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## A MULTIDISCIPLINARY DESIGN OPTIMIZATION SCHEME FOR CONTAINERSHIPS

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### Abstract

A multidisciplinary design optimization scheme for ships has been developed for use in an integrated ship design environment. Although the system was designed with the intention of using analysis techniques based on first principles, the containership design examples presented in this paper make use of parametric analysis modules developed to examine problem formulation issues prior to the availability of the higher fidelity modules. A method of hull shape control based on a barycentric blend of basis hulls is developed. It requires relatively few design variables. In addition to general-purpose geometry, hydrostatic and resistance modules, containership-specific weight, cargo and economics modules were developed. The measure of merit is taken to be the required freight rate. Optimal ship size is found to depend largely on port loading and unloading capabilities. The required freight rate increases and the speed of the optimal ship decreases as voyage length is decreased or fuel cost is increased. The need for a design variable controlling ballast is demonstrated.

### Introduction

The work described in this paper was conducted as part of a project funded under the U.S. Navy's MARITECH program entitled A First Principles Approach for Shipbuilding Integrated Process and Product Development (FIRST). The goal of this project was to develop an integrated computational design environment that would enable the ship designer to reduce the time needed to produce and analyze alternative ship

designs at a high level of detail. It is envisioned that design calculations be done at a first-principles level, including manufacturing and operational econometrics.

The idea of having hydrostatic, resistance, propulsion, weight and economic analyses enabled in a common design environment led naturally to the desire to implement a multidisciplinary design optimization (MDO) capability. With MDO, the designer can break out of the traditional design-spiral approach and, what has been called, the "stove-pipe" analysis approach where each analysis proceeds more or less vertically with little interaction across disciplines.

Ship design traditionally uses the design-spiral approach. It provides a balanced solution to a given set of requirements, but it is also a solution that is not unique. In contrast, by choosing a measure of merit, which can be calculated for a candidate design, the MDO optimization process attempts to find the design which maximizes (or minimizes) this measure. In the case of the FIRST project, which is aimed at commercial ship design and which is to include first principle economic measures, we have chosen to minimize the required freight rate.

This MDO process also brings to bear the fidelity of first-principle analyses at what would normally be thought of as a preliminary design stage. Typically, basic characteristics (e.g., principal dimensions) are largely determined during the first or second turn around the design spiral. Detailed analyses are not carried out until later in the design process when flexibility to change these general characteristics has been greatly reduced. Decisions that determine these characteristics are generally made based on a single discipline's analysis. Using the MDO process, all design variables are varied based on their effect on the measure of merit and an improved design is obtained.

Two generally popular classes of algorithms for the optimization process are gradient-based and genetic algorithms. In the gradient-based algorithms, sensitivities of the objective function (the measure of merit) to changes in the design variables are calculated and the vector of design variables is adjusted in the direction so

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indicated. In the genetic algorithms, an initial set of randomly chosen designs is ranked by their objective function values. A second generation of designs is then obtained as more or less random mutations of the better designs of the previous generation. This process continues until little improvement in the objective function is seen from generation to generation.

Since genetic algorithms do not require differentiation of the objective function with respect to the design variables, they handle cases of discrete design variables (such as choice of power plant) more easily than gradient-based algorithms. On the other hand, they usually require a much larger number of objective function evaluations than is necessary for the gradient-based algorithms. Thus, genetic algorithms are practically restricted to parametric analysis methods by the computational time required. Since it is our intention to employ first-principles analysis codes, we have chosen to use gradient-based algorithms in this work. Frank et al<sup>1</sup> present a further discussion of optimization methods

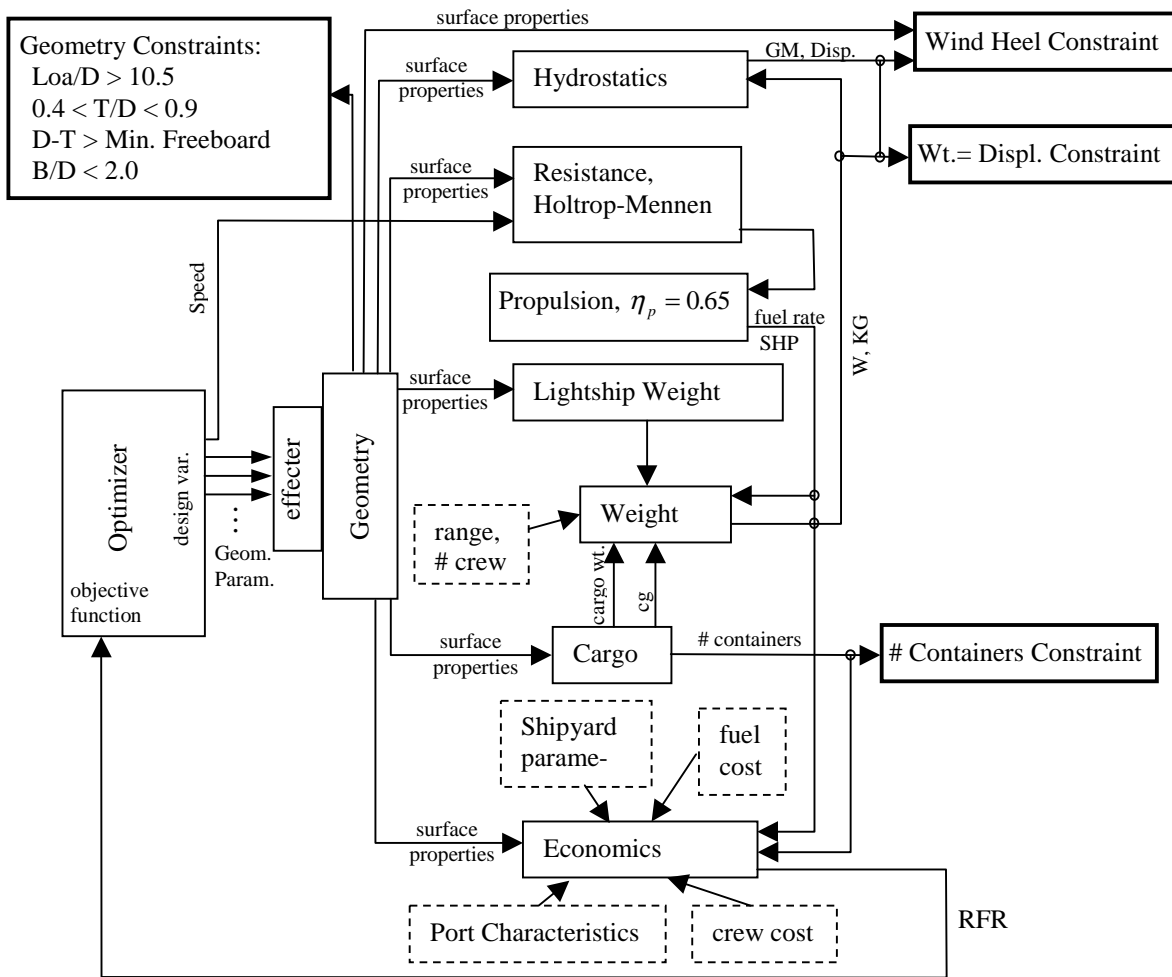
in the context of MDO.

Keane et al<sup>2</sup> present another example of gradient based methods applied to ships. An application of a genetic algorithm to minimizing hull resistance is given by Day and Doctors.<sup>3</sup> Sen<sup>4</sup> and Ray and Sha<sup>5</sup> present approaches to the multicriteria optimization problem.

The following sections provide an overview of the system software modules that comprise the computational code, a brief description of each module, a discussion of the constraints and several example applications.

### System Overview

The computational code consists of a number of analysis modules, an optimizer and a user interface. Figure 1 is a “wiring diagram” of the system. Only a few of the key parameters used are shown. The code is written with a target platform of Microsoft Windows NT and uses Microsoft’s Component Object Model (COM) framework. This was done so that the MDO



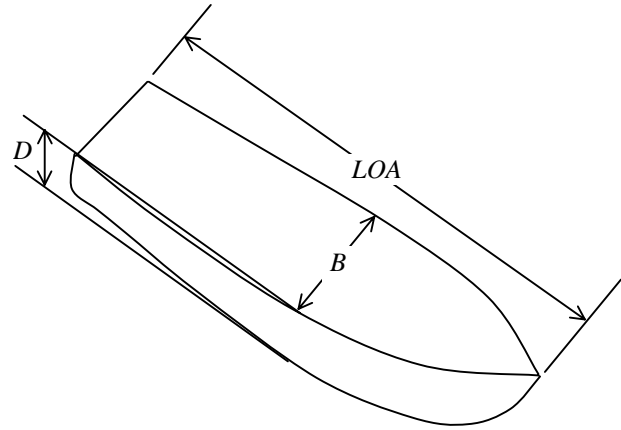
**Figure 1: General construction of the software system. Constraints are in heavy boxes, parameters in dashed boxes.**

system will be compatible with the larger FIRST project design tool into which it will be integrated. In the world of COM, each module acts as an independent server exposing its services to other independent client modules through one or more interfaces. Thus, as long as the interfaces are the same, the modules supplying analysis services may be replaced by another module providing the same service with negligible impact on the rest of the code.

This feature was important in that both the MDO system and the larger FIRST tool of which it is to be a part, were being developed simultaneously. The higher fidelity analysis tools, which will ultimately be used in this system, were not yet available and thus surrogate analysis modules were written. To explore problem formulation issues, these surrogate modules needed to perform in the same general manner as the high fidelity modules, and thus simple parametric representations of the analyses were used. The modules are each based on proven, published parameterizations. However, only simple attempts have been made to update the many parameters and coefficients to reflect current costs and construction practices.

The C++ analysis modules are orchestrated by a main program we call an optimization manager and a user interface, both written in Visual Basic. The user interface presents a standard set of MS Windows menus from which the user may open and save data files or manipulate the initial value of the design variable vector and its side bounds. He or she may turn on and off and alter the magnitude of many of the constraints, adjust the values of the parameters used in the analysis modules and adjust the parameters controlling the operation of the optimizer. Once the optimization is started, the value of the objective function is plotted at each iteration and a table of the current values of the design variables is constantly updated. The user may stop the calculation, adjust the design variable vector and restart the process at will. Once the optimization has stopped, either by satisfying the convergence criteria or by reaching the maximum number of iterations specified, the user may restart it, using as the initial point the point in the design space where it had stopped. A menu option allows the user to plot iteration histories of the design variables and several other important quantities.

The Design Optimization Tools (DOT) package from Vanderplaats Research and Development, Inc.<sup>6</sup> was chosen as the optimizer. DOT includes the choice of three gradient-based optimization methods, a modified method of feasible directions, sequential linear programming, and sequential quadratic programming. We have made the DOT FORTRAN subroutines into a Microsoft COM object by writing a C++ wrapper



**Figure 2: Definition of basic dimensions length overall,  $LOA$ , beam,  $B$ , and depth,  $D$ .**

around the DOT FORTRAN source code. Our tests have shown that, for this problem, the quickest and most consistently reliable results are obtained using sequential linear programming. It is used for the examples presented below.

Besides the optimization module, the system has modules which perform the following functions: calculate a NURBS (Non-Uniform Rational B-Spline) hull geometry surface, calculate a mesh of offsets on the surface described by the NURBS net, integrate the surface and calculate hydrostatic properties, calculate ship resistance, calculate propulsive efficiency, powering requirements and fuel rate, calculate lightship weight and  $CG$ , calculate payload weight and  $CG$ , calculate roll period, minimum  $GM$  and freeboard, and calculate economic characteristics. Each of these is discussed briefly below.

Clearly the weight and economics modules must depend on the ship type. A containership design problem was chosen for the construction this prototype MDO system.

The design variables, i.e., those variables that the optimizer manipulates, are chosen to be the basic dimensions, defined in Figure 2, length overall ( $LOA$ ), maximum beam ( $B$ ) and depth ( $D$ ) of the hull, the draft (distance from the lowest point on the hull to the water surface), the cruising speed, and a (set of) parameter(s) that controls the hull shape. The hull shape manipulation is discussed in the next section. The constraints imposed are discussed further below.

## HULL GEOMETRY

As a means of controlling the hull shape, the hull is represented as a barycentric blend of basis hulls. This is similar to the blending of basis shapes in airfoil

shape optimization as is done, by Vanderplaats.<sup>7</sup> The blending can be represented as

$$\text{Resultant Ship Hull} = \sum C_n \text{Basis Hull}_n$$

where,

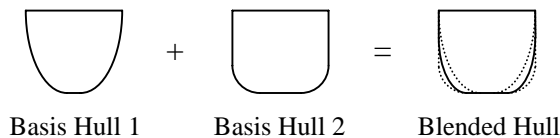
$$\sum C_n = 1$$

and,

$$0 \leq C_n \leq 1, \\ n = 1, 2, \dots, N.$$

Thus, the hull resulting from this blending process is restricted to being a member of the hull shape space bounded by the basis hulls. Figure 3 illustrates the blending concept for the midship section in a case of only two basis hulls.

The blending coefficients,  $C_n$ , are the design variables that adjust the hull shape. Because of the constraint,  $\sum C_n = 1$ , the number of design variables the optimizer must adjust is  $N - 1$ . The blending is applied to the NURBS net points of the basis hulls (which have standard dimensions) and the resulting hull is then scaled to the necessary length, beam and depth.



**Figure 3: Illustration of geometry blending technique.**

### Hydrostatics

The NURBS net obtained by the blending and scaling discussed above, naturally yields a set of unequally spaced points located on the hull surface it represents. Hull volumes and areas are calculated from this mesh of surface points and the displacement, the hydrostatic coefficients, and the metacentric height are calculated by the hydrostatics module. The displacement of the ship must balance the weight. The hydrostatic coefficients are used in the resistance and cargo capacity calculations. The metacentric height, which depends on the shape of the water plane area (largely the size of the beam) and the displacement, determines the initial stability of the ship. With the ship in the upright position, the metacenter must be above the center of gravity for stability.

### Resistance and Propulsion

The ship's resistance at the current cruising speed is calculated using the Holtrop/Mennen regression formula.<sup>8</sup> Additional resistance due to appendages is ignored; however, the effect of a bulbous bow is accounted for. The propulsion module, at present, simply assumes an overall propulsive efficiency of 0.65, a

typical value. Thus a shaft horsepower is obtained and, from a specific fuel consumption that is input as a parameter, a fuel rate is calculated.

### Weights

Parametric relationships for lightship weights and centers of gravity were obtained from Benford<sup>9</sup>, Taggart<sup>10</sup> and Schneekluth.<sup>11</sup> Lightship weight is broken into three categories: hull steel, outfit and propulsion machinery, each with its own parametric equations for weight and center of gravity. Because the coefficients used in the parametric equations obtained from the above references did not reflect modern design and construction practices, the weight equation coefficients were recomputed based on seven modern container-ships ranging in length from 186 to 263 m. A three percent margin is added to the calculated lightship weight and a 0.3 m margin is added to the vertical center of gravity.

Fuel weight is based on the specified ship range, its speed and the calculated fuel rate. A ten percent reserve is added to the fuel weight. Relations for miscellaneous weights, including, crew and provisions, fresh water and lube oil, were obtained from Erichsen.<sup>12</sup>

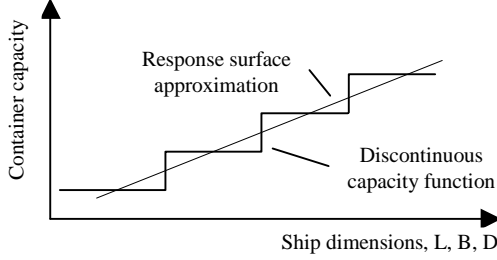
### Cargo

It is necessary to calculate the container carrying capacity as the ship's dimensions vary. Two relations were developed, one for containers, in terms of TEU's (Twenty foot Equivalent Unit, 6.1 m x 2.44 m x 2.44 m), below deck and one for TEU's above deck.

For TEU's below deck, the integer number of containers that will fit along each of the length, beam and depth directions is found, allowing for wing tank and double bottom spaces. These integer values are multiplied together to form a block capacity, which is then multiplied by a stowage factor that is a function of block coefficient. The stowage factor was determined from the known capacities of twelve existing ships.

The relation for the number of containers above deck is similar to that below deck, except that the number of tiers of containers above deck is substituted for the number that would fit depthwise and a different stowage factor is used. The number of tiers above deck is a parameter specified by the user. Since a tier above deck may not extend over the entire ship, the number of tiers above deck is not required to be an integer.

Cargo weight is simply the total number of containers multiplied by an average container weight. The center of gravity of the containers above deck is calculated considering them to be of uniform density and raised off the deck by a hatch coaming height. The CG of the containers below deck is raised from the mid



**Figure 4: 2-D illustration of container capacity function and linear response surface.**

height of the available depth by a factor that depends on block coefficient.

With this scheme, the container capacity, cargo weight, etc., is a discontinuous function of the ship's dimensions (Figure 4). This results in a discontinuous, saw-tooth like objective function (the required freight rate) with many local minima that can trap the optimizer. Also, the values of the numerically calculated gradients can be significantly in error in the vicinity of the discontinuities, which is a problem for gradient-based methods. To remedy this situation, we have chosen to fit a linear response surface to the discontinuous container capacity function as is illustrated in two dimensions in Figure 4.

### Economics

To calculate the required freight rate, the economics module must determine building costs and annual operating costs. These are obtained using the relations of Benford<sup>9</sup> and Erichsen.<sup>12</sup>

Building cost is broken into labor and materials costs for each of: hull steel, outfit, hull engineering and propulsion machinery, miscellaneous costs, accommodation costs, overhead costs, yard's profit and owner's expenses. Each of these costs has its own parametric relation that is ultimately based on one or more components of lightship weight, installed horsepower, or number of crew. The building cost ( $BC$ ) is multiplied by a capital recovery factor ( $CR$ ) to distribute it into an annual cost over the life of the ship. The annual building cost,  $ABC$ , is then

$$ABC = BC \cdot CR.$$

$CR$  is defined by

$$CR = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where  $i$  is the interest rate and  $n$  is the life of the ship in years.

To calculate annual operating costs, the number of round trips made annually by the ship must be known.

This depends on the time spent at sea, which depends on cruising speed, and on time spent in port. The port time includes waiting time and time spent loading and unloading the ship. The loading/unloading time depends on the number of cranes being used. The number of cranes can be specified or can be calculated based on the ship's length. The annual operating cost ( $AOC$ ) is then formed as the sum of individual relations for wages, stores and supplies, insurance, maintenance and repair, port expenses, and fuel cost.

The required freight rate ( $RFR$ ) is then expressed as the total average annual cost per ton of cargo carried per mile.

$$RFR = \frac{ABC + AOC}{NT \cdot W_C \cdot D}$$

where  $NT$  is the number of round trips made per year,  $W_C$  is the weight of the ship's cargo capacity, and  $D$  is the round trip voyage distance.

Important parameters used by the system but not mentioned above include labor rates, material costs for hull, outfit and engineering, number of containers handled per day per crane, and fuel price. No per container cargo handling charges are included since they vary widely from port to port and they do not affect the point in the design space at which the minimum occurs but serve only to increase the value of the required freight rate for all designs.

### Constraints

The condition that weight equal displacement is enforced as a constraint. We treat draft as an independent design variable rather than enforce the weight-displacement balance through an internal loop at each design iteration. This has been called an optimization based decomposition approach. Tests have shown that this quickens the calculation over an approach where the design is balanced at each iteration.

The U.S. Coast Guard wind heel criterion for minimum initial stability and the U.S. Coast Guard minimum freeboard requirement are also imposed as constraints. The wind heel criterion establishes a minimum on the distance between the center of gravity and the metacentric height,  $GM$ . This distance also determines the natural rolling period. The rolling period is inversely proportional to  $GM$ . The user may select constraints on minimum rolling period, maximum displacement, maximum shaft horsepower, and both upper and lower bounds on container capacity. The freeboard is the difference between the depth and the draft. It is the amount of hull above the waterline.

Two modifications of the constraints were needed to ensure convergence from an infeasible starting point with a negative  $GM$ . First, since the natural roll period

is undefined for  $GM < 0$ , it was artificially extended into this region as an even function of  $GM$ . Second, the initial stability constraint is formulated as

$$g = 1 - \frac{GM}{GM_{min}} \leq 0.$$

For  $GM \ll 0$ , the derivative of  $g$  with respect to beam,  $\frac{\partial g}{\partial B}$ , can become positive (due to the dependence of  $GM_{min}$  on beam) indicating that the beam should be decreased rather than increased and the optimizer fails to find a feasible solution. To overcome this, we hold  $GM_{min}$  equal to its initial value while  $GM < 0$ .

### Example Applications

Three groups of examples are presented below. The optimization scheme was initially constructed and run without the  $B/D$  constraint included in Figure 1. These results are presented in the first section. They are reasonable except that the resulting ships have a large beam to depth ratio averaging about 2.9. This is a ship with a beamy, flat cross-section that would have trouble supporting the longitudinal bending moment it would be subjected to in rough seas. This results from the lack of a structural constraint.

As a surrogate for a true structural constraint, the  $B/D$  constraint was added. While the value of  $B/D$  for existing ships is influenced by allowable draft and stability issues, limiting it to the more typical value of 2.0 does insure ship dimensions that would allow the designer to satisfy the structural requirements. The results from this modification and an interesting lesson learned are presented in the second section.

In the third section, an effort is made to remove the approximation on the container capacity that was introduced by the linear response surface fit to the step-wise discontinuous capacity function.

In each example, the hull shape is adjusted by blending two basis hulls. Only one shape design variable is needed,  $C_1$ . Basis hull 1 is finer than basis hull 2. The important parameter values used in each case are: ship life = 20 yrs, interest rate = 8%, weight per TEU = 12 mt, and specific fuel consumption = 120 g/BHP/hr.

#### Initial examples

For each of the initial examples, the number of tiers of containers on deck is fixed at 5.5. Except in Example 4, the number of cranes loading and unloading is calculated based on one crane every 135 feet over 75% of the ship length. For the 300 m designs that result below, this means 6 cranes. Except in Example 5, voyage distance = 7000 nmi. Except for Example 6, the fuel price used was \$80 per mt. In light of the re-

**Table 1: Design variable bounds and initial values for Example 1.**

	Lower limit	Initial value	Upper limit
LOA	130.0	200.0	300.0
Beam	15.0	28.0	43.0
Depth	10.0	20.0	30.0
Draft	4.0	10.0	13.5
Speed	4.00	19.0	35.00
$C_1$	0.00	0.5	1.00

turn of fuel prices to considerably higher values in recent months (May 2000), the final example is a repeat of the first with a fuel cost of \$120 per mt.

Table 1 gives the initial values of the design variables used for Example 1 along with their upper and lower limits. The upper limits on length, beam, and draft were chosen to roughly coincide with a recently built, large containership. The initial values of the design variables result in an infeasible design with an initial  $GM$  of  $-7.4$  m, a weight of 42,000 mt, and a displacement of 33,700 mt. The results for each example are presented in Table 2. Convergence is quick; these examples each converge in 7 – 15 iterations.

Example 1 is a minimally constrained case and thus results in the lowest required freight rate of the cases considered here. The only constraints applied, other than the side bounds on the design variables, are weight equals displacement, the stability criterion and the minimum freeboard. The optimizer goes to the maximum length and beam and chooses the fullest possible ship that could result from the blending. The value of  $C_1$  is essentially zero, or the optimum ship is all basis hull 2. It is interesting to note that the required freight rate is relatively insensitive to the value of the blending coefficient. The optimum ship has a  $B/D = 3.1$  and a  $L/D = 21.6$ , both very high. This is the result of the absence of a structural constraint. The use of the minimum allowable freeboard is also not typical of containerships.

Example 2 is the same as Example 1 except that the lower bound on the speed has now been raised to 25 knots. Rather than going for the fullest hull, the optimizer now chooses the finest possible hull (indicated by the lower block coefficient); the optimum is all hull 1,  $C_1 = 1$ . The ship carries fewer containers but has a larger displacement. This is due, in large part, to the increased engine and fuel weight, which also causes a drop in  $GM$  and subsequent rise in natural roll period. The required freight rate jumps about 20%. Both Examples 1 and 2 have the minimum required freeboard.

Example 3 is the same as Example 1 except with the additional constraint of a 25 second natural rolling

**Table 2: Design variable values and various ship characteristics at the optimum point for the first set of examples.**

	Ex. 1	Ex. 2	Ex. 3a	Ex. 3b	Ex. 4	Ex. 5a	Ex. 5b	Ex. 6
LOA (m)	300.0	300.0	300.0	300.0	209.0	300.0	299.8	300.0
Beam (m)	43.0	43.0	36.1	39.2	43.0	43.0	43.0	43.0
Depth (m)	13.9	16.6	14.7	16.6	11.7	13.8	13.7	13.9
Draft (m)	9.14	11.9	9.44	10.1	8.29	9.06	8.96	9.10
Speed (kn)	17.1	25.0	17.5	17.8	15.1	16.8	15.3	15.9
$C_I$	0.0	1.00	0.003	.012	0.008	0.008	0.013	0.0
Displacement (mt)	85,030	88,370	73,320	83,780	54,400	83,960	82,900	84,520
# TEU's	5203	5049	4427	4996	3393	5183	5165	5195
Shaft horsepower	22,040	72,650	20,700	23,050	11,970	20,790	15,110	17,260
Roll period (s)	11.2	17.8	25.0	25.0	9.32	11.2	11.2	11.2
Block coefficient	0.714	0.568	0.710	0.703	0.722	0.712	0.712	.713
RFR (\$/mt/nmi)	.00106	.00126	.00111	.00111	.00149	.00124	.00212	.00115

period. Ships with the lower rolling periods of the first two examples respond sharply in roll. They are uncomfortable to ride and may cause damage to cargo in heavy seas. By using several starting points, the optimizer found two solutions to this problem that give approximately the same required freight rate. These are shown as 3a and 3b in Table 2. In both cases, the optimizer raises the freeboard, and thus raises the center of gravity since that space is filled with containers. Both this and lowering the beam reduces  $GM$  and increases the natural rolling period. Solution 3a uses a smaller beam, smaller depth, and less freeboard than does solution 3b. It consequently carries fewer containers but requires less SHP for about the same speed and so the required freight rates are similar. This illustrates that the optimizer will find local rather than global optima. The larger roll period costs about 5% in required freight rate.

The fourth example illustrates the effect of port time on the optimum design. This example is again the same as Example 1, but with only one crane being used to load and unload the ship. The increase in time spent in port reduces the benefit of investment in a larger, faster ship. The result is a much smaller, slower ship than was obtained in Example 1. The required freight rate has increased 41%.

For the fifth example, the voyage distance was halved to 3500 nmi but otherwise, the conditions were the same as for Example 1. It was thought that changes in the optimum ship in the same direction as was seen in Example 4 would be obtained since the time in port relative to that at sea was again increased; however, what was found was a very similar, only slightly slower ship with a 20% higher required freight rate shown as Example 5a. The voyage distance was then cut to 1000 nmi. The result, shown as Example 5b, was again, a very similar, but slower ship. It appears that if the cranes are available, it is worth building a large ship,

assuming of course that the market exists for the large capacity.

Example 6 looks at the effect of raising the fuel cost from \$80/mt to \$120/mt. Except for this change, the input is the same as for Example 1. The optimum ship is nearly identical to the one in Example 1 with the exception of a slower speed and the consequent smaller SHP and displacement. The fuel cost was also raised in Example 2, where a 25 kn speed is required; a nearly identical ship was obtained but its required freight rate went up by 18% to 0.00149 \$/mt/nmi.

#### Addition of the $B/D$ constraint

In place of a structural constraint, the constraint  $B/D < 2.0$  was added as discussed earlier. The results obtained are shown in Table 3. For each of the results shown in this section, the blending coefficient,  $C_I$ , is zero. Example 7 is a repeat of Example 1 except for the addition of this constraint. The results are curious. The  $B/D$  constraint is of course active, but the optimizer also shortens the ship to the point that the  $L/D$  constraint is active and raises the speed giving a tremendous shaft horsepower. The  $GM$  (stability) constraint is also active. It is obvious to anyone who has looked at a few ship designs that this is not a very good one.

After some ponderance of the issue, it was realized that the  $B/D$  constraint was making it difficult to satisfy the stability constraint. Shortening the ship will have a small effect on  $GM$  but the only truly effective way to raise  $GM$  is to widen the beam and lower the center of gravity. Unfortunately, due to the  $B/D$  constraint, widening the beam meant raising the depth and along with it, the center of gravity. The only means the optimizer had been provided to lower the center of gravity was to increase the weight of the power plant and fuel, both of which are placed low in the ship, by increasing the resistance. Shortening the ship and widening the beam will increase the resistance per unit



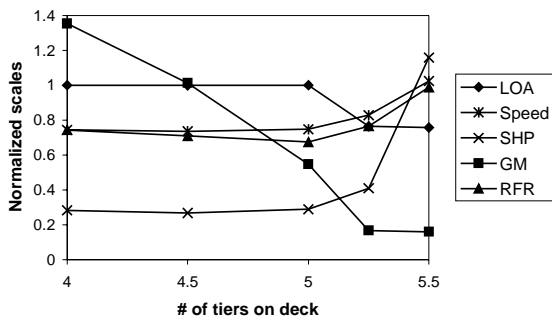
**Table 3: Design variable values and various ship characteristics at the optimum point for the second set of examples implementing the  $B/D$  constraint.**

	Ex. 7	Ex. 8	Ex. 9	Ex. 10	Ex. 11
$LOA$ (m)	227.3	300.0	299.8	300.0	229.3
Beam (m)	43.0	43	42.4	42.7	43.0
Depth (m)	21.5	21.6	21.2	21.3	21.5
Draft (m)	12.4	10.6	10.9	11.3	11.6
Speed (kn)	25.6	18.6	18.4	18.7	20.7
# tiers on deck	5.5	4.0	4.5	5.0	5.25
Displacement (mt)	85,420	94,280	95360	100,140	79,830
# TEU's	4596	5189	5363	5723	4494
Shaft horsepower	115,868	28,292	26,724	28,855	40,984
Roll period (s)	69.1	22.7	26.1	36.2	66.6
$GM$	0.24*	2.03	1.52	0.82	0.25*
RFR (\$/mt/nmi)	.00173	.00130	.00124	.00118	.00134

\* $GM$  (stability) constraint active

displacement. Raising the speed will greatly increase the resistance. The optimizer was forced to do both of these.

In Example 8, the number of tiers of containers on deck has been reduced to 4.0. This lowers the center of gravity but also reduces the cargo capacity of the ship. The system now has no trouble meeting the stability constraint and behaves as expected. Examples 9 and 10 are for 4.5 and 5.0 tiers of containers on deck respectively. As the number of tiers is increased, the cargo capacity increases and the required freight rate drops. In Example 11 the number of tiers is 5.25. The  $GM$  constraint becomes active; the optimizer drops the length and begins increasing speed. Normalized values of  $LOA$ , speed, shaft horsepower,  $GM$ , and required freight rate are shown in Figure 5.



**Figure 5: Normalized values of  $LOA$ , speed, shaft horsepower,  $GM$ , and required freight rate from the second set of examples.**

#### Secondary optimization

The last set of examples concerns refining the optimum design by returning to the actual stepwise discontinuous TEU capacity function. Once again, Example 1 is used as a point of departure. The optimization

is first run with the response function approximation for the TEU capacity, as illustrated above. The discontinuous (integer) TEU capacity function is then substituted for the response surface, the side bounds on  $LOA$ ,  $B$  and  $D$  are set as the boundaries of the plateau of the TEU capacity function where the first optimization stopped, and the optimizer is restarted. While moving in this region, the number of TEU's does not remain constant since, besides the basic dimensions, it also depends on the block coefficient, which is still free to vary. Typically, the optimum will be near the lower limit of length and beam (if this yields a feasible solution) for any TEU capacity plateau since this will be the least expensive ship to build and operate for its cargo capacity. It is necessary to start the optimizer on the plateau where the primary optimization stops and on neighboring plateaus to verify that a "global" (in a local sense) optimum has been found. Example 1 is a good example of this procedure since the response function approximation is not a particularly good fit to the integer TEU capacity function in the region of the optimum (5203 vs. 4750). Since the step between plateaus in the depth dimension is a large percentage of the depth, it is not usual for the final optimum to move off the primary depth plateau.

This procedure is illustrated by the results given in Table 4. The primary optimization is that of Example 1, whose results are repeated here for convenience. It stops at the upper bound in both length and beam. This falls on a plateau of the TEU capacity function that extends from 294.6 to 301.0 m in the length dimension and from 42.7 to 43.9 m in beam. This plateau is truncated by the original bounds of 300 and 43 m and the optimization is restarted using the integer TEU capacity function.

The results are listed under the secondary 1 column in Table 4. As expected, the optimum is at the

**Table 4: Results for the primary and secondary optimizations using the integer TEU capacity function and discussed in the third set of examples.**

	primary	Secondary 1	Secondary 2	Secondary 3	Secondary 4	Secondary 5
<i>LOA</i> (m)	300.0	294.6	288.2	294.7	288.2	294.6
Beam (m)	43.0	42.7	42.7	41.5	41.5	40.3
Depth (m)	13.9	13.6	13.4	13.5	13.5	13.5
Draft (m)	9.14	9.0	8.9	8.9	9.0	8.9
Speed (kn)	17.1	17.5	16.8	17.4	17.1	17.1
$C_T$	0.0	0.29	0.19	0.10	0.21	0.19
Displacement (mt)	85,030	77,300	75,630	76,440	74,140	73,140
# TEU's	5203	4649	4582	4621	4487	4402
Shaft horsepower	22,040	21890	19290	21790	19910	19430
Block coefficient	0.714	0.673	0.687	0.699	0.684	0.687
<i>LOA</i> lower limit	130.0	294.6	288.2	294.6	288.2	294.6
<i>LOA</i> upper limit	300.0	300.0	294.6	300.0	294.6	300.0
<i>B</i> lower limit	15.0	42.7	42.7	41.5	41.5	40.3
<i>B</i> upper limit	43.0	43.0	43.0	42.7	42.7	41.5

lower bound in each of the length and beam dimensions but due to the change in calculated container capacity, it balances out to a significantly finer ship at a different draft and speed.

Secondary optimizations 2, 3 and 4 examine the surrounding plateaus, stepping down in length, beam and both length and beam respectively. It is found that secondary optimization 3, the step down in the beam dimension, gives a lower required freight rate than that found for the first secondary optimization. An additional optimization, stepping down once again in beam is necessary to verify that this is our optimum. The results of this last step are given as secondary 5. It is seen that the required freight rate increases with this last step and the secondary 3 case is taken as the optimum.

## Conclusions

A prototype MDO tool for ship design has been developed based on Microsoft's COM framework. With this design, the analysis modules can be replaced with a minimum of programming effort. Surrogate parametric analysis modules have been developed for the purpose of exploring problem formulation issues while higher fidelity analysis modules are being developed. A geometric shape manipulation scheme was developed in which the hull was formed by blending a set of basis hulls.

The MDO system was exercised on a set of containership design problems with the objective being to minimize the required freight rate. It was found that without being otherwise constrained, the optimizer sought the largest allowed length and beam. In the absence of a structural constraint, the optimizer seeks a design with a high  $B/D$  ratio.

Test exercises have shown that if the loading/unloading time is constrained, investment in larger, faster ships is not beneficial. The required freight rate decreases with increasing voyage distance but vessel size is determined by how fast it can be turned around in port. The limited study performed indicates that fuel cost affects the required freight rate and optimum speed but not the principal dimensions of the ship.

A constraint on  $B/D$  was implemented as a surrogate for a structural strength constraint. It was found that, in order to satisfy the stability constraint, the optimizer produced a ship with a large resistance. This was because the only means it had of lowering the center of gravity was to increase the fuel and power plant weights. In the future, a design variable will be added to control ballast.

A method of eliminating the linear response surface approximation to the stepwise discontinuous TEU capacity function in a secondary optimization was explored. It was found that the minimum of the required freight rate occurred at the lower limits of length and beam on each TEU capacity plateau. A systematic search of TEU plateaus in the vicinity of the primary optimum was necessary to define the secondary optimum.

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