

# CFD Hull Form Optimization of a 12,000 cu.yd. (9175 m<sup>3</sup>) Dredge

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Fig. 1: *M/V Glenn Edwards* at sea trials

## Abstract

Manson Construction Company's 12,000 cu.yd. (9175 m<sup>3</sup>) trailing suction hopper dredge *M/V Glenn Edwards* is the newest and largest hopper dredge in the U.S. fleet. Unusual among large hopper dredges, the *Glenn Edwards* is propelled by three 1,920 kW azimuthing Z-drive units fitted with nozzles. This paper describes the formal CFD hull form optimization process for the *Glenn Edwards*. An unusual feature of this formal hull form optimization process was the CFD evaluation of performance both in deep and shallow water operations, as both regimes are important to the operation of a hopper dredge. The paper describes the development of the constraint set, CFD modeling considerations, the optimization process and the results obtained. Comparison is made between CFD results and results obtained from model tests of the selected optimum hull at MARINTEK in Trondheim, Norway. Mention will also be made of observations and results from sea trials and early service.

## Keywords

Hull form; optimization; CFD; parametric geometry; wavemaking resistance.

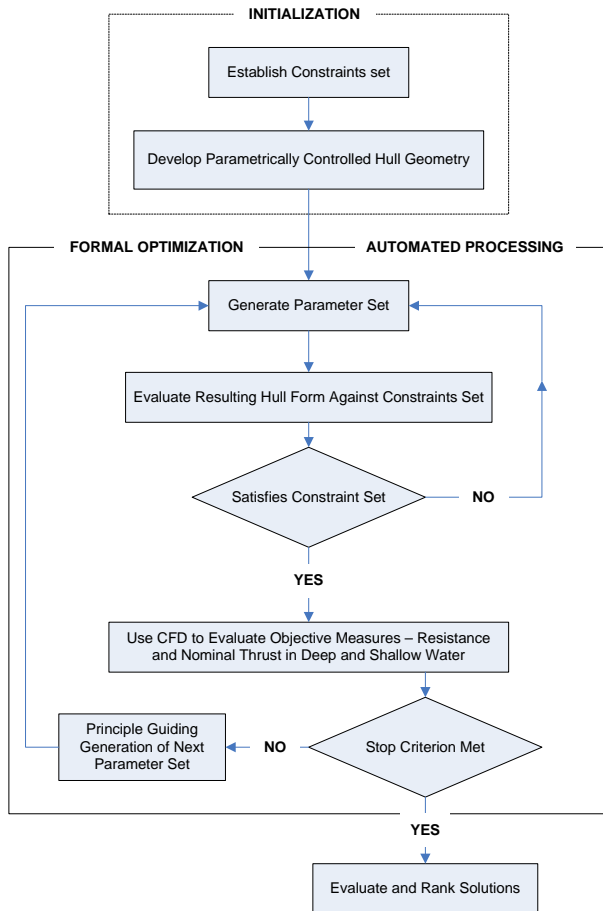
## Nomenclature

(1+k)	form factor as given by Holtrop (1984)
$C_{TS}$	thrust loading coefficient of propeller
$F_N$	Froude number
$GM_T$	transverse metacentric height
$L_{OA}$	length overall
$L_{WL}$	length at waterline
$R_{PT}$	pressure resistance
$R_{PRP}$	pressure induced additional resistance of the acting propeller on the hull
$R_{PRV}$	change of viscous resistance due to propeller action
$R_{PRW}$	change of wave making resistance due to propeller action
$R_T$	total resistance
$R_V$	viscous resistance
T	thrust
$\tilde{T}$	first approximation to the thrust
t	thrust deduction fraction

## Introduction

Manson Construction Company's 12,000 cu.yd. (9175 m<sup>3</sup>) trailing suction hopper dredge *M/V Glenn Edwards* (Fig. 1) is the newest and largest hopper dredge in the U.S. fleet. The *Glenn Edwards* is 112.2 m LBP, with a beam of 23.17 m and a design draft of 7.47 m. The *Glenn Edwards* is propelled by three 1,920 kW azimuthing Z-drive units fitted with nozzles, an unusual arrangement for its class.

This paper describes the formal CFD hull form optimization process used to develop the hull form for the *Glenn Edwards*. As depicted in Fig. 2, that process begins with the formulation of a constraints set, followed by development of a parametrically defined hull geometry (or perhaps one should say family of geometries) that expresses the different attributes thought to be candidates for a successful hull. The optimization process then proceeds by stages. First, a coarse survey of parameter space is accomplished; this is followed by a directed search for near optimum hulls, beginning from the region of parameter space determined to be most promising from the survey.



**Fig. 2: Hull form optimization process**

Each parametrically generated candidate hull is first checked for compliance with the constraints set. In general, not all candidates comply, and if the problem is over-constrained few will comply. Non-compliant hull forms are discarded without further analysis. Objective functions are evaluated for each compliant hull form

using nonlinear free surface potential flow CFD, empirical values for the form factor and ITTC friction.

Typically, the objective measure of merit might be the scalar value of resistance or nominal thrust at a design service speed. However, given the nature of the service for a suction hopper dredge, the objective measure of merit for the *Glenn Edwards* was the two component vector comprising the nominal thrust in both deep and shallow water. In the nonlinear free surface potential flow computation, the influence of the propulsors was modeled using a source distribution on the propeller disc, representing a specified thrust of the propeller.

The first, exploratory phase examined about 150 different hull designs, of which 47 conformed to all of the given constraints. The second phase commenced from the best design identified during the exploratory phase, and proceeded to seek an optimum hull form using a Tangent Search Method. The rate of improvement essentially vanished after 136 successive designs were evaluated.

The hull form recommended by this process was then subjected to a detailed RANS evaluation. During the RANS computation, actuator discs were introduced and the thrust was adjusted to balance the resistance force – thus simulating a free running propulsion test.

Compared to other CFD hull form optimization methods, this approach based on parameterized hull geometry is thought to be both practical and superior for the following reasons:

1. The parameterized hull geometry can be devised such that it is only capable of generating realistic (and 'fair') hull forms that one would genuinely consider building.
2. The procedure is automated so that it is practical to evaluate hundreds (upwards to thousands) of geometries for compliance with constraints, and the objective functions can be evaluated for hundreds of compliant hull forms using nonlinear free surface potential flow CFD.

The parameterization of the hull geometry minimizes the degrees-of-freedom (DOF) to a practical and manageable level. Twenty (20) free parameters were used in the optimization of the *Glenn Edwards*, of which thirteen (13) were handled implicitly in the geometric modeling, and the remaining seven (7) were explicitly explored during the optimization process. Compared, for example, to automated hull form optimization procedures that make each vertex on the hull form mesh a free (vector) variable (see for instance Hendrix *et al* 2001), the present approach based on parameterized geometry represents a reduction in DOF by many orders of magnitude.

The present approach is advantageous, too, when compared to man-in-the-loop hull form optimization procedures guided by experience and judgment. Man-in-the-loop procedures can evaluate only a very few hull forms (typically two to six), and therefore are unable to offer any convincing evidence that a near optimum has been achieved. Usually, at best, they can only claim improvement over the initial hull form, but cannot provide

any genuine confidence that the potential for further gains has been (nearly) exhausted.

## Constraints Set

Hull forms were validated against a set of constraints established by the naval architect in consultation with the owner at the beginning of the hull form optimization effort. The constraints set and parametric geometry model embodied hull constructability, as well as other concerns.

In the service of brevity, the full rationale behind each constraint will not be described here. Care should be taken in establishing the constraints set to determine those constraints that are truly necessary and to avoid otherwise overly constraining the problem, as over-constraint will needlessly reduce the number of constraint compliant hull forms, and may prevent finding a desirable optimum.

Constraints are presented under class subheadings, such as: symmetry, length, volume, etc. More generally, there are conceivable useful constraints that may fall under headings not used for the *Glenn Edwards*, and some of these possibilities will be briefly discussed at the conclusion of this section.

### Symmetry

It may appear obvious and even trivial, but the number of planes of symmetry is an appropriate constraint. The parametric exploration for the *Glenn Edwards* was constrained to one plane of symmetry. On a concurrent double-ended ferry project, however, there were two planes of symmetry.

### Length

For the *Glenn Edwards*, constraints were set on several lengths:  $L_{OA}$ , wetted length,  $L_{WL}$ , waterline beam, draft, still water trim and midship bilge radius. Most of these were constrained by exact equalities, an unusual choice. More typically, these might be constrained to fall within some acceptable range.

Following the initial exploration of parametric design space, it was realized that a constraint (acceptable range) on the position of the longitudinal center-of-buoyancy was also required.

### Area

There were no constraints measured as areas for the *Glenn Edwards*, but more generally there could be constraints in this classification. Examples might be minimum (and/or maximum) waterplane area.

### Volume

A minimum displaced volume of  $17,047 \text{ m}^3$  was set for the *Glenn Edwards*, corresponding to a minimum displacement of 17,200 long tons in salt water. While displacement is the most obvious volume constraint, on some projects there have been other volume constraints, such as the tank volume between specified transverse boundaries.

## Other Geometric Constraints

Other geometric constraints for the *Glenn Edwards* included the following:

- Clearances for the azimuthing Z-drive propulsors imposed with a 2.713 m clearance circle in a plane 3.901 m above base and centered on the rotation axis for Z-drive azimuth.
- Minimum extent (and location) of parallel mid-body.
- Aft hopper door clearance enforced by requiring the bottom tangent for the flat of bottom to fall outside (aft of) a specified control point.
- A requirement that the main deck (30 foot (9.1 m) elevation) be maintained at full breadth to within 72 feet (22.0 m) forward of the transom.
- A requirement that the poop deck (42 foot (12.8 m) elevation) continue at full breadth all the way aft to the transom.

## Gaussian Curvature

Except in the forebody and bilge radius, it was desired/required that the hull be a developable surface with zero Gaussian curvature. To the maximum extent possible, it was desired that the forebody also be comprised of developable surfaces. This constraint was handled implicitly within the parametric modeling.

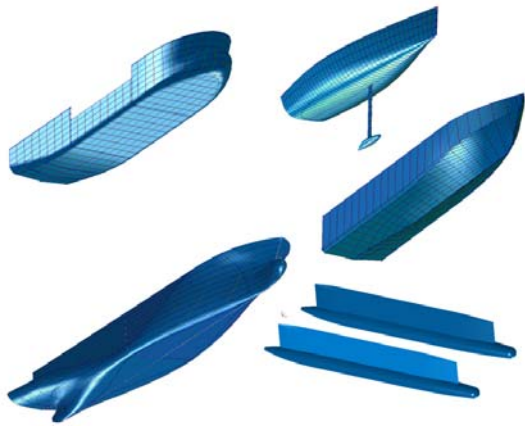
## Other Possible Constraints

As mentioned at the beginning of this section, only necessary constraints should be established, and the optimization problem should not needlessly be over-constrained. With these caveats in mind it is useful briefly to note constraints that have been found both necessary and practical in other projects. These include measures of transverse stability (e.g.,  $GM_T$ ) and non-submergence of a margin line following damage between specified transverse stations. Also useful have been specific control points necessary for clearance around machinery or outfit (e.g., reduction gears).

## Parametric Geometry Model

### Parametric approach

In order to generate and vary functional surfaces of complex shape such as ship hull forms with a degree of freedom suitable for optimization, a parametric approach is preferred. A context-dependent and solution-oriented description is established, allowing production of those shapes that are beneficial in performance and acceptable with regard to the many constraints from as small a data set as possible. Fig. 3 depicts a selection of different parameterizations provided for different design tasks ranging from fully appended round bilge sailing yachts, hard chined hulls, container carriers and multi hull arrangements such as SWATH.



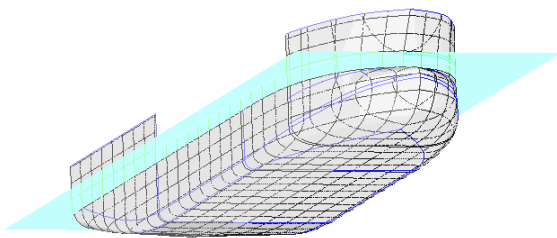
**Fig. 3:** The FRIENDSHIP-Modeler provides specific parametric models for various design tasks

The *FRIENDSHIP-Modeler* grants a high-level definition of hull shapes via form parameters such as beam, deadrise, draft, entrance angles, sectional areas, etc., and was therefore selected for the modelling of the dredge hull. For details see (Harries and Abt, 1999), (Harries *et al*, 2001) and (Harries and Heimann, 2003). Also, see <http://www.FRIENDSHIP-SYSTEMS.com> for more information.

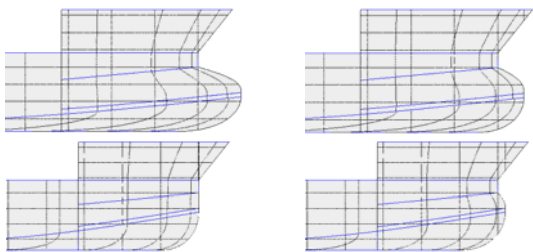
#### Form parameters

Fig. 4 depicts the hull geometry of the dredge generated with the *FRIENDSHIP-Modeler*. The shape of the dredge called for a specific parameterization which was developed by FRIENDSHIP SYSTEMS on the basis of a baseline design by Hockema and Assoc. The form features were closely examined via curvature plots and other measures, and suitable form parameters were identified.

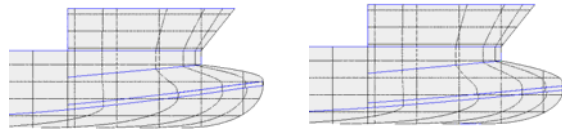
Fig. 5 through Fig. 12 illustrate eight of the parametrically controlled geometric ‘modes’.



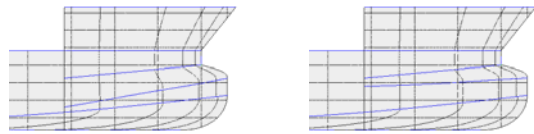
**Fig. 4:** Perspective view of the parametrically modeled dredge hull



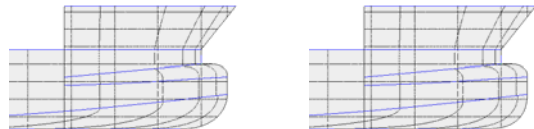
**Fig. 5:** Parametric dredge model: Variation of bulb length



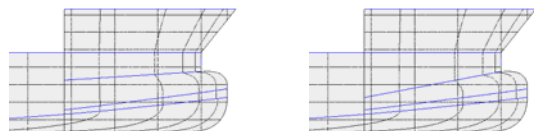
**Fig. 6:** Parametric dredge model: Modification of vertical position of straight part of bulb



**Fig. 7:** Parametric dredge model: Variation of straight length at intersection to hull



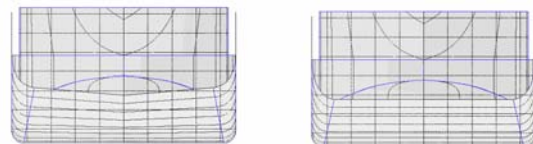
**Fig. 8:** Parametric dredge model: Variation of fullness of bulb's top and bottom



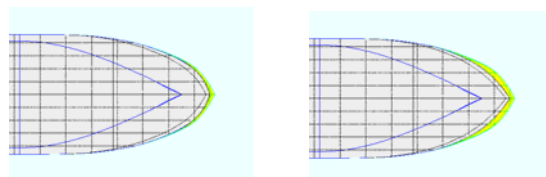
**Fig. 9:** Parametric dredge model: Variation of bulb height at FP and intersection to hull



**Fig. 10:** Parametric dredge model: Variation of run configuration



**Fig. 11:** Parametric dredge model: Variation of transom deadrise



**Fig. 12:** Parametric dredge model: Variation of bow plan view

#### Overview of Optimization Process

The complete process of generating a new hull form geometry, checking the constraints and eventually evaluating the measure of merit was setup by means of the FRIENDSHIP-Optimizer. This generic optimization toolkit facilitates building a process chain from a selection of arbitrary programs to generate a new design based on a number of controlling parameters. It then

triggers the tools necessary to evaluate the design features and applies a variety of methods for design space exploration and formal optimization in order to find a superior design.

Constraints can be included and monitored during the optimization. The program has an advanced graphical interface, and can also be run in batch mode for time consuming numerical computations on mainframe computers.

In addition to a wide selection of well known formal algorithms, advanced users may also incorporate their own algorithms to control the optimization, while still taking advantage of the file and directory handling provided by the FRIENDSHIP-Optimizer.

Fig. 13 depicts the principal setup of such an optimization chain. For the problem at hand, the FRIENDSHIP-Modeler was used to generate the new hull geometry, and the well known Rankine source panel code SHIPFLOW (Larsson, 1997) was used to evaluate the wave making resistance in deep and shallow water.

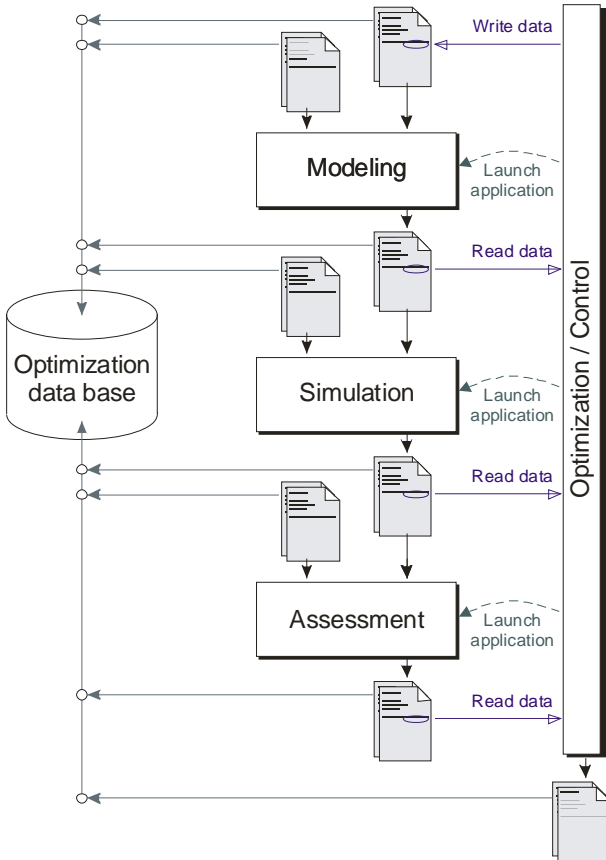


Fig. 13: Automated formal optimization process

### Objective Functions in Deep and Shallow Water

As the main objective, the nominal thrust in deep water for a speed of 6.69 m/s (13.0 kts) was considered, corresponding to a Froude number of  $F_N=0.199$ .

$$T = R_T + R_{PRP} + R_{PRW} + R_{PRV} = \frac{R_T}{1-t} \quad (1)$$

Additionally, the nominal thrust in shallow water (depth 45 ft or 13.7 m) and a speed of 6.43 m/s (12.5 kts) was monitored during the optimization procedures.

The nominal thrust, used as an objective function, was computed from the results of the free surface flow solution with the activated propeller source model by pressure integration over the hull panels. The viscous components were approximated using the ITTC'57 base line and a form factor estimate.

As the form factor might change with changes in the geometry, an approximation for the form factor in relation to geometric characteristics as introduced by Holtrop (1984) was employed.

The thrust must be input into the panel code. Before the parameterization, the value is unknown, and would require a time consuming iterative calculation. In order to speed up the optimization, a constant value for the thrust loading coefficient,  $C_{TS}=0.850$ , – giving a first approximation to the thrust of  $\tilde{T}$  – was used. An algebraic correction was developed to approximate the total pressure resistance at the correct thrust,  $R_{PT}(T = R_T)$ :

$$R_{PT}(T) = R_{PT}(\tilde{T}) - t[\tilde{T} - R_{PT}(\tilde{T}) - R_v] \quad (2)$$

$R_{PT}(\tilde{T})$  denotes the calculated pressure resistance when using the thrust  $\tilde{T}$  in the calculation,  $t$  is the thrust deduction factor as calculated by comparing calculations with and without acting propeller.  $t = 0.22$  and  $0.23$  for the deep water and the shallow water conditions, respectively.

Using the approximation above, the objective for the total nominal thrust becomes:

$$T = R_{PT}(T) + R_v \quad (3)$$

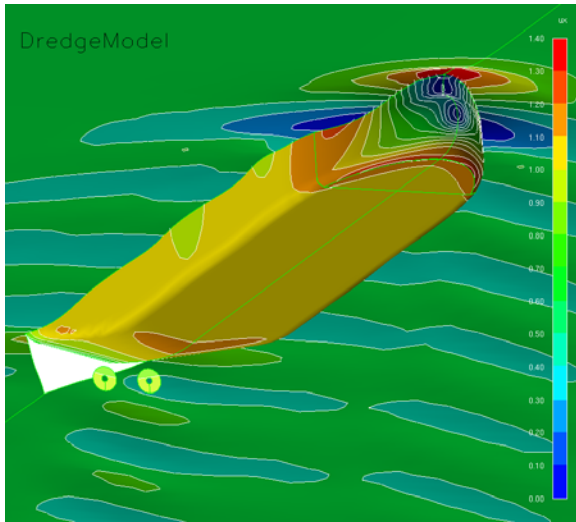
### Computational Fluid Dynamics Tool

For the performance assessment, the well-known code SHIPFLOW was employed. The wavemaking resistance was calculated by the potential-flow module *xpan* with nonlinear free-surface boundary conditions. In addition, viscous calculations were performed using SHIPFLOW's boundary layer module *xbound* and RANS module *xvisc*.

The potential module of the code SHIPFLOW employs a Rankine source panel representation of the hull, appendages and free surface geometry, and adjusts the source strength on each panel to fulfill the boundary conditions on the surface of the body and on the elevated free surface, respectively. Dynamic sinkage and trim are considered.

The Froude number of the dredge being  $F_N=0.199$  for the deep water case, and the transom being submerged substantially, no flow clearance was expected; instead, a recirculating flow region just aft of the ship was anticipated. The flow past the large submerged transom cannot be adequately described as long as viscous effects are neglected. After discussing the issue with representatives of Flowtech A/B, it was decided not to impose any boundary conditions in that region. The transom and a triangular region of the free surface right behind the transom were left unpanelized, see Fig. 4. Within SHIPFLOW, the pressure integration is carried out over

the panelized surface of the hull; the hydrostatic and hydrodynamic pressures on the transom are not accounted for in the code. It was therefore decided to add the hydrostatic component, and to neglect the hydrodynamic effect on the transom. This would certainly bias the resulting value for the wavemaking resistance; however, as the optimization was focused on the forebody, it was felt that the ranking would not be influenced severely, as the aft part of the hull remained largely unchanged.

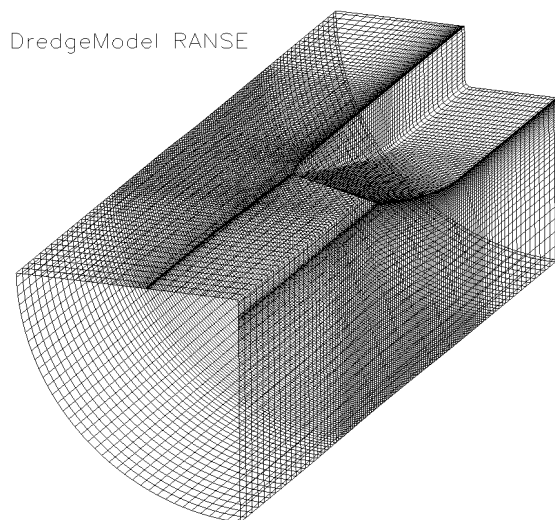


**Fig. 14: Free surface flow computation with propeller disks and open transom**

Since the SHIPFLOW code is limited to modeling only twin propellers, the effect of the triple screw configuration was approximated by using twin screws with accordingly changed loadings.

As the dredge is to operate regularly in shallow water, the wavemaking resistance was also calculated by adding environment panels at a depth of 45 feet (13.7 m) below the waterline.

For the RANS calculations, the aft half of the hull was covered with a grid of 120x40x40 nodes in the longitudinal, circumferential and radial directions, respectively. Thus a grid with 180999 nodes was used.



**Fig. 15: Discretization of fluid domain about hull**

The grid structure was improved by Poisson smoothing with respect to orthogonality of the cells, and a cell height at the boundary adequate for the actual Reynolds number. The grid cells were clustered in the vicinity of the transom to improve the resolution in that region. The grid extended beyond the hull 40% of the waterline length downstream. The radius of the grid was 25% of the waterline length. Fig. 15 shows the computational domain.

The inflow condition was calculated from a double body potential flow simulation and a boundary layer calculation, using a Reynolds number of 6.1 million and conforming to a model scale of 1:25.

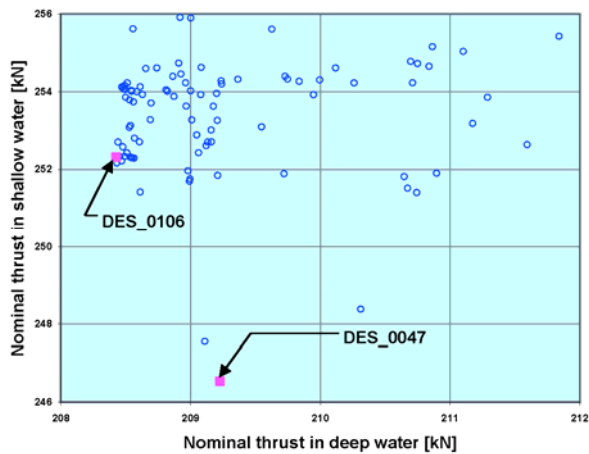
### **Hierarchy of Search Strategies**

As the dependence of the objective function on the generating parameters is considered rather complex, a multimodal problem with many local minima is very likely. Therefore, as first step of the optimization, a design space exploration was conducted to investigate the full range of the design space for possible areas with promising design properties. In order to provide a uniform distribution of hulls within the design space, a Sobol sequence (Press *et al*, 1988) was used. As a quasi-random strategy, the Sobol sequence ensures a statistically well represented design space, with increasingly finer resolution as more samples are produced, while avoiding clustering the design parameters. Within this phase, about 150 different hull designs were examined, of which 47 conformed to all of the given constraints. The best parametric design was identified as a suitable starting point for the subsequent directed search.

The focus of the second phase of the optimization is to converge to the optimum design in the vicinity of the starting point. Therefore, the direction of advancement for the free variables was triggered by the achieved values on the objective function (nominal thrust) while subject to the considered constraints. The Tangent Search Method, as described by Hilleary (1966), was considered an adequate strategy, as this method implicitly handles the optimization of an objective function within a constrained domain. The rate of improvement essentially vanished after 136 successive designs were evaluated, and the optimization was considered converged.

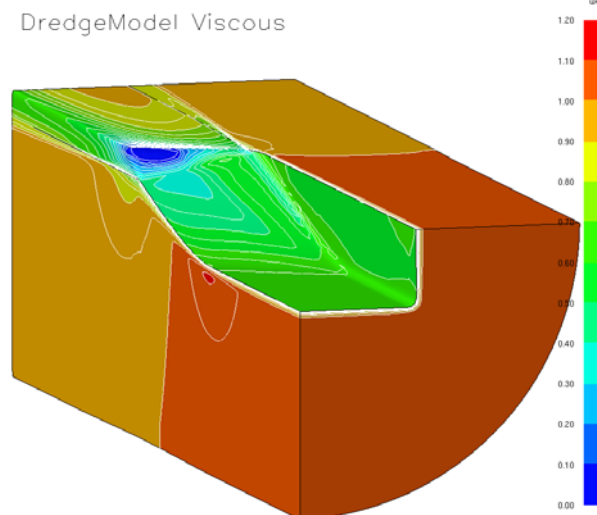
### **Results of Optimization**

The optimization achieved a significant improvement in the nominal thrust. As shown in Fig. 16, the most advantageous design with respect to deep water was candidate DES\_0106. However, DES\_0047 exhibited significant advantages in shallow water, with only a modest degradation in deep water performance relative to DES\_0106. Since the client indicated that performance in shallow water should be emphasized, DES\_0047 was selected as the basis for the new suction hopper dredge *Glenn Edwards*.



**Fig. 16: Nominal thrust of solutions in deep and shallow water**

Fig. 17 shows a color-coded plot of the axial velocity with acting propulsors as computed by the RANS code for DES\_0047. There were no indications of premature flow separation on the bilge radii, a result similarly indicated in the model tests.



**Fig. 17: Axial velocity on the run of the dredge**

### Model Tests

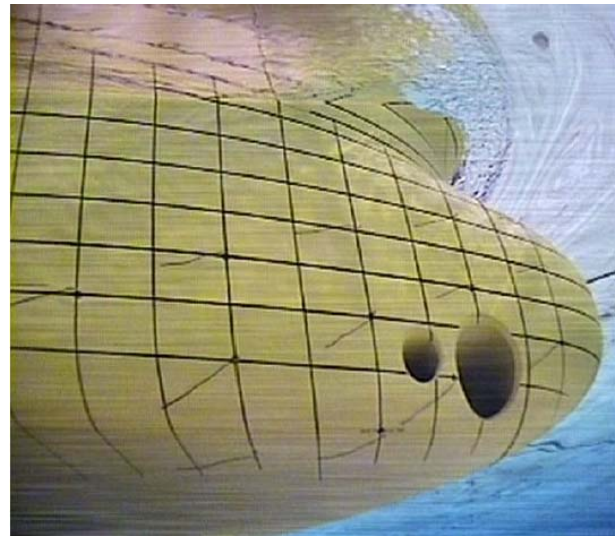
Model tests at 1:17.333 scale were performed at MARINTEK in Trondheim, Norway. The test program commenced with self-propelled course stability tests in deep water with various skeg configurations. A single centerline skeg was found to be acceptable, and was selected for the remainder of the program in shallow water (45 foot (13.7 m) depth full-scale equivalent).

The shallow water test program was carried out at two drafts, one corresponding to full-load (7.47 m draft) and the other corresponding to a no-load operating condition with trim aft. The shallow water test program included flow visualization, resistance, self-propulsion, detailed wake surveys in the propeller plane, and longitudinal wave cuts of wake-wash, see Fig. 18.

At the full-load draft in shallow water, the thrust deduction fraction averaged 0.261, which is slightly higher than the value of 0.23 estimated for that same condition

using SHIPFLOW. The form factor determined from a Prohaska plot was  $(1+k) = 1.2881$  from the model tests, while a form factor of  $(1+k) = 1.34$  was predicted from SHIPFLOW RANS calculations.

Thrust power at 12.5 knots from the model tests in shallow water was 2,312 kW which may be compared to 2,001 kW estimated as the nominal thrust power in the optimization process, which included an estimated correction for the submerged transom. The thrust estimated from a direct pressure integration without such correction was higher than that determined from the model tests. It should be noted, however, that the CFD model did not account for additional resistance due to the double bow thruster opening, skeg and thruster supports which were present in the model test.



**Fig. 18 Model test at MARINTEK with tuft flow visualization on the bow of the dredge**

### Full Scale Experience

Manson Construction Company has reported that they are very pleased with the hydrodynamic performance of the *Glenn Edwards*. They have reported that expectations regarding speed and power have been met or exceeded, and they have particularly noted the low wake wash when operating in shallow and/or restricted channels.

### Conclusions

The approach to formal hull form optimization used for the dredge *Glenn Edwards* is practical and produced measurable improvement to performance both in deep and shallow water operations. Optimization is subject to a constraint set defined by the naval architect. Proper definition of that constraint set both engages the practicing naval architect and imposes a discipline to identify only the truly essential constraints. The parameterized geometry makes possible the limitation of optimization DOF to practical values, while simultaneously (and implicitly) enforcing selected constraints. The parameters of the geometry are physical (not abstract), and hence, intuitive for practicing naval architects.

This approach gives the ability to investigate compliance of thousands of potential hull forms with the constraints, and to evaluate the relative hydrodynamic performance of hundreds (or potentially thousands) of constraint compliant hull forms. This breadth of investigation, together with the application of directed search strategies, ensures that the final selected hull form is a credible near optimum, while the parametric geometry ensures that the selected hull adheres to conventional notions of fairness. All of these contribute to acceptance of the optimized hull by owners. Finally, the favorable results obtained in actual service are recognized and appreciated by owners.

### Acknowledgement

The authors gratefully acknowledge the support of owners of the *Glenn Edwards*, Manson Construction Company, and of Hal Hockema, the lead and managing naval architect for the project.

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