier found by the genetic algorithm. The figure nicely shows the limitation of a deterministic search strategy like the SIMPLEX algorithm. As a general rule it is difficult to identify a global optimum and the search goes quickly to the (nearest) local optimum. While neglecting FUEL an agreement of the optimization result with the *Pareto* frontier should therefore not be expected. Further investigations with different starting points and objective functions depending on both ETA and FUEL achieved no improvement.

Table 1 and Fig.6 compare SIMPLEX and MOGA optimization results at different sea conditions. The time minimum routes of the SIMPLEX and *Pareto* routes of the MOGA are depicted. For the genetic algorithm 7000 route variants were investigated (one population consists of 70 individuals, 100 generations). The SIMPLEX converged most of the time with less than 400 iterations but never matched the time minimum route found by MOGA. An advantage of the SIMPLEX is time saving due to smaller computational effort. The MOGA, however, is capable to fill up the solution space, to identify a Pareto frontier and therefore to provide a meaningful data base for the routing decision support. Each route presented by a square in Fig.4 can be selected and taken into account for the decision making of the naval officer considering ETA and FUEL. But also individual preferences concerning slamming probability or allowable accelerations can be regarded. Consequently a more conscious decision can be made about which route to take. Sometimes this will yield fuel savings for arriving at the desired time. Sometimes this will show which route is still the best (or least worse) for severe conditions. Furthermore, only the MOGA found the shortest route at calm sea condition (although maximum significant wave heights of about 5 meters occurred during the crossing, the constraints for slamming and accelerations did not affect the optimization as they all turned out to be inactive, therefore the time minimum route has to be the shortest one).

Fig.6 nicely shows the influence of the sea condition to the minimum attainable ETA. In rough weather an arrival on schedule was impossible. The different fuel consumptions were caused by the ship speed, the necessary distance of the journey to avoid severe weather conditions and also the added resistance due to waves.

Fig.7 illustrates four steps of an example route in rough weather, here with lowest ETA (143h). The contour lines represent the current significant wave height during the crossing, the route and the actual position of the ship (a dot at the end of the bold black line) are drawn, too. The decrease of fuel consumption in comparison to the optimum route at calm sea condition is caused by low ship speeds during the first 50 hours (below 18kn). From an optimization point of view this was necessary to let a wave field, crossing the route from south to north, pass (first picture of Fig.7). The fuel savings due to the reduced velocity exceeded the additional fuel consumption due to waves and due to a longer distance of the journey.

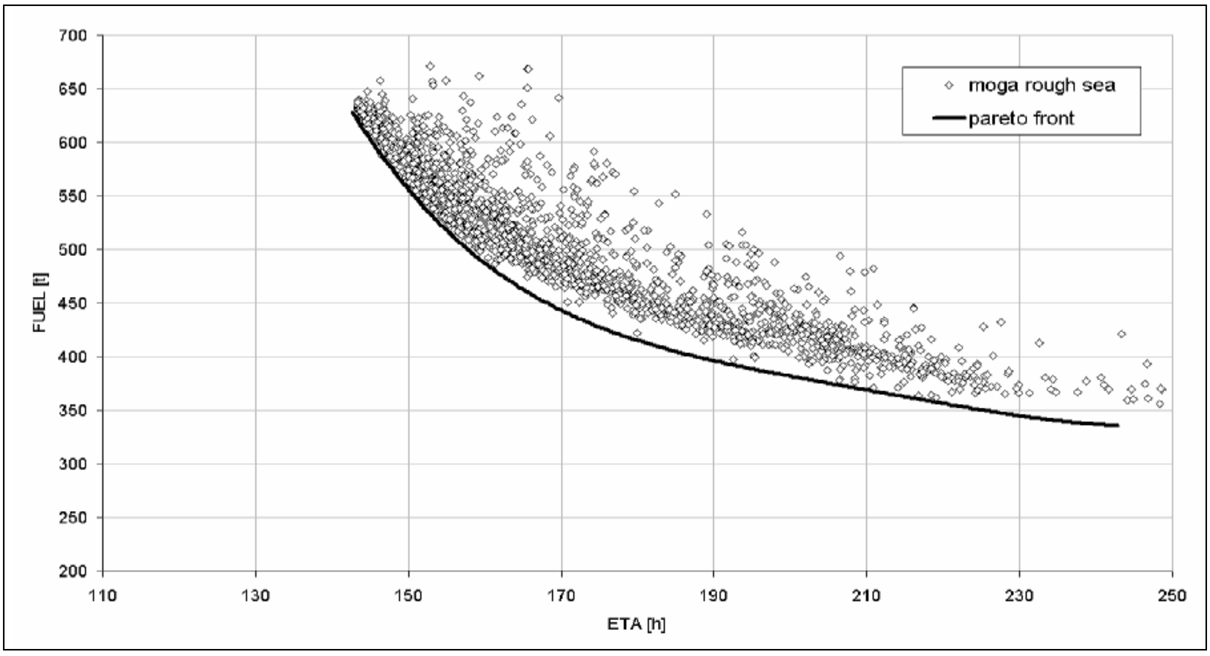

Fig.4: MOGA results and Pareto frontier

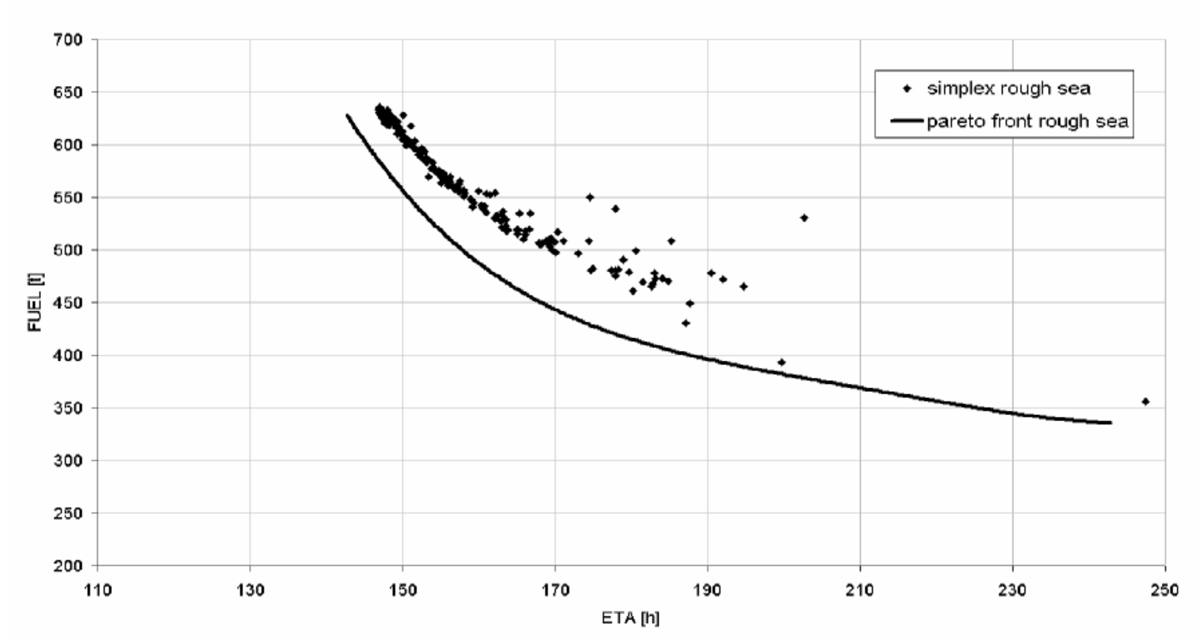

Fig.5: SIMPLEX optimization and Pareto frontier obtained by MOGA

Table 1: time minimum routes for different optimization strategies and sea conditions

ETA	FUEL	MOGA		SIMPLEX	
distance	design number				
calm sea condition		114 h	696 t	118 h	624 t
		2716 nm	7000	2722 nm	392
intermediate sea condition		119 h	686 t	121 h	713 t
		2717 nm	7000	2789 nm	302
rough sea condition		143 h	639 t	147 h	633 t
		2756 nm	7000	2813 nm	368

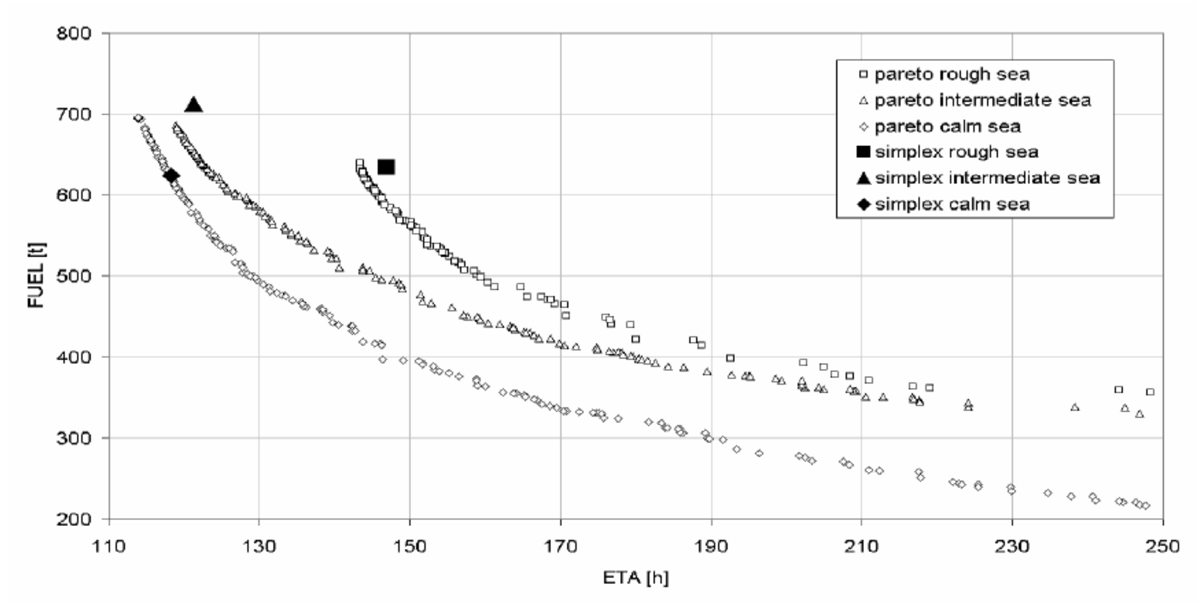

Fig.6: MOGA Pareto designs and time minimum routes obtained by SIMPLEX

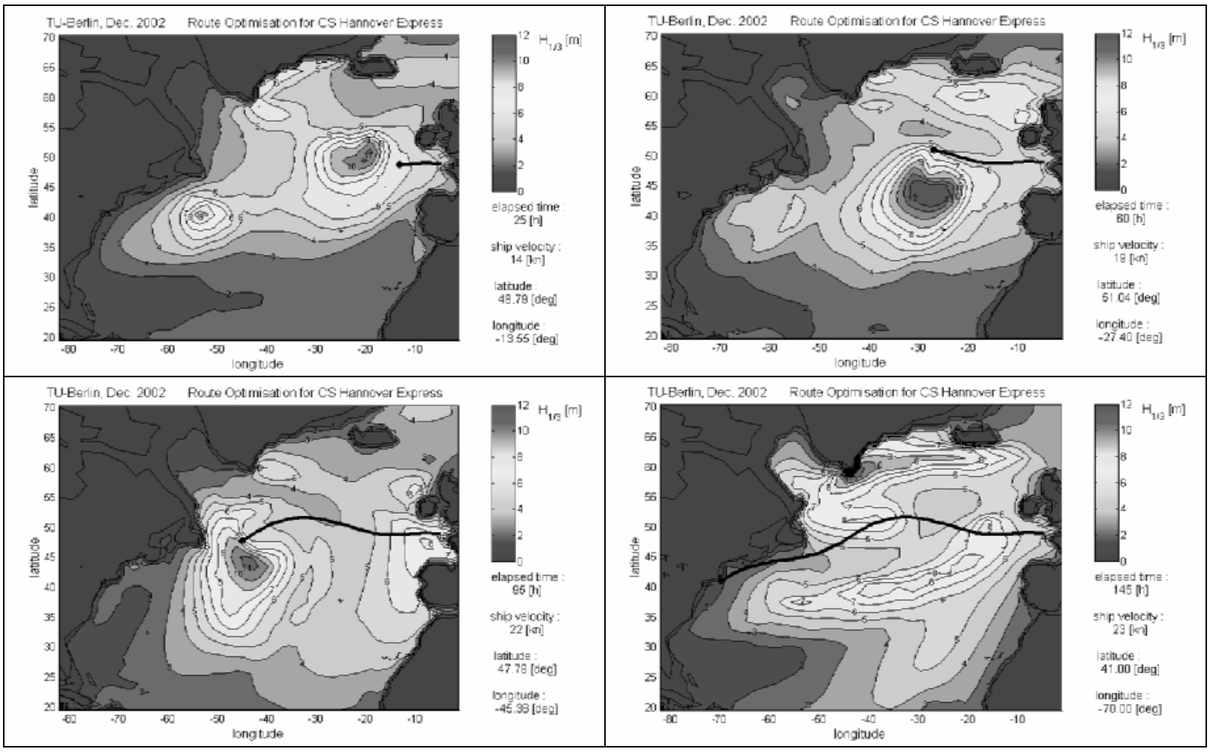

Fig.7: Optimized route, ETA = 143 h, fuel consumption 639 t

6. Summary and conclusions

Initially the paper provides a brief introduction into the mathematical description of a ship in waves used within the presented route optimization. A new approach for the spatial and temporal generation of design variants based on parametric curves has been presented. Investigations concerning the number of free variables showed that at least 9 variables for the description of the velocity profile and 7 variables to describe the course are necessary to obtain a sufficient temporal and spatial resolution of the route that correlates to the wave pattern as well as to the geographical conditions in the North Atlantic. The chosen B-spline description turned out to be a reliable method for the set-up of the route optimization task. The major advantage of parametrically modeled route- and velocity profiles lies in the reduced number of free variables. This enables the application of a stochastic algorithm with a reasonable time exposure.

Comparative investigations with different optimization methods showed that the algorithm must be able to avoid a premature stop at local optima. Two strategies, the deterministic SIMPLEX and the stochastic MOGA were utilized here. With the MOGA one may identify meaningful optima. (Other strategies, for instance simulated annealing, might also be considered but were beyond the scope of this study.) The decision making of the naval officer is supported by building up a significant amount of information from which the best compromise (Pareto optimum) can be found in accordance with individual preferences. A further aspect that should be kept in mind in the future is the probabilistic character of the weather and its forecast, *Hoffschildt et al. (1999).* As the optimized routes are guided closely along areas of rough sea condition, Fig.7, the reliability of the forecast has to be included into the evaluation of the optimization results and robustness ought to be taken into account.

Acknowledgement

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References

HOFFSCHILDT, M.; BIDLOT, J-R..; HANSEN, B.; JANSSEN, P.A.E.M. (1999), *Potential benefit of ensemble forecast for ship routing*, ECMWF Techn. Memo. 287, Internal Report, ECMWF, Reading/UK

HOLTROP, J.; MENNEN, G.G.J. (1984), *An approximate power prediction method*, International Shipbuilding Progress, Vol. 31

ITTC (1978), *Performance prediction method for single screw ships*, 15th Int. Towing Tank Conf., The Hague

JOURNEÉ, J.M.J. (2001), *User and Theoretical Manual of SEAWAY, Rel. 4.19,* TU Delft

MAN B&W (2000), *K90MC MK6 Project Guide Two-stroke Engines*, 5th Edition, www.manbw.dk

LEWIS, E.V. (Ed.) (1998), *Principles of Naval Architecture - Motions in Waves and Controllability*, SNAME, Jersey City

YASAKI, A. (1962), *Design diagrams for modern four, five, six and seven-bladed propellers developed in Japan*, 4th Naval Hydrodynamics Symp.