Pareto Optimal Routing of Ships

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ABSTRACT

The paper proposes a *pareto* optimal approach to selecting advantageous ship routes 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). Two weather situations - actual wave data for relatively calm sea as well as a severe storm passing through the North Atlantic - are considered. Differences in routing and the impact on operational criteria are discussed. The container ship's hydrodynamics is simulated via the sea keeping code SEAWAY.

Time loss, fuel consumption, accelerations and slamming are minimized on the basis of several performance models. The routes in adverse weather conditions are established as perturbations to a parent course near the optimum in calm weather that is assumed to be concatenated great circles between way points. Utilizing a B-spline technique rather than graph theory, the number of free variables for describing both the course and the voluntary speed reduction is kept low. In this way a high number of variants can be considered from which *pareto* optimal solutions may be identified. The commercial optimization package modeFRONTIER is applied to drive the optimizations and support the decision-making process.

The paper is intended to disseminate research that has been partly undertaken within the European R&D project SEAROUTES (Advanced Decision Support for Shiprouting based on Full-scale Ship-specific Responses as well as Improved Sea and Weather Forecasts including Synoptic, High Precision and Realtime Satellite Data).

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 and 20. to 30. of January 2002 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 routing 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 wave spectrum according to *Bretschneider*, cp. [8]:

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

$\omega_p = \frac{2\pi}{T_p}$, the modal frequency

$T_1 = 0.772 \cdot T_p$, transformation from mean to peak period, cp. [6].

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 [6] 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 according to *Gerritsma* and *Beukelman* as well as the integrated pressure method according to *Boese*, cp. [6]. 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 smother distribution over the wave frequency ω than its radiated energy counterpart).

Fig. 1 and 2 display the RAOs of heave, pitch, relative motion at the bow and the RFs of the added resistance due to waves as computed with SEAWAY. The figures serve to illustrate the input to the response simulations within the optimization.

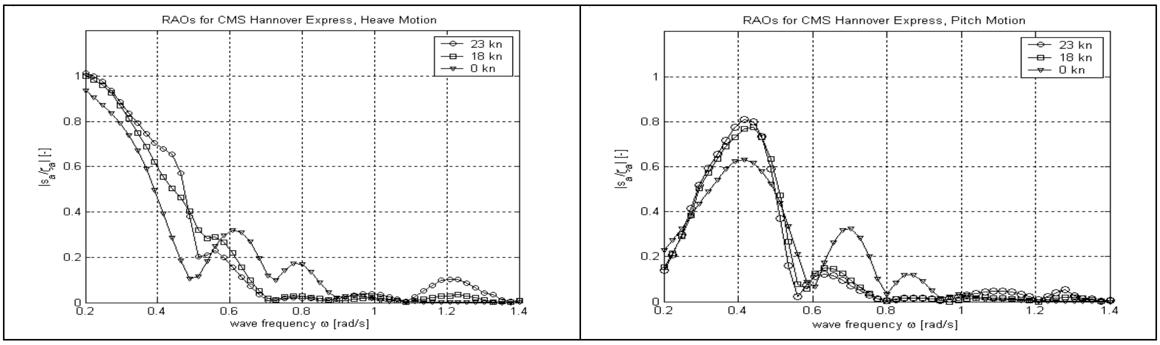

Fig. 1, RAOs of the heave and the pitch motion

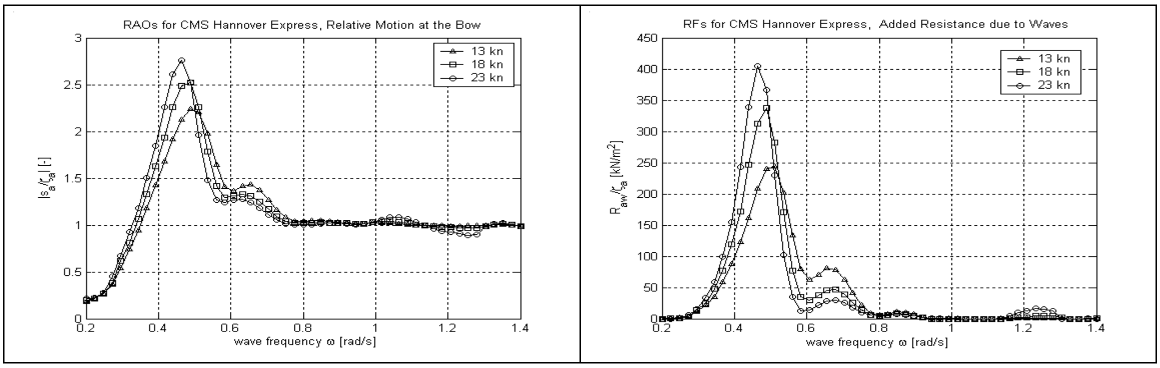

Fig. 2, RAOs of the relative motion at the bow and RFs of the added resistance

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:

$$\ddot{s}_{a1/3} = 2.0 \cdot \sqrt{m_{4s}} \,. \tag{4}$$

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*, cp. [6], 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 of 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:

$$R_{AW} = \int_{0}^{\infty} RF \cdot S_{\zeta}(\omega)\, d\omega . \qquad (7)$$

The determination of the calm water resistance is based on a regression analysis of model tests and full-scale data, as presented in [4].

The operating point of the propeller was calculated according to the ITTC power prediction method [5], using the characteristic of a propeller with the same diameter, number of blades, similar pitch and blade area ratio as given in [9].

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 [7].

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). 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. The geographical feasibility was checked during the optimization process.

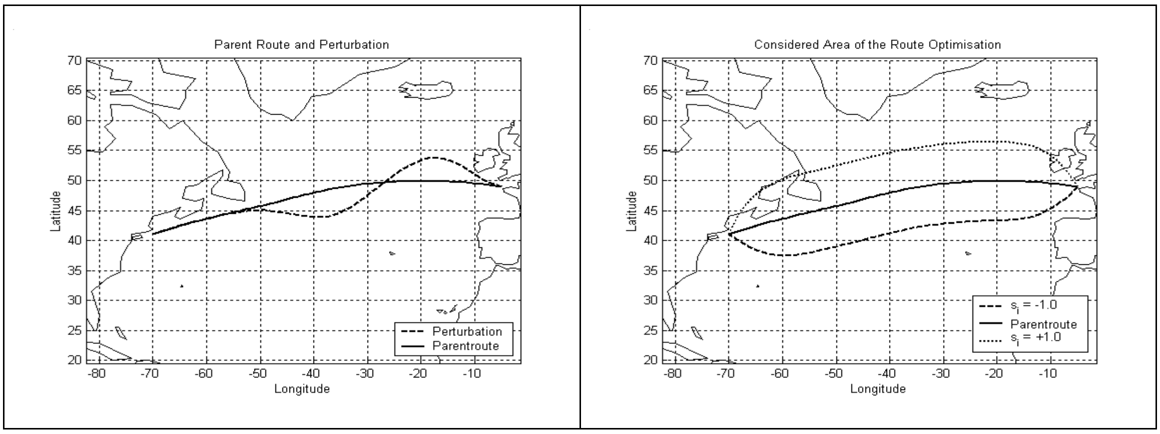

Fig. 3, parent route, perturbation and investigated area

Fig. 3 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.

Constraints were imposed by defining limiting values for the slamming probability (3%) and for the lateral (0.2 g) and vertical accelerations (0.12 g, g = 9.807 m/s^2).

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. The objective functions were formulated as follows:

$$\text{Objective} = \text{weight} \times (\text{actual value} - \text{target value})^2. \qquad (8)$$

The target values for the rough weather condition were derived from the optimum results at calm water conditions (ETA = 110 hours after departure, FUEL = 700 tons). The ETA value matches the estimated duration of a journey as stated in the sailing lists of the ship operator. The utilization of a target value for the fuel consumption helps to avoid unrealistically slow velocities.

The weight assigned to ETA and FUEL were 1.0 and. 0.1, respectively, so as to produce objectives of an equal magnitude at the biggest deviants of the target values.

5 OPTIMISATION WITH modeFRONTIER

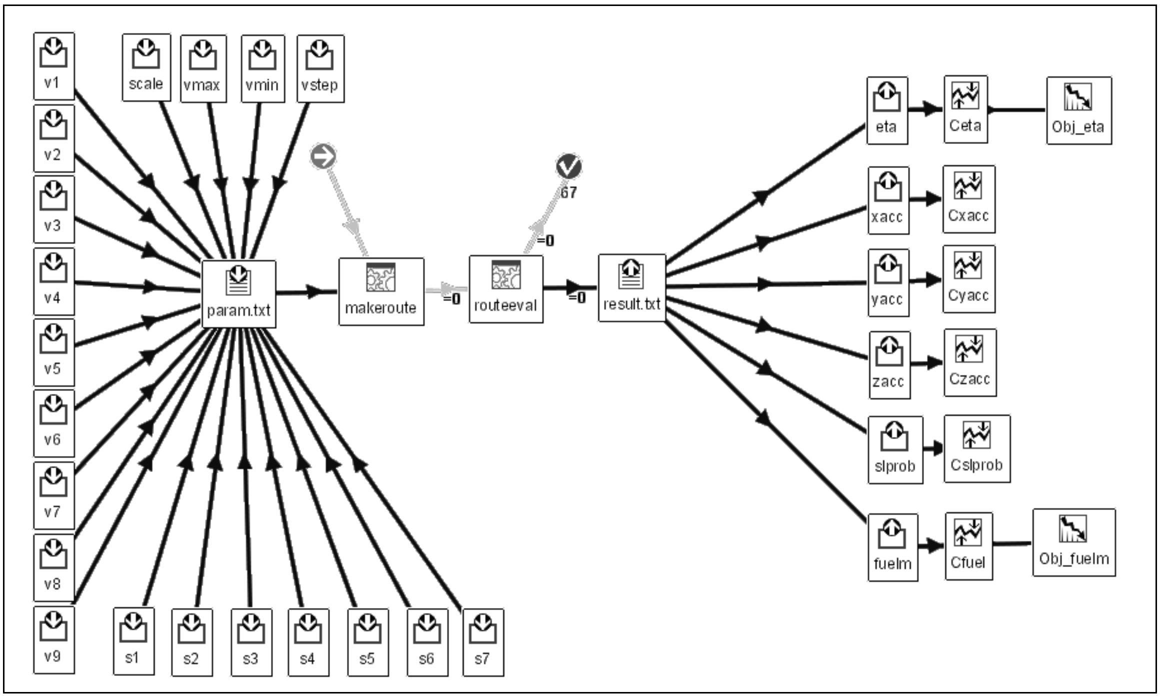

Fig. 4, modeFRONTIER flow chart

For the optimization task the generic optimization software modeFRONTIER was utilized, cp. [1]. The process flow depicted in Fig. 4 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 (routeeval) is evaluated to return the result file (result.txt). Finally, the optimization routine observes the constraints, calculates the objectives and, if necessary, launches a new investigation.

Studying the calm sea condition served as a test case for evaluation. Aiming to arrive as early as possible, the optimum route could easily be found by running a deterministic search strategy (SIMPLEX). 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. The optimum route was the shortest feasible route at design speed. Running a multi-objective genetic algorithm (MOGA) gave the same results but with much more computational demands.

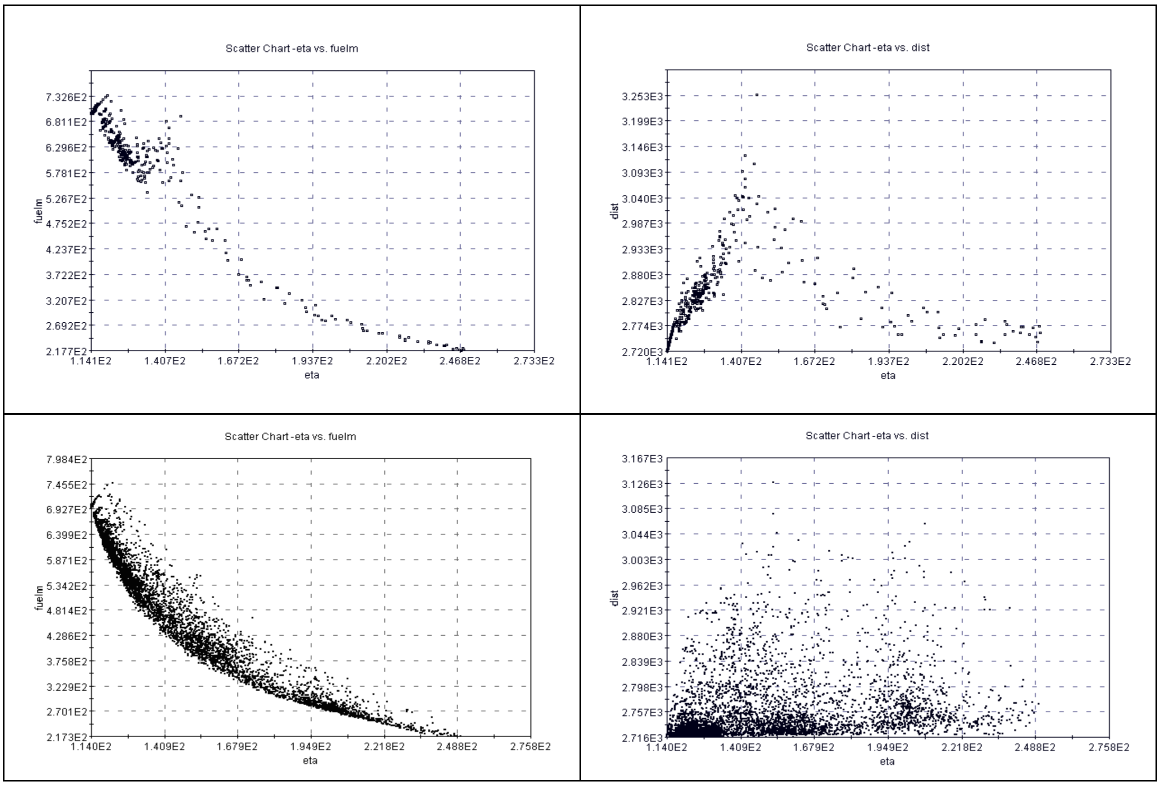

Fig. 5, results of the investigations at calm sea condition

Fig. 5 summarizes the results The upper part of Fig. 5 shows the SIMPLEX results, the lower part those of the MOGA. On the left side the fuel consumption is depicted while the distance of the journey versus the estimated time of arrival is presented on the right side. Both methods show that the fastest route is also the shortest. This is no surprise but rather confirms the validity of the set-up.

First optimizations regarding the rough weather case showed a strong dependency of the optimization results on the applied optimization method as well as on the formulation of the objectives. To avoid infeasible designs due to active constraints, the initial designs had to be generated at a low speed level. Again a SIMPLEX algorithm and a MOGA had been applied. Compared to the calm water situation the results strongly differ, because the SIMPLEX algorithm was only able to find a local optimum (as is expected with a deterministic search strategy).

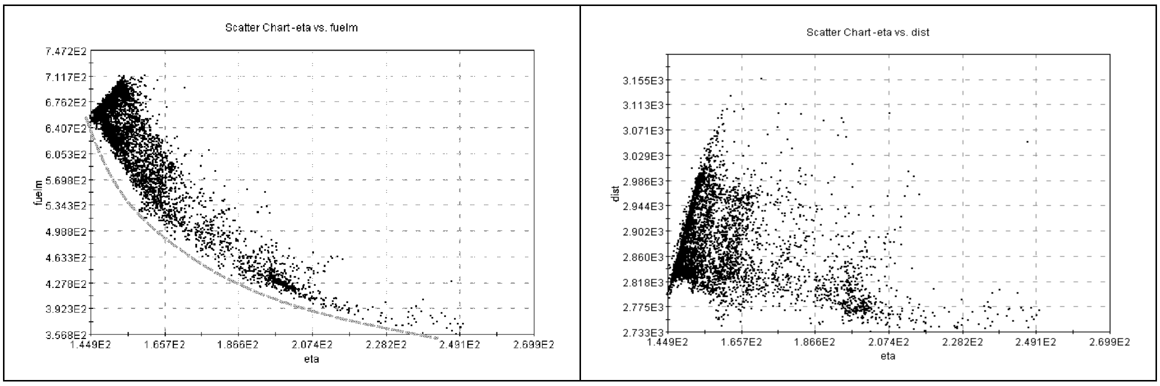

Fig. 6, MOGA results of the investigations at rough sea condition

The left part in Fig. 6 nicely shows the Pareto front for FUEL vs. ETA – 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 front. Those variants that are closest to the front display low passage time for reasonably low fuel consumption. Apparently, it is impossible to decrease ETA below certain limits without impairing FUEL.

Fig. 7 illustrates four steps of an example route here with lowest ETA (145h). The isolines represent the current significant wave height during the crossing, the route and the actual position of the ship 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 exceed the additional fuel consumption due to waves. The extreme speed reduction causes a somewhat unreliable operating condition for the main engine. To overcome this reduced speed phase at the beginning of the journey, one could also delay departure or wait in sheltered sea areas.

Compared to a route optimization based on the *Bellmans* isochrone method [2,3], the advantage of the route optimization presented here lies in the provision of a feasible domain for decision support. Each route presented by a dot in Fig. 6 can be selected and taken into account for a route decision considering ETA and FUEL. But also individual preferences concerning the slamming probability or allowable accelerations can be regarded. Consequently a more conscious decision can be made on 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.

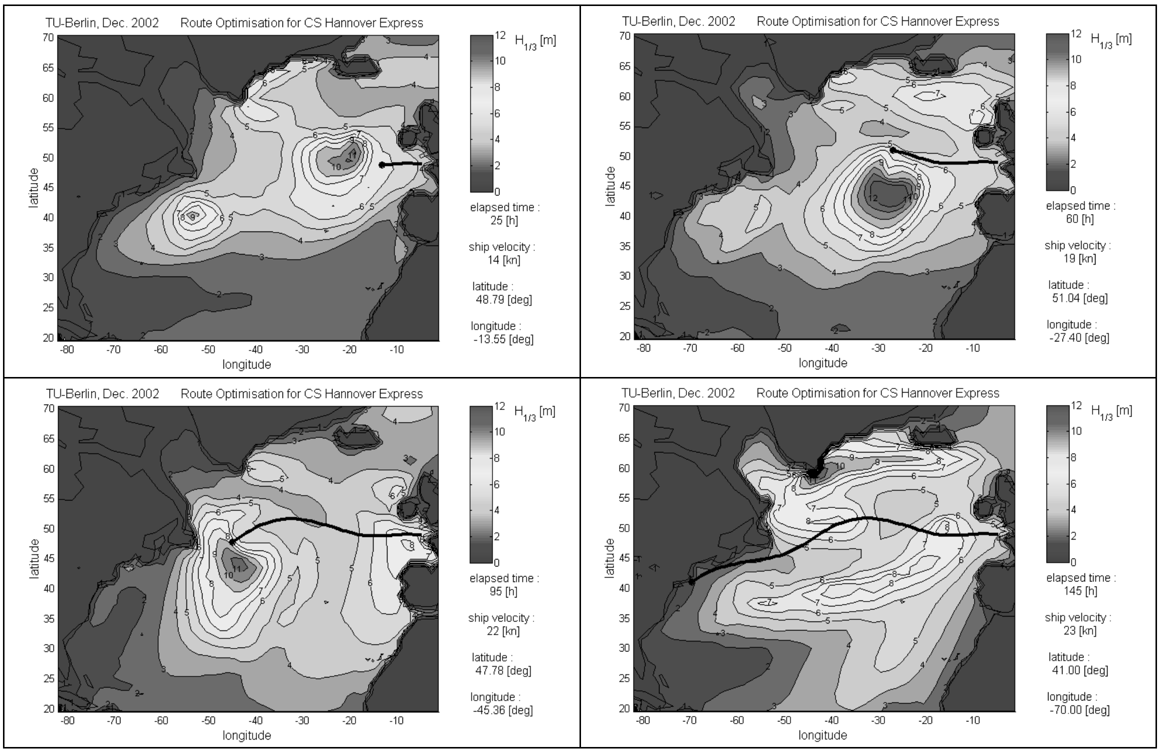

Fig. 7, optimised route, ETA = 145 h, fuel consumption 656 t

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.

First passes show that the utilization of a MOGA provides meaningful results, in particular when optimizations are governed by opposing targets. The investigations concerning the two different optimization methods at different weather situations are summarized in Tab. 1. The values belong to calculations that were aimed at the earliest arrival.

sea condition	calm sea, Jun. 2001		rough sea, Jan. 2002	
objective	SIMPLEX	MOGA	SIMPLEX	MOGA
ETA [h]	114	114	182	145
FUEL [t]	698	699	465	656
distance [sm]	2720	2716	2765	2796

Tab. 1, summarized optimization results

Besides the applicability of the MOGA to identify a meaningful optimum the decision making of the naval officer is supported by means of 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 forecast, cp. [3]. As the optimized routes are guided closely along areas of rough sea condition (cp. Fig. 7) the reliability of the forecast has to be included into the evaluation of the optimization results.

7 ACKNOWLEDGEMENT

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