Hull form optimization of a high-speed wave piercing monohull

Conference Paper · January 2006

2 authors:

Evangelos Boulougouris
University of Strathclyde

Apostolos Papanikolaou
Hamburgische Schiffbau-Versuchsanstalt GmbH

HULLFORM OPTIMIZATION OF A HIGH SPEED WAVE PIERCING MONOHULL

Evangelos K. Boulougouris[1] and Apostolos D. Papanikolaou[2]

ABSTRACT

During the last decade an increased interest in the design of wave-piercing (tumblehome) monohulls is noted. This hullform concept has been also within the EU research project VRSHIPS-ROPAX2000 as a candidate for fast shortsea RoPax operations. An optimization procedure has been developed and applied to investigate possible improvements of the hydrodynamic performance of the initial hullform with respect to total resistance and seakeeping by the introduction of a bulbous bow and the main results of this study are presented herein.

KEY WORDS

Hullform design; wave-piercing-monohull; hydrodynamics; optimisation; multi-objective; genetic-algorithms; seakeeping; resistance

INTRODUCTION

During the last decade *an increased interest in the design of wave-piercing (tumblehome) monohulls is noted.* The advantages of this type of hullform have been acknowledged through a wide range of applications, varying from naval combatants such as U.S. Navy's next generation destroyer DD(X), to innovative large RoPax ferries. The latter is the case for the hullform design developed by ALSTOM - Chantier de l'Atlantique within the EU Research project VRSHIPS-ROPAX2000 (Goubault et.al. 2004). To investigate any further improvements of the hydrodynamic performance of the initial hullform, an optimization procedure for minimum total resistance and improved seakeeping behavior has been developed and is presented herein, based on previous experience of NTUA-SDL (Zaraphonitis et.al 2003; Boulougouris et.al. 2004) and the integration of a number of specialized software packages. The results from the application of the above procedure to the optimization of the forebody of the initial hullform design are herein presented and discussed.

BACKGROUND

The design proposed for the VRSHIP-ROPAX is based upon a novel type of displacement hullform with very fine extremities; a wave piercing bow and a low block coefficient (see Figure 1). According to the designers this type of hullform had shown very good calm water performance when operating at the corresponding Froude numbers of about 0.40 (Goubault et.al. 2004). The final principal particulars of the ROPAX 2000 are given in Table 1.

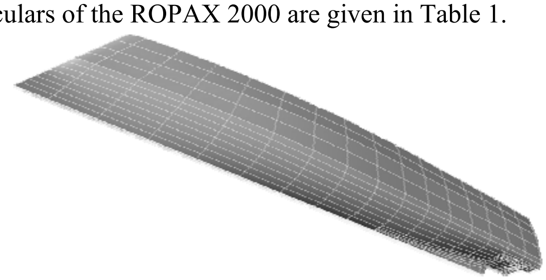

Figure 1. RO-PAX 2000 hullform

[1] National Technical University of Athens, School of Naval Architecture and Marine Engineering, Ship Design Laboratory, vboulg@deslab.ntua.gr
[2] National Technical University of Athens, School of Naval Architecture and Marine Engineering, Ship Design Laboratory, papa@deslab.ntua.gr

Table 1. Principal Particulars

Length overall	237.2 m
Beam overall	32.0 m
Draft	7.0 m
Hull depth (to strength deck)	21.1 m
Waterline length	229.2 m
Waterline beam	29.1 m
Payload	
Lane meters	2000
Passengers	2000
	400 cabins
Service Speed	38 knots
Range	
Nominal	500 NM
Long transit	2 000 NM

OPTIMIZATION PROCEDURE

The set objective was to improve the hydrodynamic performance of the initial ROPAX 2000 hullform with the addition of a properly designed bulbous bow. The hydrodynamic performance characteristics that were herein of interest, were the resistance and the seakeeping. For achieving the above objective, a generalized optimization procedure was developed and implemented.

SDL Optimization Outline

An optimization procedure of a system ***S*** is comprised in general of the following elements (Nowacki et.al. 1970):

- The Input E_I
- The Design Variables ***D***
- The Design Parameters ***P***
- The Merit functions ***M***
- The Constraints ***G***
- Output E_O

The setup of these elements in order to properly formulate the optimization procedure is shown in Figure 2.

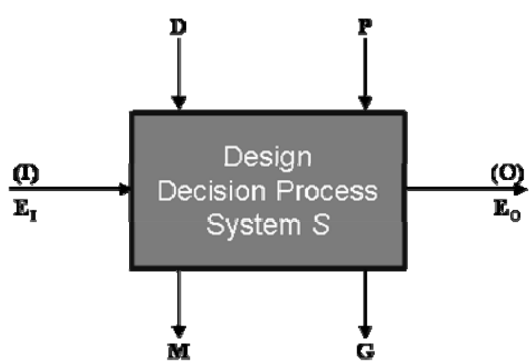

Figure 2. Generic Optimization procedure setup (Nowacki et.al. 1970)

Based on the above definition, SDL-NTUA has developed a generic ship design optimization framework for the internal compartmentation (Boulougouris et.al. 2004) and external hullform development (Zaraphonitis et.al. 2003), shown in Figure 3. The procedure implemented in the present optimization problem is part of this framework. The design pool in the heart of this framework is created by a parametrically defined design and a systematic variation of the design variables, using a set of design parameters (shown at the top in Figure 3). The procedure considers the fulfillment of a set of constraints (shown at the bottom-left) while at the same time a set of objectives is optimized (bottom-right). The whole process is initialized by the provision of relevant owner's (mission) requirements or in our case by the parent/initial hullform.

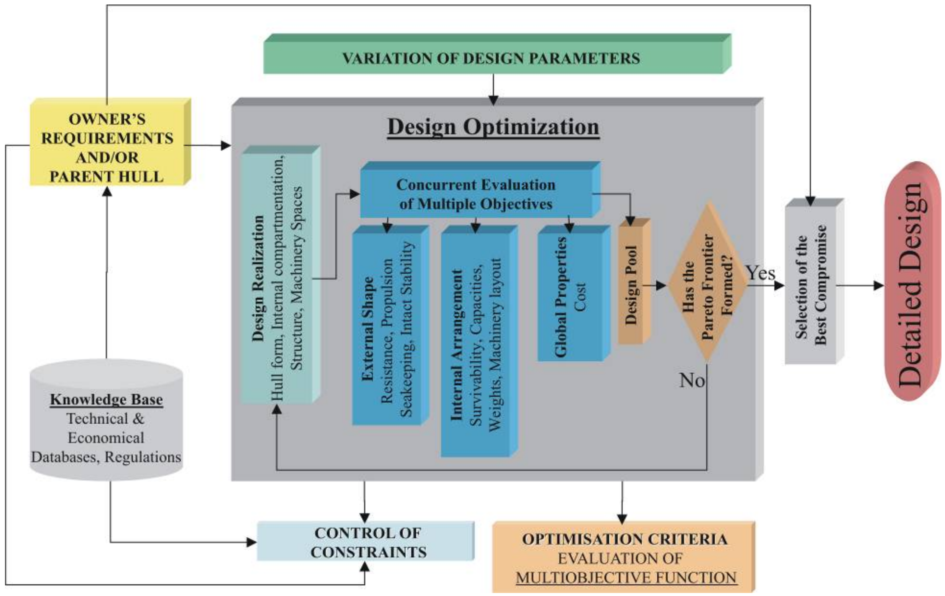

Figure 3. Ship Design Optimization procedure (Boulougouris 2003)

In the present optimization problem the following objectives should be optimally met:

- Minimization of ship's resistance.
- Minimization of ship's motions.

While the former objective definition is straight forward, the latter is less exactly defined. The ship is moving in six (6) degrees of freedom and one might consider motions, velocities and accelerations at ship's centre of gravity or at critical locations e.g. at passenger cabins or at the bridge as a criterion for minimization. There are two (2) basic approaches to this problem:

- To select a subset of motions, velocities and acceleration and a number of critical of points on the ship and treat each of them as an independent objective functions.
- To generate a 'seakeeping performance index' that integrates all the above by assigning weighting factors to the various seakeeping quantities of interest that could also be parameters in the global optimization problem.

In the present optimization procedure the seakeeping performance was optimized only with respect to a minimization of the vertical motion response of ship's CoG at pitch resonance. Given the fact that there is very little information about the mathematical properties of the objective space of the present problem and in order to handle multiple objectives and constraints, the adoption of multi-objective genetic algorithms (GA) seems like the only rational option for the present optimization problem (Sen and Yang 1998).

Software Tools

The implementation of the presently presented optimization procedure requires the use and integration of a number of specialized software applications, namely:

- A geometric parametric definition procedure for building the parametric model of the ship.
- Reliable resistance prediction code able to handle the complex hydrodynamic behavior of the novel hullform.
- Seakeeping prediction code able to assess the performance of the ship in irregular waves, given by seaway spectra.
- Optimization software able to coordinate the calculations of the various applications and detect the actual Pareto frontier i.e. the non-dominated designs.

For the parametric definition of the hullform SDL-NTUA selected the well known naval architecture software ***NAPA* (**NAPA 2005). The geometry of the original hullform was redefined based on the IGES file but using a hull definition of curves and surfaces that permitted a more efficient parameterization. The body plan of the delivered hullform as it was defined in NAPA is shown in Figure 4.

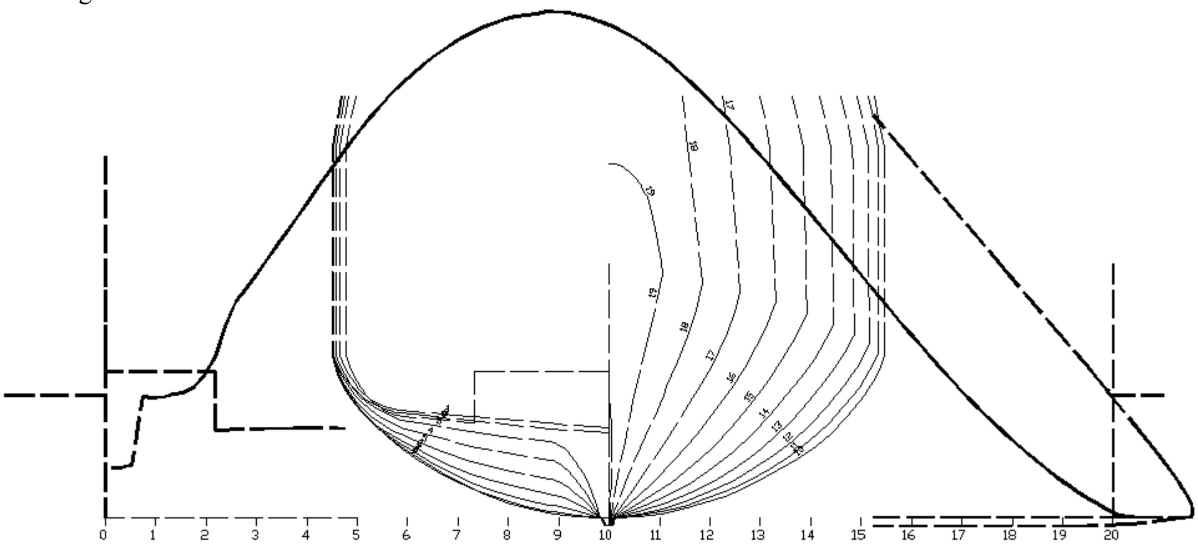

Figure 4. Bodyplan of original hullform

Shipflow, a well-known commercial CFD code of *Flowtech* is employed for the calculation of resistance. The code actually considers both potential (ideal) and viscous flows. Due to the enormous calculation effort, however, viscous flow calculations are not suitable for optimization studies requiring the assessment of a large number of alternative hull forms. Therefore, applying the basic assumptions of ideal fluid and irrotational flow, potential flow theory is used for the wave resistance calculation, and the viscous part of resistance is approximated by use of the ITTC frictional drag coefficient formula adding a form factor. The potential flow calculations module integrated within Shipflow is based on a 3D Rankine sources distribution method, with the sources being distributed over the ship's wetted surface and over the sea free surface (Larsson et.al. 1990).

The seakeeping calculations are herein conducted using the SDL-NTUA code ***NEWDRIFT***. It is a 6DOF, 3D panel code for the seakeeping and wave induced loads analysis of ships and arbitrarily shaped floating structures, including multi-body arrangements. The code enables the evaluation of 6DOF first- and quasi second-order motions and wave-induced loads, including drift deviations, forces and moments and is applicable to arbitrarily shaped 3D floating or submerged bodies (like ships, floating structures or underwater vehicles), operating at zero or nonzero forward speed, finite or infinite water depth and being excited by sinusoidal linear waves or arbitrarily frequency and heading. The consideration of natural seaway excitation is enabled through a spectral analysis postprocessor, given the incident seaway spectral characteristics (Papanikolaou and Zaraphonitis 2001).

A sample of the panelisation of the original hullform for use in the hydrodynamic calculation programs is illustrated in Figure 5.

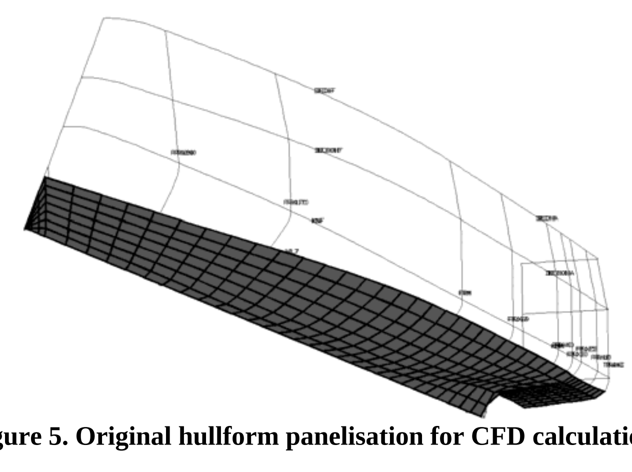

Figure 5. Original hullform panelisation for CFD calculations

The optimization scheduler is the commercial software *modeFRONTIER* (E.STE.CO 2003). Important features of *modeFRONTIER* are:

- It is written 100% in Java making it completely portable.
- It offers a menu of several optimization algorithms: genetic algorithms, conjugate gradient method, quasi-Newton method, sequential quadratic programming, simplex. Algorithms can be combined, e.g. genetic algorithms for global search and another algorithm for local search (refinement).
- It can handle both real and integer variables
- It can integrate software on different platforms in networks, e.g. a hull description in NAPA under *MS Window 2000* and a CFD code under *UNIX* on another computer.
- It allows checking first boundary conditions, before an objective function is evaluated. This is important if the objective function requires far more CPU time than the (violated) boundary condition.
- It runs on parallel architectures.

The data flow between the 4 applications is shown in Figure 6.

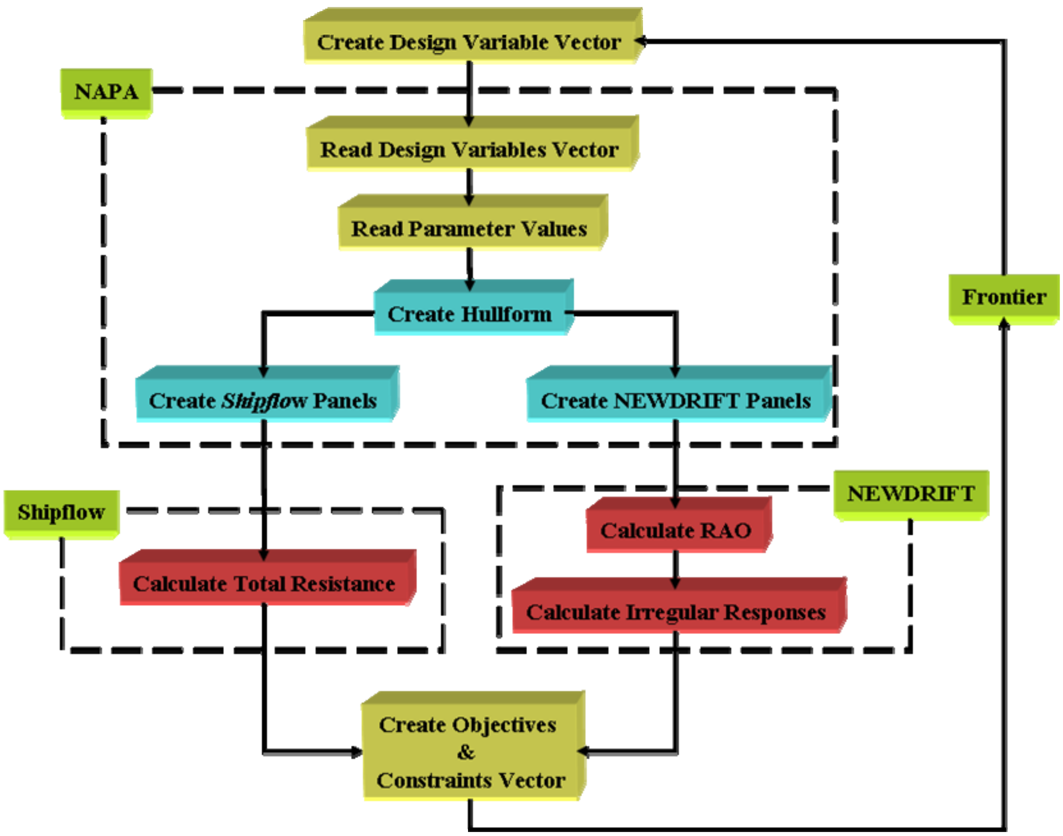

Figure 6. VRS SDL-NTUA optimization data flowchart

Initial runs

Due to the novel character of the ROPAX 2000 hull form and the fact that existing hydrodynamic software had not been validated before with respect to this type of hull form, it was considered necessary to use the results of model tests so that the hydrodynamic software could be fine-tuned before going to the actual hull form optimization. The preliminary results of the model tests and the extrapolated values provided by MARIN (2005) were used for this purpose.

Using the initial hullform, a SHIPFLOW input file was prepared and calculations were first performed modifying systematically the mesh densities of the geometric model of the hullform, the sea surface and the extent of the sea surface modeled around the ship. The selection of the final mesh density was a compromise between satisfactory accuracy and calculation time. In Figure 7 the wave elevation from one of these runs is shown.

Based on model measurements, MARIN extrapolated the full scale Total Resistance Coefficient, namely C_t and the Total Resistance of the bare hullform MARIN (2005), shown in Figure 8. The latter was compared with the C_t calculated numerically using SHIPFLOW. The results show that SHIPFLOW calculated values of C_t are approximately 75% of the predicted values according to the model tests. On the other hand, qualitatively both resistance curves show the same characteristics. This is also shown in Figure 8.

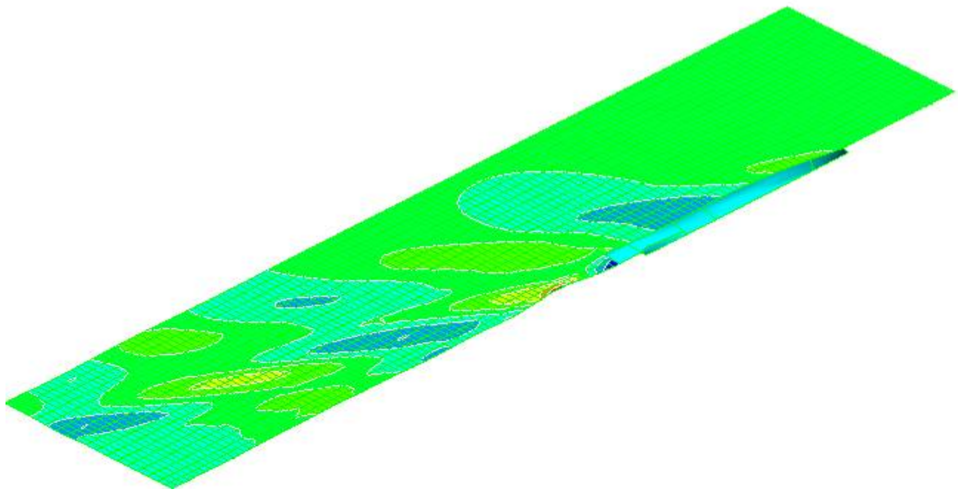

Figure 7. Wave pattern of RO-PAX 2000 hullform according to numerical calculations

Another comparison made for the verification of the employed resistance code was that of the dynamic trim calculated numerically against the relevant values measured in the model tests. The results are shown in Figure 9. It is obvious in this case that although the match of the numerical values is not satisfactory, the same trend is present.

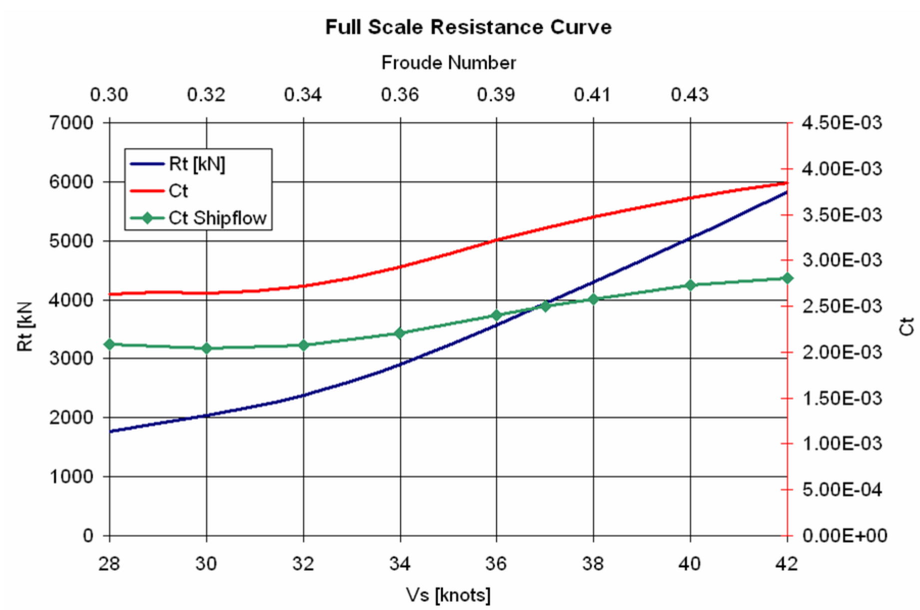

Figure 8. Full scale Resistance Curve according to model tests and comparison of C_T coefficient results of model tests and SHIPFLOW calculations

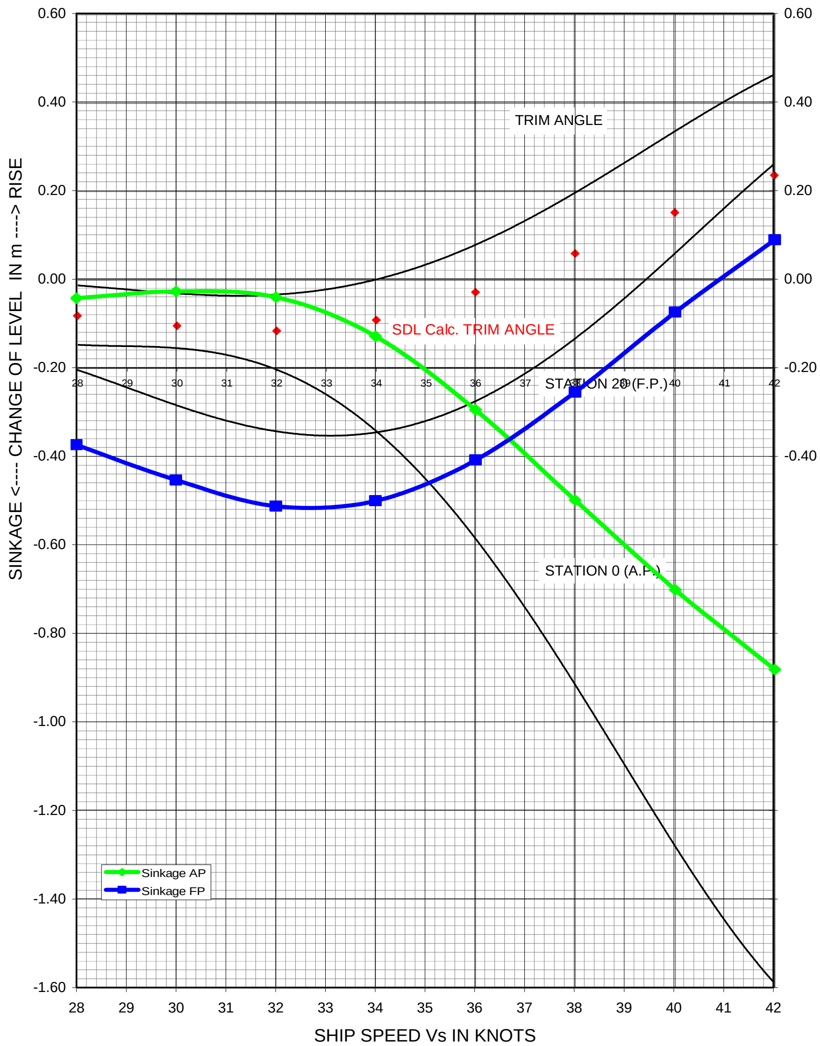

Figure 9. Trim diagram according to model tests and numerical calculations

Similar verification calculations were performed using the NEWDRIFT seakeeping code. The results for head waves excitation are presented in the form of the Response Amplitude Operators (RAO) for various speeds.

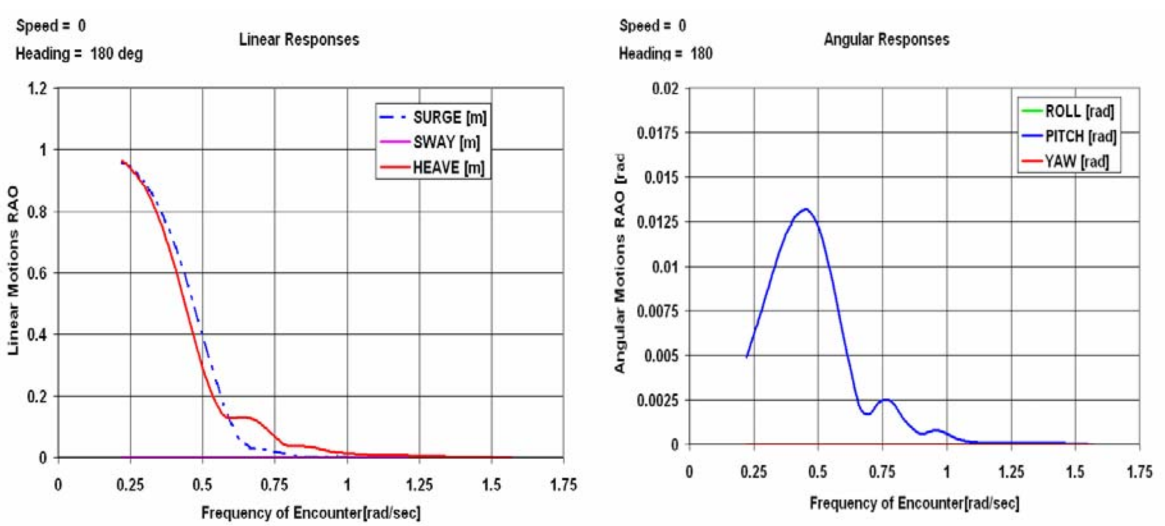

Figure 10. RO-PAX 2000 RAOs in head seas, at zero speed

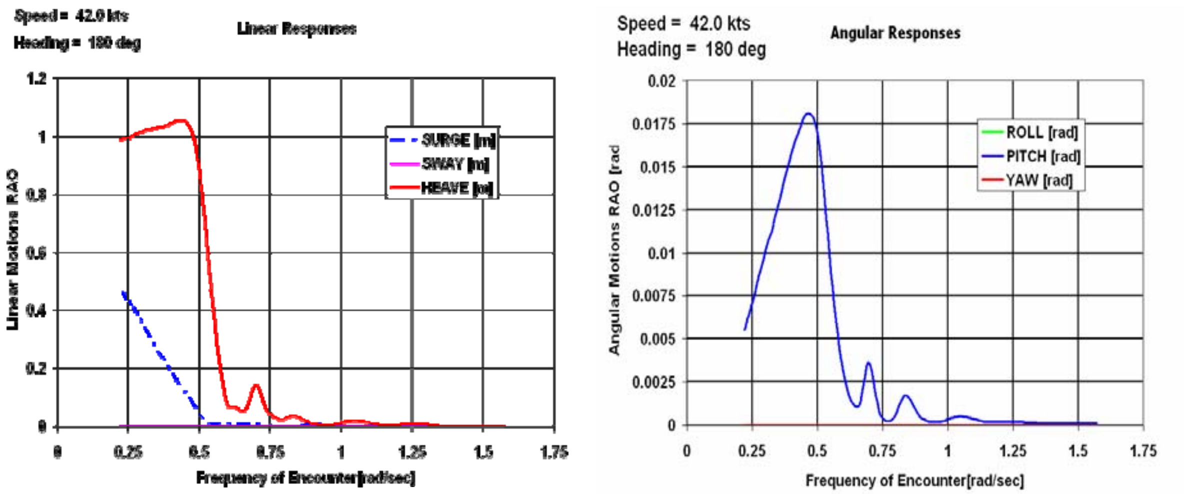

Figure 11. RO-PAX 2000 RAOs in head seas, at 42 kts

Parametric model

The parametric definition of the bulbous bow of ROPAX 2000 was based on the use of three (3) sets of parameters:

Kracht's bulbous bow parameters (Kracht 1978)

- LBLB: length of bulbous bow
- HBLB: height of bulbous bow at max length
- YBLB: max half breadth of bulb at FP

Kvaerner Masa-Yards' additional parameters (Hamalainen and Heerd 2002)

- ZB1: Height were max half breadth of bulb at FP
- BB1: max half breadth of bulb at FP+LBLB/2
- ZB2 : Height were max half breadth of bulb at FP+LBLB/2

Additional 3 parameters introduced for the specific problem

- ZSTEMax: Maximum height of bow profile at stem
- XBBMAX: length of bulbous bow at max height
- ZBBMAX : Maximum height of bow profile

Using the introduced 9 bulbous bow design parameters a large number of offspring hullforms were created. An example is shown in Figure 12.

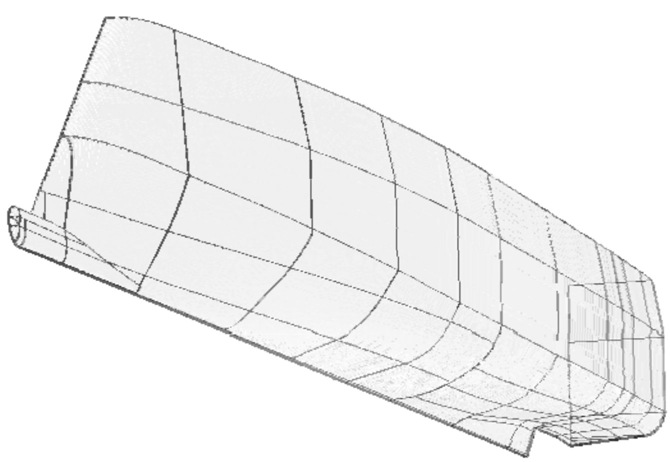

Figure 12. Sample of offspring hullform with bulbous bow

Link with numerical tools

Using NAPA macros, a link was established between the parametrically defined hullform and the numerical tools, namely SHIPFLOW and NEWDRIFT. A sample grid for the NEWDRIFT seakeeping code is shown in Figure 13.

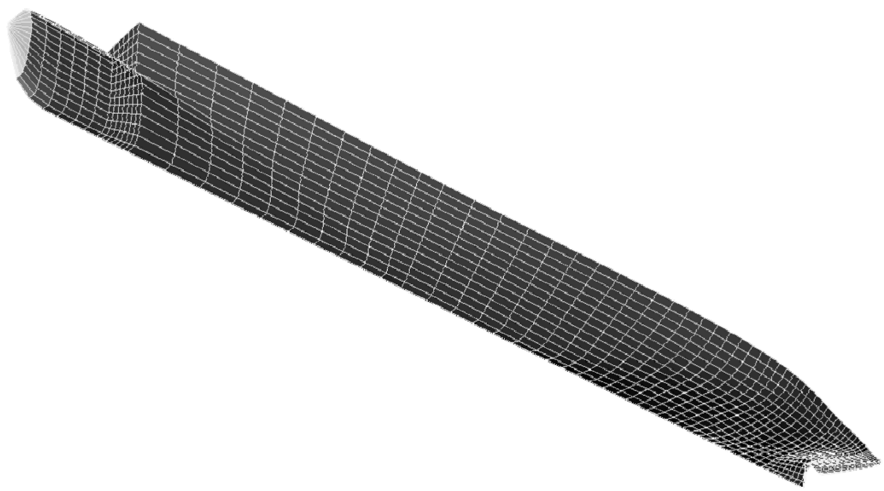

Figure 13. Sample mesh grid for NEWDRIFT calculation code

Multiple Objectives

The set-up procedure addresses the optimization of multiple objectives, namely herein:

- Minimization of ship's resistance@38 kts
- Minimization of ship's motions@38kts
- Minimization of ship's displacement volume increase (due to the addition of a bulbous bow)

The multiple objectives and the little information about the design space supported the selection of the Multi-Objective Genetic Algorithm (MOGA) for the investigation of the Pareto Frontier. The process flow defined in *modeFrontier* is shown in Figure 14.

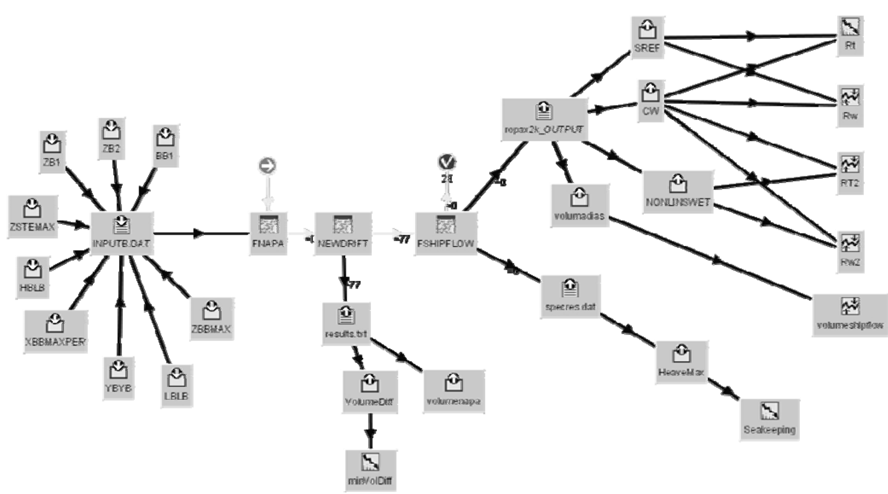

Figure 14. Optimization process flow in *modeFrontier*

RESULTS

SHIPFLOW requires the identification of any free-surface piercing bodies by the user. Therefore, two different sets of calculations were performed. The first one included fully submerged bulbs and the second one included only surface piercing bulbs.

Fully submerged bulb designs

A number of approximately 215 designs have been created for the exploration of the feasible design space. The scatter diagram of these results is depicted in Figure 15 and Figure 16 below.

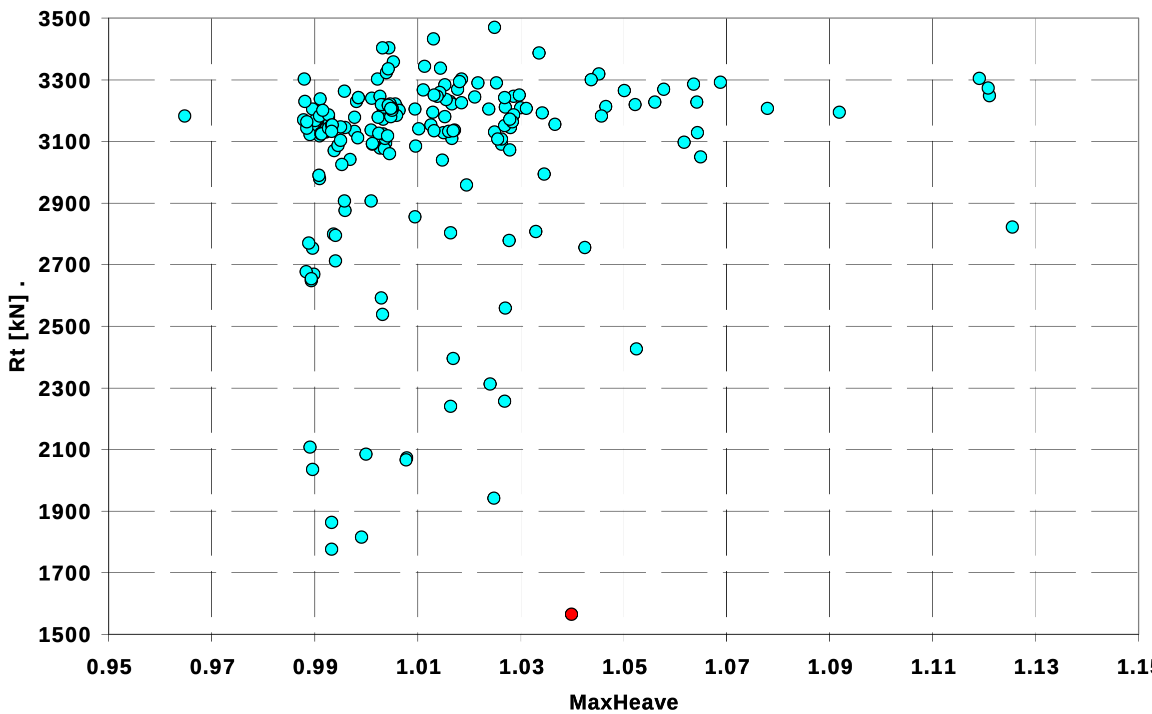

Figure 15. Total Resistance vs. maxHeave for designs

Some of these designs appear to have unrealistic very low resistance but unfortunately this was due to 2 types of *SHIPFLOW* code failures:

- Prediction of unrealistic, negative values of C_W that resulted to total resistance values below 1600 kN (see red dot at the bottom of Figure 15).
- Prediction of unrealistic very small positive values of C_W due to the fact that the code did not converge at the user-defined number of iterations.

The Pareto designs were identified and a new set of calculations with coarser computational grid was initiated to verify the results. Unfortunately, the reverse resistance prediction for those identified optimal designs did not confirm the first set of calculations. The resistance calculated with the second set of calculations appeared very close to the resistance of the initial hullform (without bulb). This outcome revealed that there was a risk of choosing "virtually" good design. This has been also pointed out earlier by the SHIPFLOW developers (Janson and Larsson 1996). Therefore, the following procedure was established to minimize this risk:

- Criteria were set for accepting the resistance of a design as realistic. These were the consistency it presented using different computational grid densities and the small sensitivity to draught change.
- A set of apparently good designs was selected and their resistance was calculated with a finer computational grid.
- Those designs that were relatively insensitive to computational grid density were checked again at a slightly reduced draught (16cm lower that design draught).

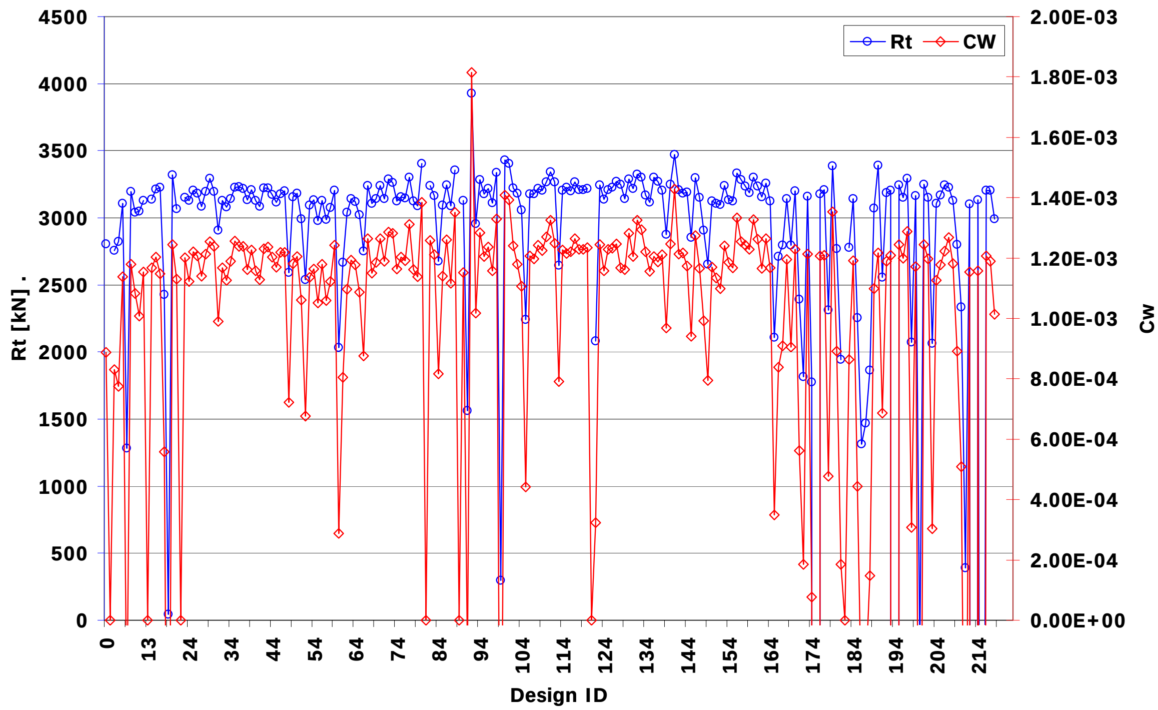

Figure 16. Total Resistance and C_W acc. to SHIPFLOW for light mesh

The first set of designs with apparently low resistance, ranging from 1745 to 2957 kN, included 37 hulls. The results are shown in Figure 17. Their panelisation is depicted in Figure 18 to Figure 53.

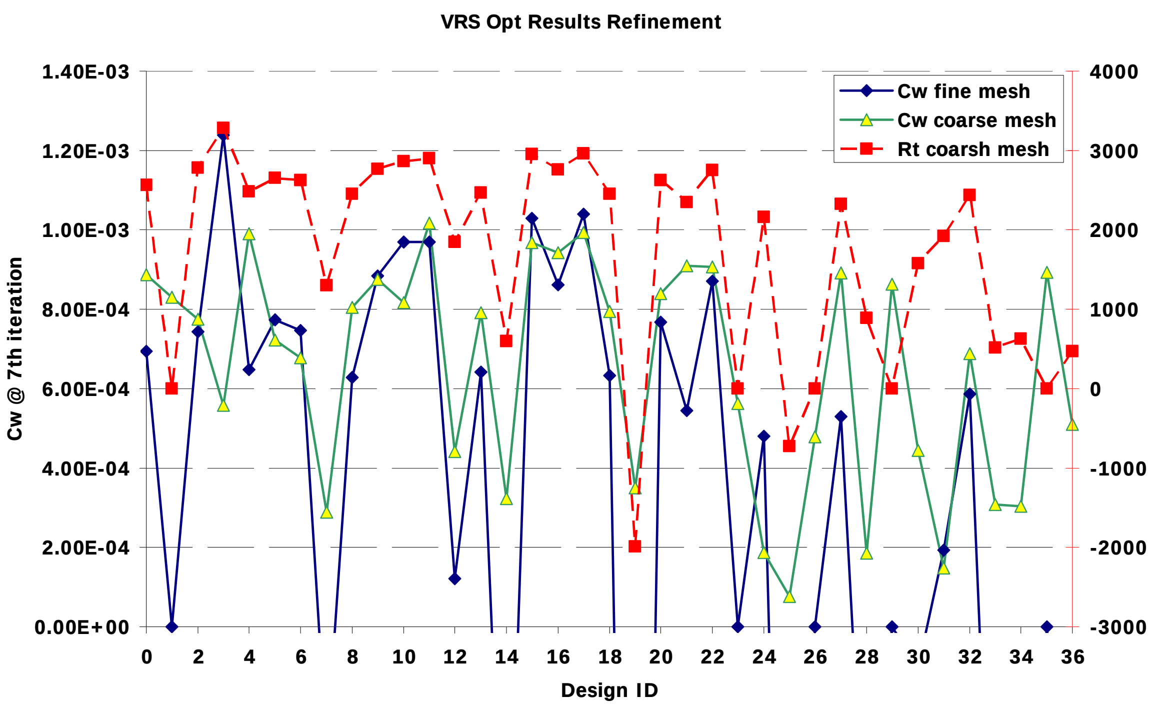

Figure 17. Total Resistance and C_W calculation for dense mesh

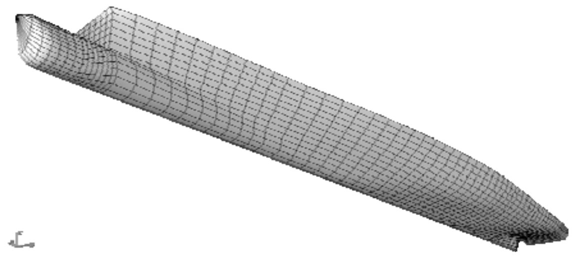

Figure 18. Panelisation of Design_0000

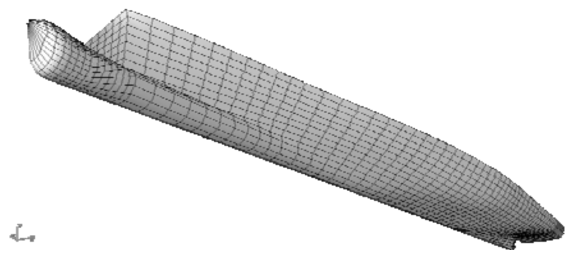

Figure 19. Panelisation of Design_0001

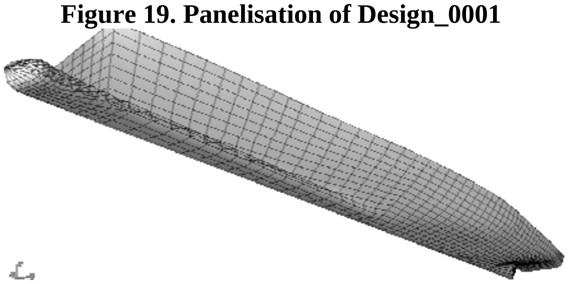

Figure 20. Panelisation of Design_0002

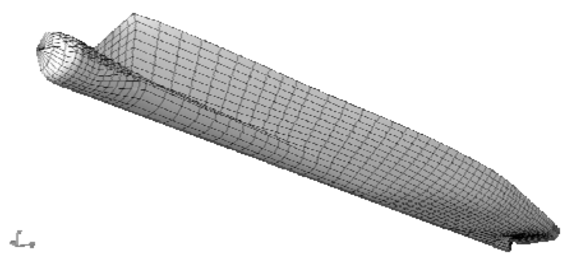

Figure 21. Panelisation of Design_0003

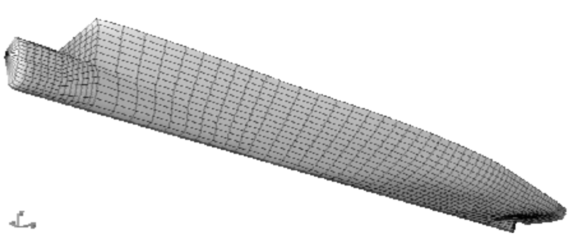

Figure 22. Panelisation of Design_0004

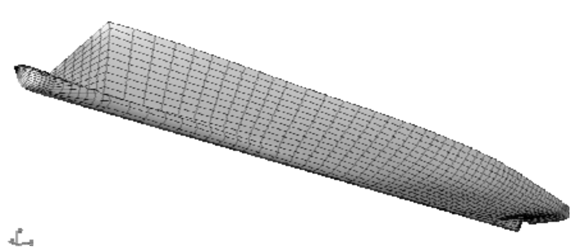

Figure 23. Panelisation of Design_0005

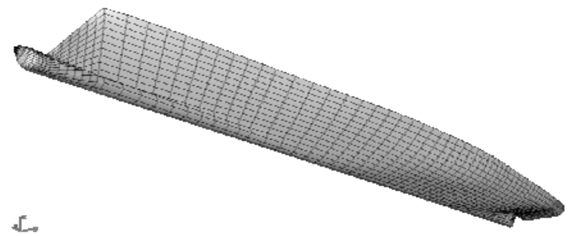

Figure 24. Panelisation of Design_0006

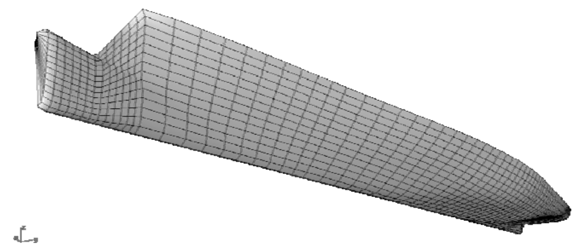

Figure 25. Panelisation of Design_0007

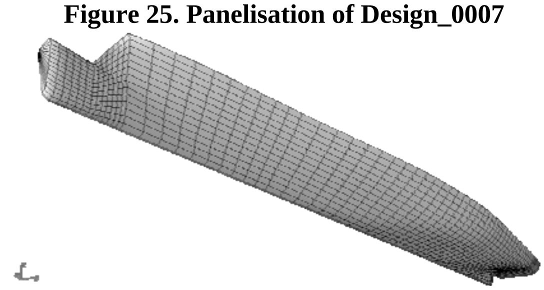

Figure 26. Panelisation of Design_0008

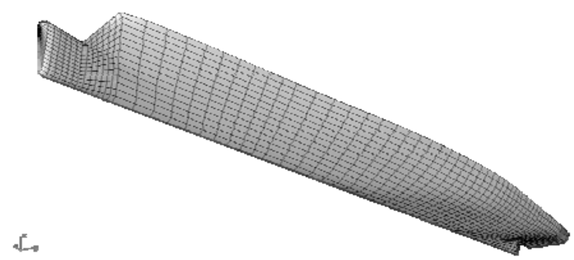

Figure 27. Panelisation of Design_0009

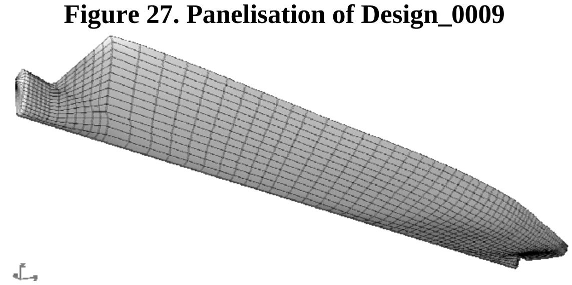

Figure 28. Panelisation of Design_0010

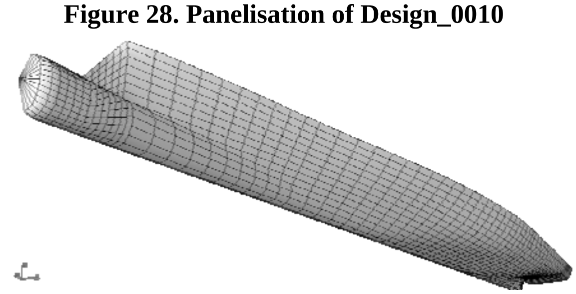

Figure 29. Panelisation of Design_0011

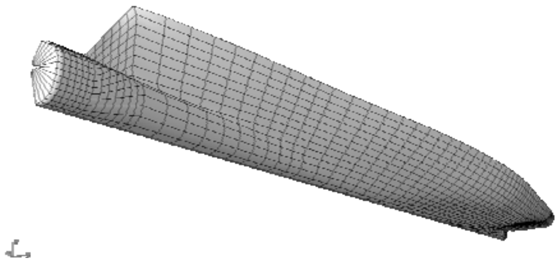

Figure 30. Panelisation of Design_0012

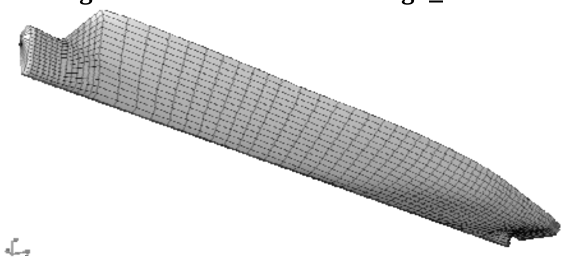

Figure 31. Panelisation of Design_0013

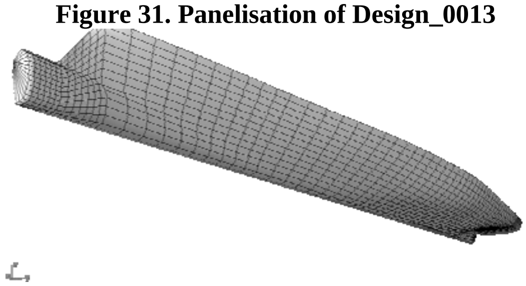

Figure 32. Panelisation of Design_0014

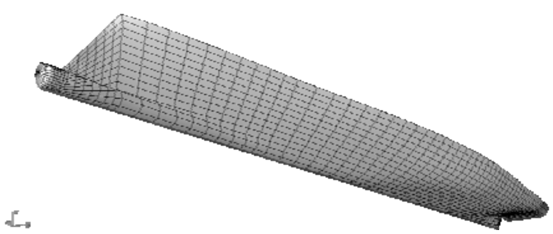

Figure 33. Panelisation of Design_0015

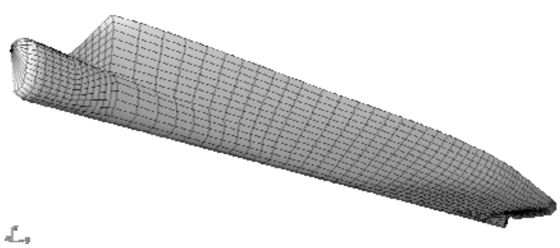

Figure 34. Panelisation of Design_0016

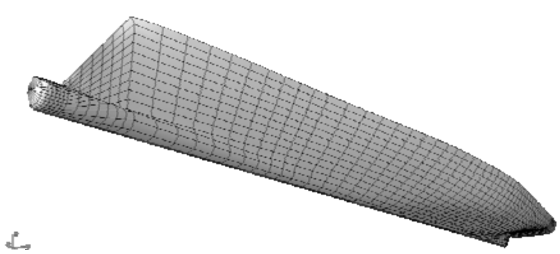

Figure 35. Panelisation of Design_0017

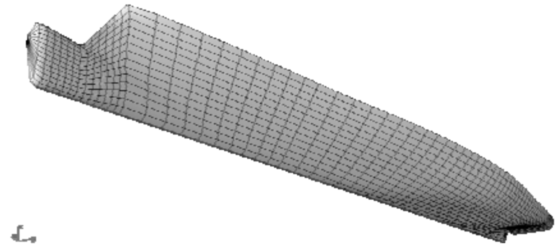

Figure 36. Panelisation of Design_0018

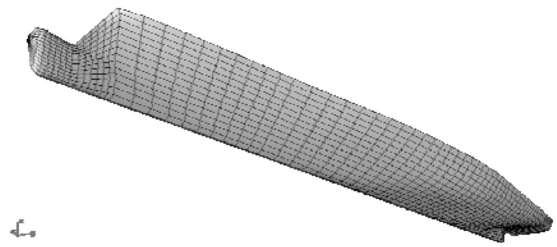

Figure 37. Panelisation of Design_0019

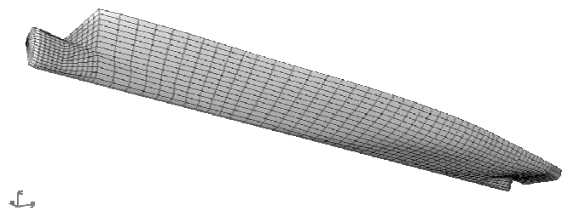

Figure 38. Panelisation of Design_0020

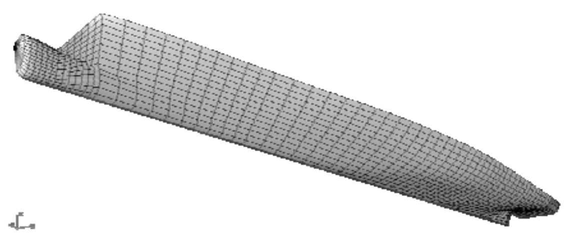

Figure 39. Panelisation of Design_0021

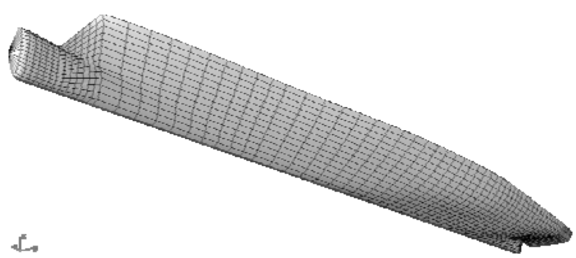

Figure 40. Panelisation of Design_0022

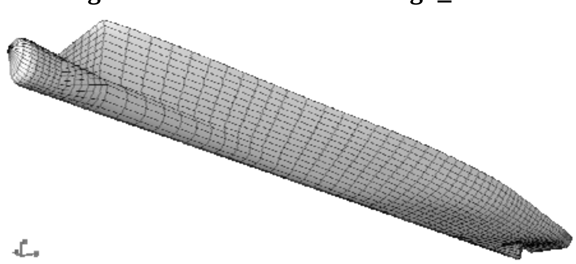

Figure 41. Panelisation of Design_0023

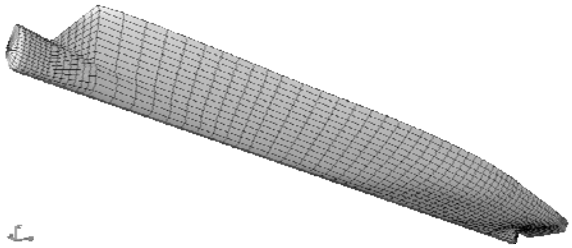

Figure 42. Panelisation of Design_0025

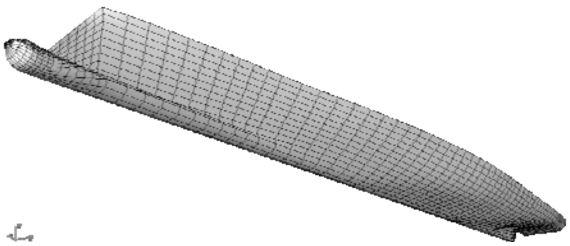

Figure 43. Panelisation of Design_0026

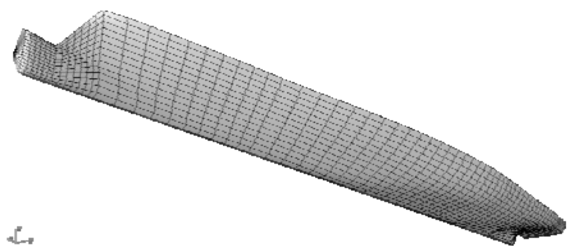

Figure 44. Panelisation of Design_0027

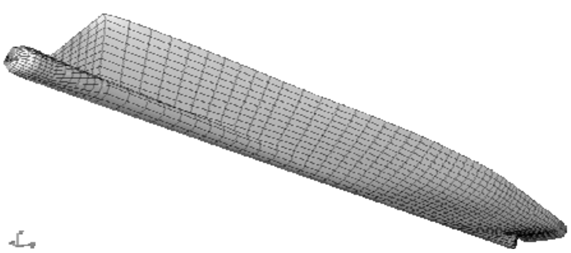

Figure 45. Panelisation of Design_0028

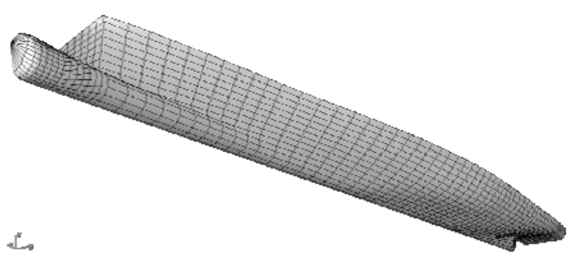

Figure 46. Panelisation of Design_0029

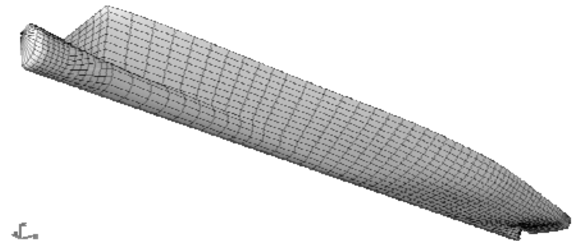

Figure 47. Panelisation of Design_0030

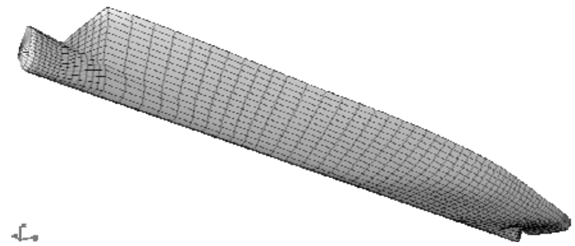

Figure 48. Panelisation of Design_0031

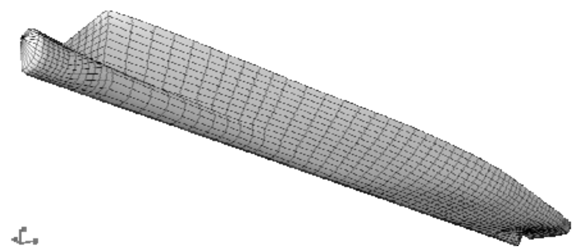

Figure 49. Panelisation of Design_0032

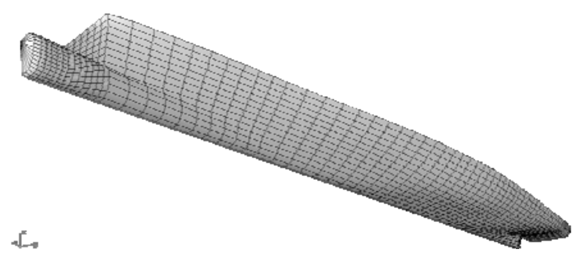

Figure 50. Panelisation of Design_0033

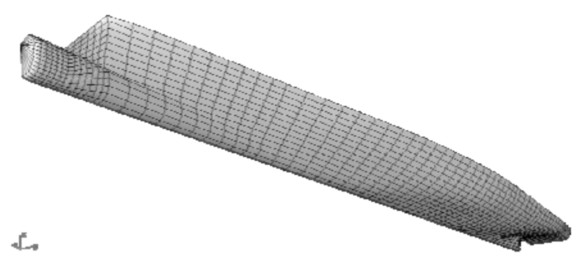

Figure 51. Panelisation of Design_0034

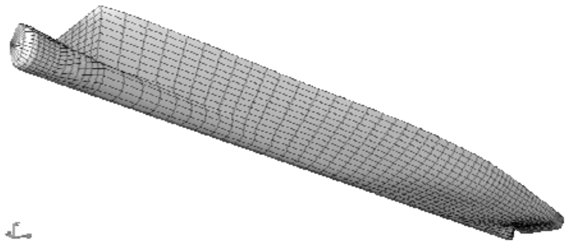

Figure 52. Panelisation of Design_0035

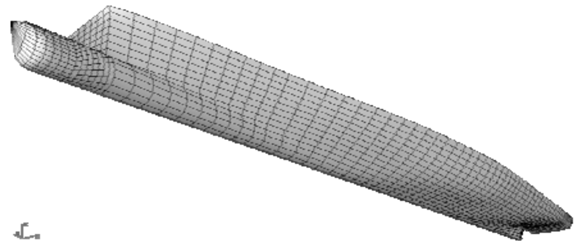

Figure 53. Panelisation of Design_0036

Selecting twelve (12) designs that presented the smallest deviations for the different panel densities, a new calculation was launched at a slightly smaller draught (-16cm). These results are shown in Figure 54 and in Table 2.

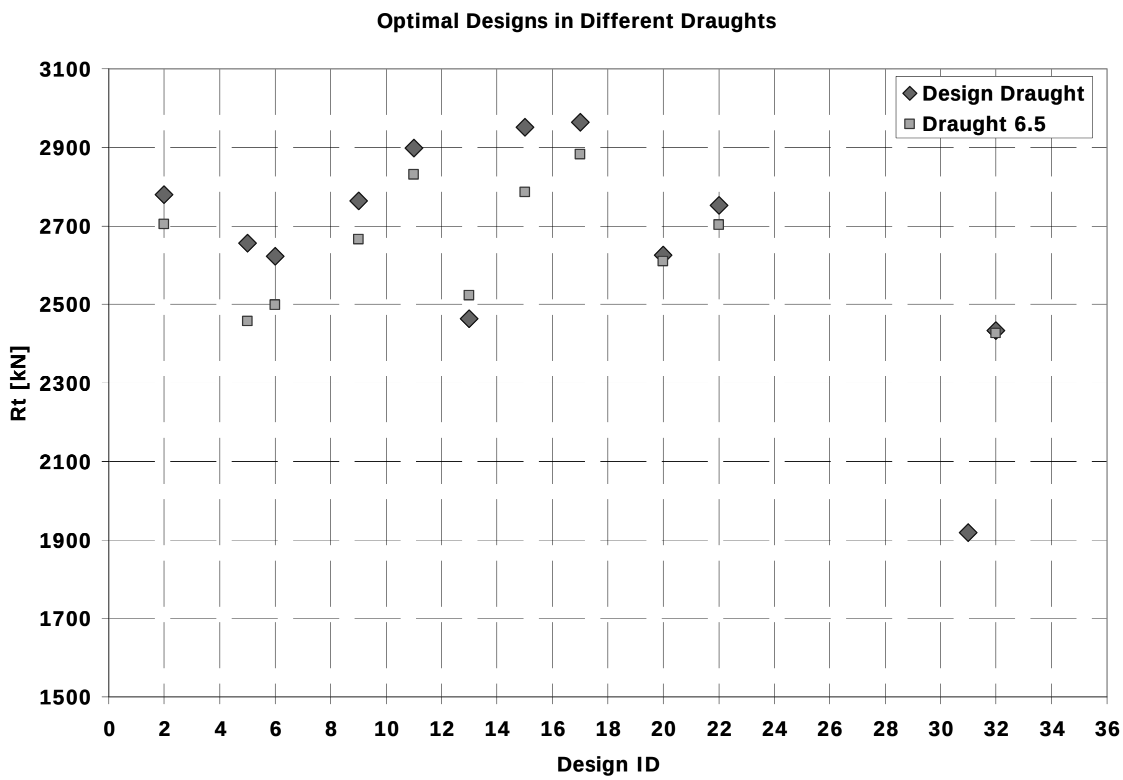

Figure 54. Total Resistance for two different draughts

For the eleven out of these designs the difference in R_T in the two draughts is -7% to +2%. Excluding Design #31 that failed to converge, the rest of the designs have shown reasonably good behavior both for different computational grid densities and different draughts.

Ranking the designs based solely on resistance performance, Design #32 would be the optimal design, showing 23% reduction of the total resistance. On the other hand the optimization showed 3 different types of candidate bulbs:

- The flat-wide bulb represented by Design #2, showing a reduction of the computed total resistance R_T by 12%.
- The narrow-tall bulb represented by Designs #9, 13, 20, 22 (and 31), showing a maximum reduction by 22% (Design 13).
- The more "traditional" bulbs represented by Designs #5, 6, 11, 15, 17 and 32.

Table 2. Improved designs R_T sensitivity to draught change

Design ID	Total Resistance Difference in reduced draught δR_T ($T_{6.5}$-T_d)	Computed Total Resistance R_T @ T_{design}	Reduction ref. to original hullform $\Delta(R_{T,original}-R_T)$
2	-3%	2779.834	12%
5	-7%	2655.127	16%
6	-5%	2621.849	17%
9	-4%	2763.332	12%
11	-2%	2897.553	8%
13	2%	2463.639	22%
15	-6%	2950.509	6%
17	-3%	2963.11	6%
20	-1%	2625.022	17%
22	-2%	2751.603	12%
31	-	1918.123	-
32	0%	2433.29	23%

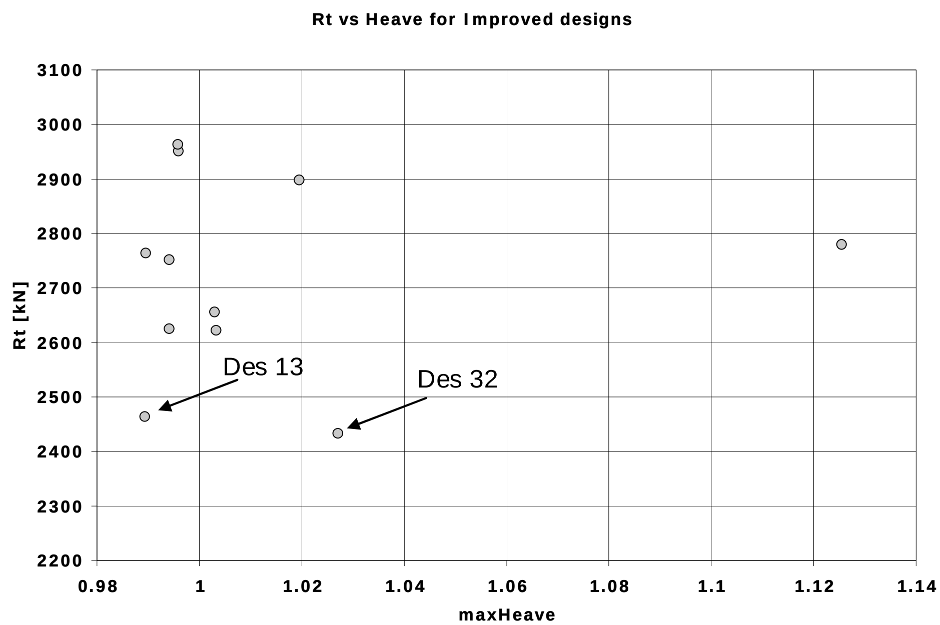

Figure 55. Scatter diagram of Coarse Mesh R_T vs. maxHeave objective

In case both the resistance and the seakeeping performance are considered, the scatter diagram shown in Figure 55 has to be considered. It is obvious that another Pareto optimum design exists, namely Design #13 which has slightly increased R_T but better seakeeping performance.

Surface piercing bulb (SPB) designs

A set of 24 different bulb designs was created using the pseudo random *Sobol* sequence Design of Experiments (DOE) algorithm in *modeFrontier*. Its selection was based on uniform distribution of the experiments in the design variable space, achieved by this algorithm.

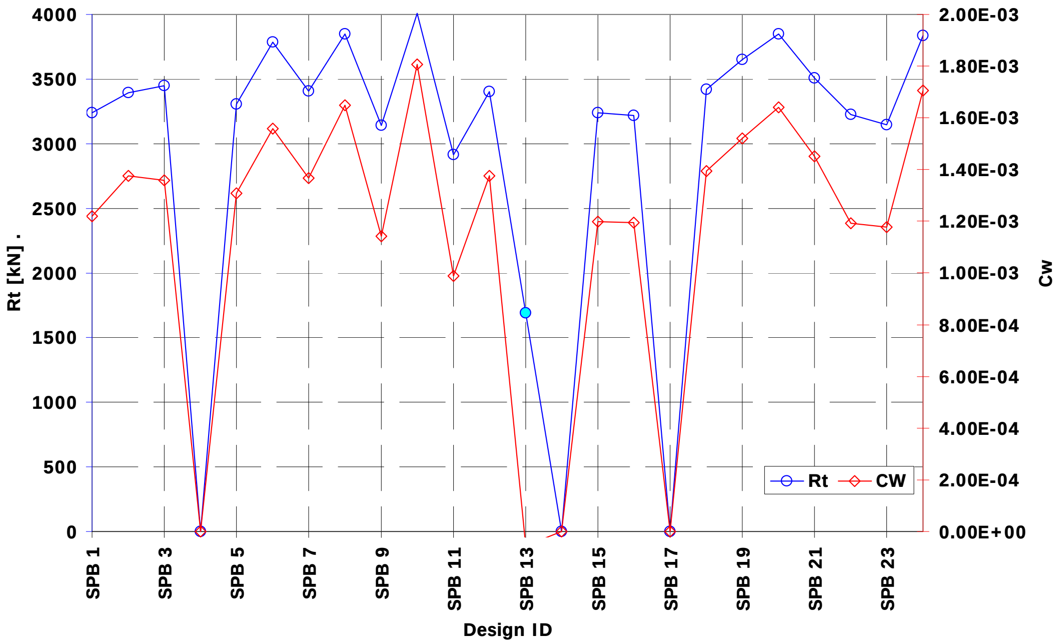

Figure 56. R_T and C_W for surface piercing bulbs

From those 24 designs only 1 showed a significant reduction of the resistance, namely SPB #11 (shown as full dot in Figure 56). Its C_W was 9.88E-04 and its R_T 2915 kN (7% reduction compared to initial hullform). For this design an additional calculation was performed using a finer computational grid. The outcome was a C_W of 9.57E-04 (3% difference) which shows that this design could be considered as a candidate optimal design. Its panelisation is shown in Figure 56. According to the numerical results this design is dominated by most of fully submerged designs. Therefore, it is not considered an optimal design.

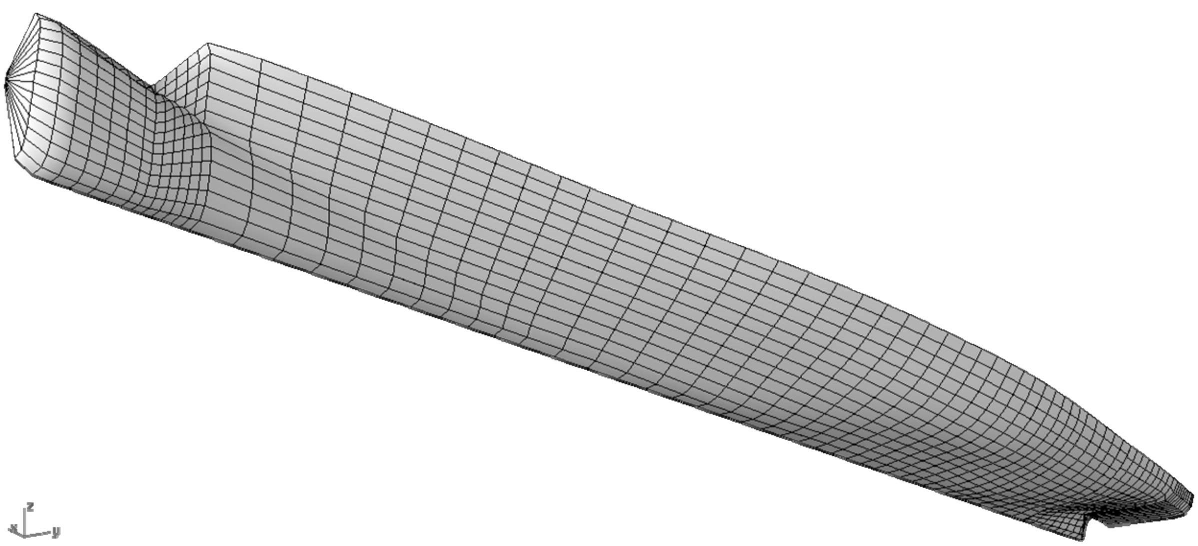

Figure 57. Panelisation of SPB #11

Performance characteristics of optimal design

Based on the numerical results two Pareto optimal designs have been identified, namely Design #13 and Design #32. Their performance has been examined more thoroughly and their resistance curve and heave RAO are compared in the following figures against the original hullform.

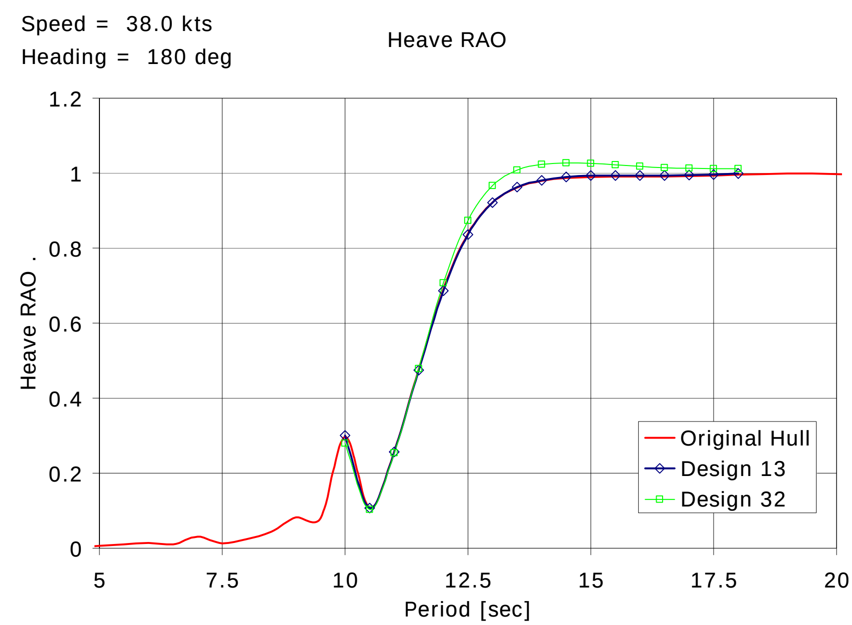

Figure 58. Comparison of Heave RAOs of the original hull with the two Pareto Designs

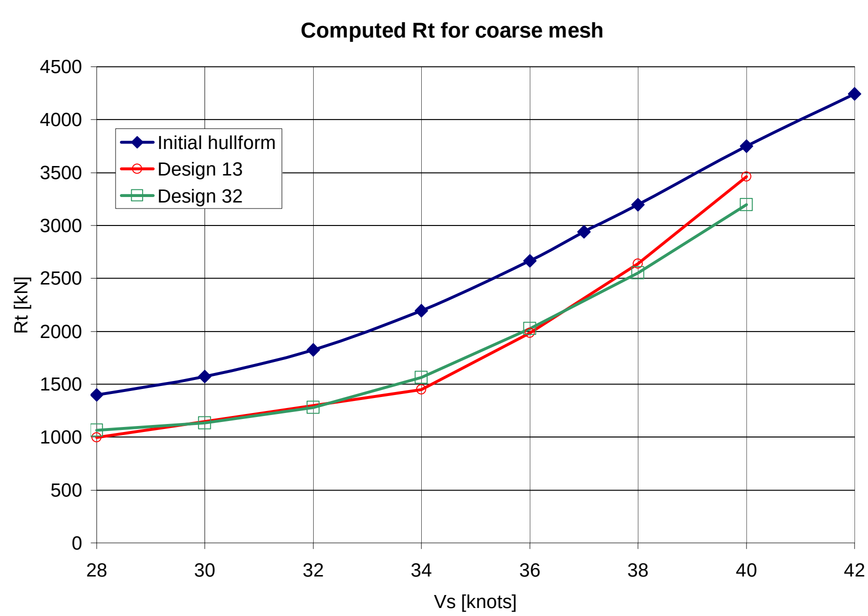

Figure 59. Comparison of computed R_T using coarse mesh of the original hull and the two Pareto designs

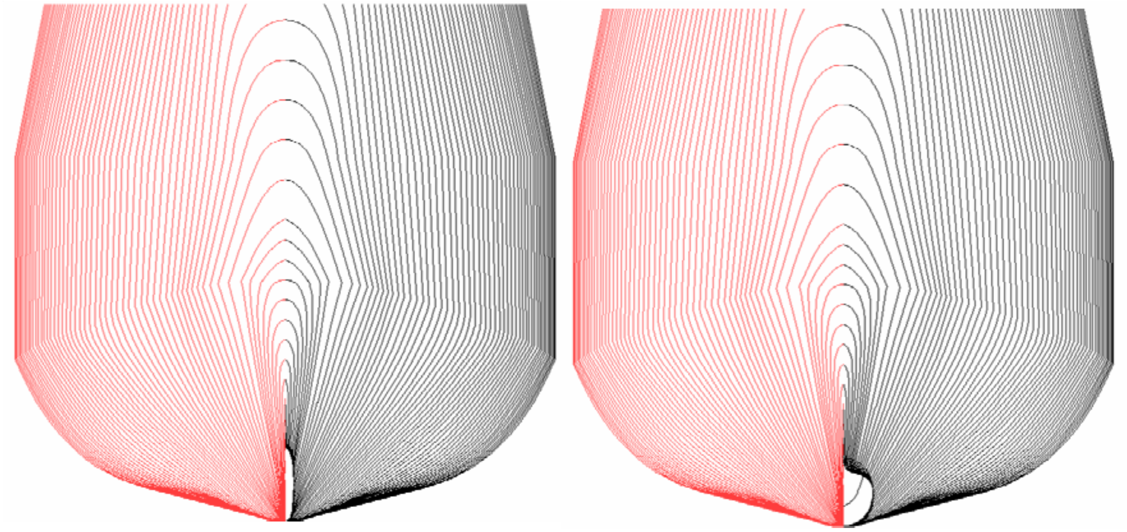

Figure 60. Comparison of the original hull (red color) with design 13 (left) and design 32 (right)

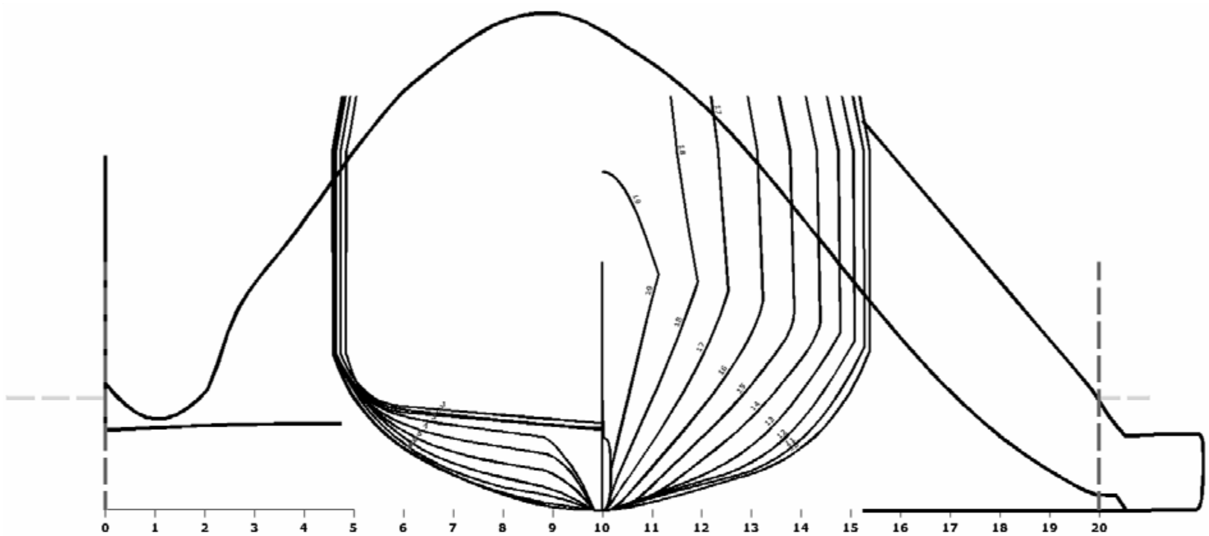

Figure 61. Bodyplan of Design #13

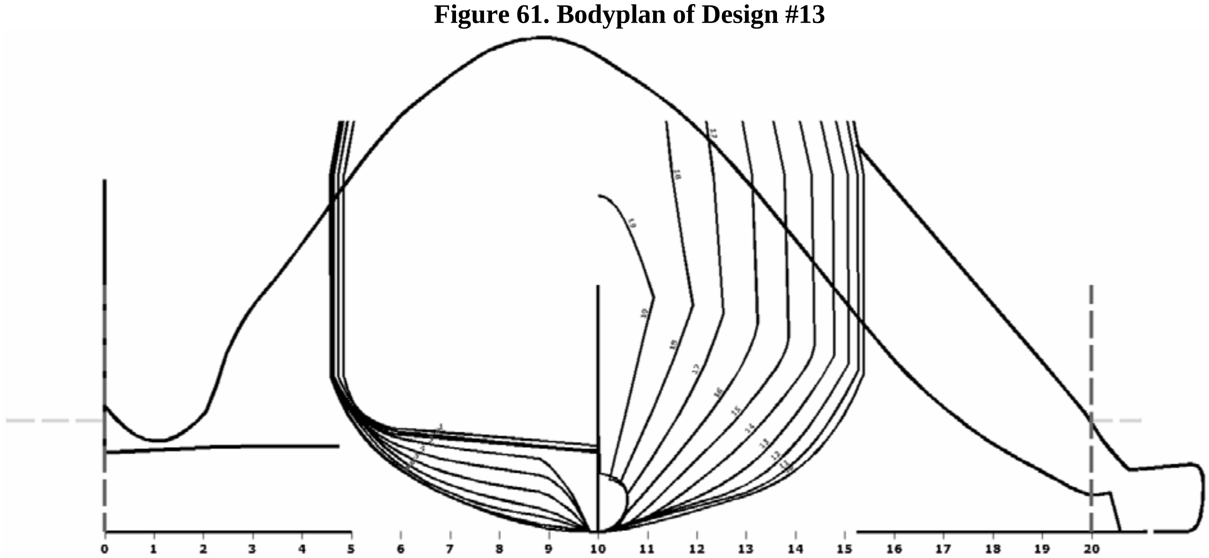

Figure 62. Bodyplan of Design #32

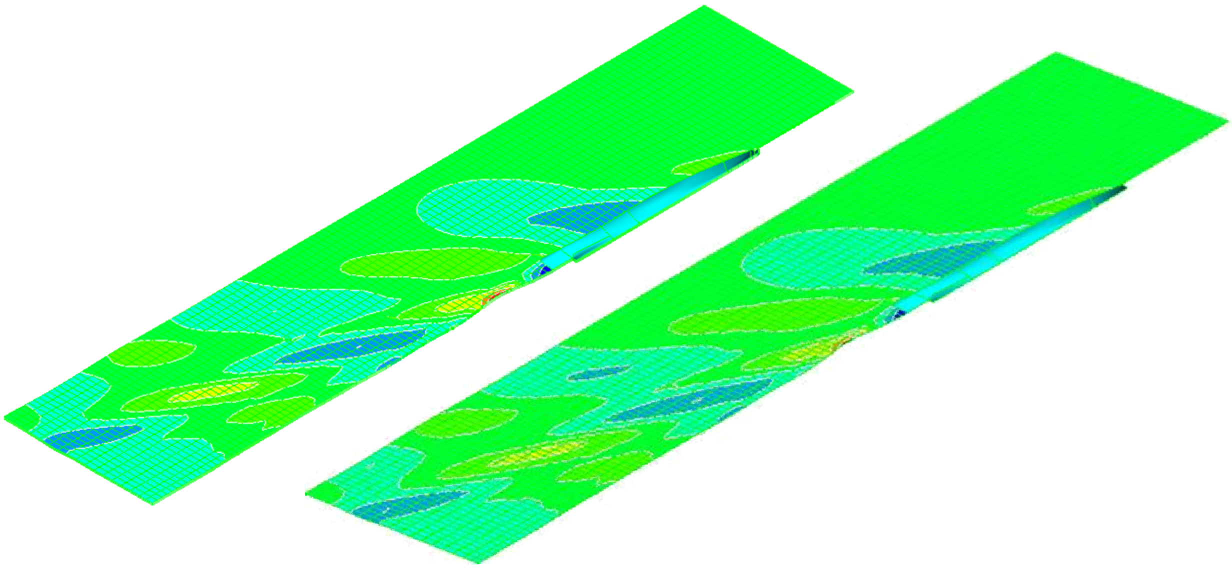

Figure 63. Wave pattern of Design #13 at 38 kts (left) compared with the original hullform (right)

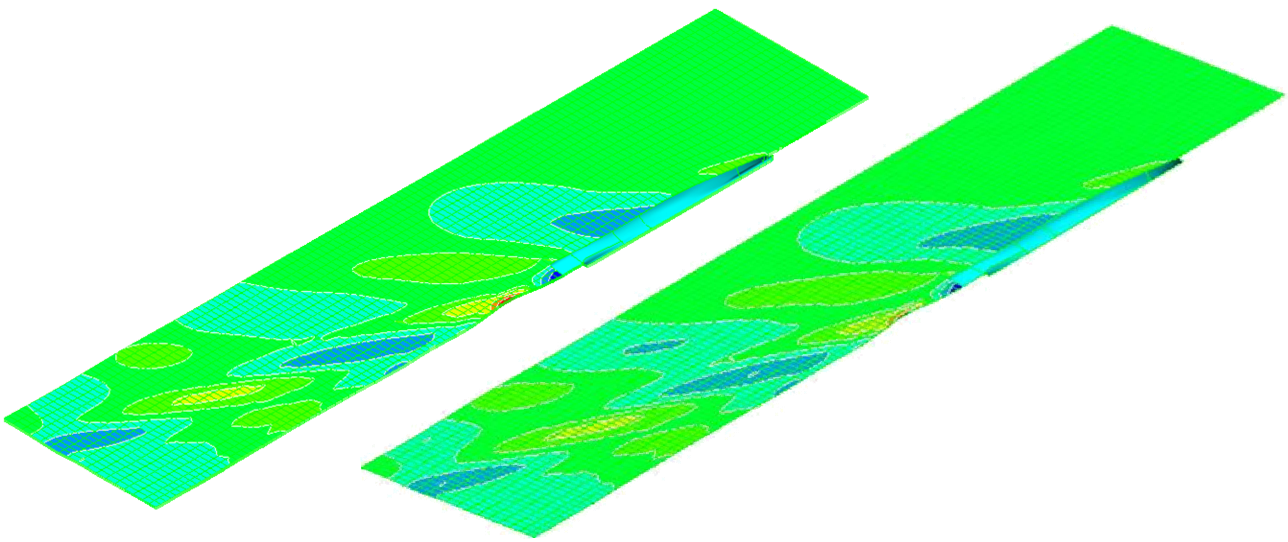

Figure 64. Wave pattern of Design #32 at 38 kts (left) compared with the original hullform (right)

Computational effort

The coarse computational grid in SHIPFLOW is made of 3847 panels, while the finer one consists of 6833. The computational time for a typical 7 iteration run was about 850 seconds (CPU time) for the coarse computational grid and up to 3700 seconds for the finer one, using a DEC XP1000 workstation. The computational grid of NEWDRIFT consists of 1064 points forming 968 panels. The computational time was about 20 seconds per frequency running on a PC with Pentium 4 @ 2.4 GHz.

CONCLUSIONS

The undertaken work demonstrated the applicability of multi-objective optimization to the resistance and seakeeping performance of innovative hull forms, like the ROPAX 2000 design.

The analysis of the results has shown that the application of a formal optimization procedure by genetic algorithms is very promising for the exploration of the performance of very different bulbous bow shapes. The undertaken numerical calculations indicate that it is possible to reduce significantly the resistance of the ROPAX 2000 hull form using a bulbous bow. On the other hand the use of potential-flow method codes for the prediction of resistance has its own shortcomings as has already been reported (Janson and Larsson 1996). Therefore, it appears that model tests are required for the verification of the herein obtained results and for the selection of the final optimal bulbous bow.

Independently of the above, it should be noted that the presently investigated optimization problem was quite restrictive with respect to possible hullform changes for achieving an improved vessel performance, as it allowed only the modification of ship's bow region, whereas the remaining hullform remained unchanged. The applied optimization concept allows however the consideration of *globally* different hullforms of even further improved hydrodynamic performance.

ACKNOWLEDGEMENTS

The work presented herein was partially supported by the E.U. funded project "Life-Cycle Virtual Reality Ship System VRSHIPS-ROPAX 2000" (VRS), G3RD-CT-2001-00506. The authors are solely responsible for the contents of the paper, which does not represent the opinion of the Community. The Community is not responsible of any use that might be made of data appearing therein. The authors like to thank the developers of the initial hullform ALSTOM - Chantier de l'Atlantique for their permission to publish some particulars of the VRS-ROPAX2000 design.

REFERENCES

GOUBAULT P., C. GAUDIN, N. BESNARD and P. NERI, *Initial Design of ROPAX 2000*, *VRS-WP7-D3-V5*, VRSHIPS-ROPAX, G3RD-CT-2001-00506, 20 April, 2004.

ZARAPHONITIS G., PAPANIKOLAOU A. and MOURKOYANNIS D., "Hull-form Optimization of High Speed Vessels with Respect to Wash and Powering", *Proc. of IMDC 03*, Athens, Vol. II (2003): 43-54.

BOULOUGOURIS E. K., PAPANIKOLAOU A. and ZARAPHONITIS G., "Optimisation of Arrangements of Ro-Ro Passenger Ships with Genetic Algorithms", *Ship Technology Research*, Verlag Heinrich Soeding, **51**:3 (2004): 99-105.

NOWACKI H., BRUSIS F., SWIFT P., "Tanker Preliminary Design-An optimization problem with constraints", *SNAME Transactions*, **78** (1970).

BOULOUGOURIS E. K., *Ship design optimization for enhanced survivability after damage for Ro-Ro passenger and naval ships*, PhD Thesis, Ship Design Laboratory, National Technical University of Athens, November, 2003.

SEN P., YANG J-B, *Multiple Criteria Decision Support in Engineering Design*, Springer-Verlag London Limited, 1998.

NAPA Oy (2005), *NAPA software*, http://www.napa.fi/

LARSSON L., BROBERG L., KIM K.J., ZHANG D.H., "A method for resistance and flow prediction in ship design", *SNAME Transactions*, **98:**16 (1990): 1-37.

PAPANIKOLAOU A., ZARAPHONITIS G., *Computer Program NEWDRIFT v.7*, Internal Report, NTUA, Greece, 2001.

E.STE.CO (2003), "*modeFRONTIER software v.2.5.x*", http://www.esteco.it/

MARIN-MARITIME RESEARCH INSTITUTE NETHERLANDS, "Report No. 15643-1-DT, Preliminary", February, 2005.

KRACHT, A.F., "Design of bulbous bows", *SNAME Transactions*, **86** (1978): 197-217.

HAMALAINEN R. and HEERD J., "A most effective way to optimize hull form by using parametric hull definition and CFD", *Proc. of IMAM 2002*, Rethymnon, Crete, Greece, 13-17 May, 2002.

JANSON C. and LARSSON L., "A method for the optimization of ship hulls from a resistance point of view", *Proc. of 21st Symposium on Naval Hydrodynamics*, Trondheim, Norway, June 24-28, (1996): 680-693.