Formulation of a Multi-Disciplinary Design Optimization of Containerships

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(ABSTRACT)

To develop a computer tool that will give the best ship design using an optimization technique is one of the objects of the FIRST project. Choosing a containership design as a test case, the Design Optimization Tools (DOT) package is used as the optimization tool. The problem is tackled from the ship owner's point of view. The required freight rate is chosen as the objective function because the most important thing that concerns the ship owner is whether the ship will make a profit or not, and if so, how much profit it can make. DOT, as well as any other numerical optimization tool, only gives an approximation of the optimum design and uses numerical approximation during the optimization. It is very important for the users to formulate carefully the optimization problem so that it will give a stable and reasonable solution. Development of a geometric module and choosing suitable empirical formulas for performance evaluation are also major issues of the project.

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Nomenclature

Symbol	Unit	Definition	Default Value
θ	degree	Lesser of either 14 degrees or the angle of heel to the deck edge	
ρ	kg/m^3	Mass density of the water	1025.9
∇	m^3	Molded displacement volume	
$1+k_1$		Form factor describing the viscous resistance of the hull form in relation to R_F	
A	m^2	Projected lateral area of the portion of the ship and deck cargo above the waterline	
Aac	$	Annual average cost	
Abc	$	Annual building cost	
A_{BT}	m^2	Transverse sectional area of the bulb at the position where the still-water surface intersects the stem	
Accoc	$	Accommodation cost	
Afc	$	Annual fuel cost	
Aoc	$	Annual operation cost	
A_T	m^2	Immersed transom area	
B	m	Molded breadth	
B_0	m	Breadth of container	2.44
B_b		Container number below deck along the beam direction	
B_d		Container number above deck along the beam direction	
C_1, C_2, C_i		Geometric blending factor of the basis ship	
c_{14}		Coefficient accounts for the stern shape for the resistance calculation	
c_6		Coefficient related to F_{nT} for the resistance calculation	
C_b		Block coefficient	
Cdk		Coefficient for the deck department	15.4
Ceng		Coefficient for the engine department	10
C_F		Coefficient of frictional resistance	
C_f		Conversion factor from long ton to metric ton	1.016
Chhe		Coefficient for the calculation of hull engineering's man-hour	20400
Chm		Coefficient for the calculation of machinery's man-hour	6773
Chull	$/ton	Average cost for hull engineering	3500
C_{kgb}		Form factor of KG_b	
C_m		Midship-section coefficient	

Symbol	Unit	Definition	Default Value
Cmhs		Coefficient depending on the effectiveness of the shipyard for the calculation of the steel hull's man-hours	3160
Cmm		Coefficient for the calculation of material cost of machinery	38867
CN	m^3	Cubic number of the ship defined as $L_{oa}BD/100$	
Co		Coefficient for the calculation of the outfit's man-hours	8000
Cof	$/ton	Average cost of outfit	1500
C_p		Prismatic coefficient based on the waterline length	
Cr		Capital recovery factor	
Csh	$/ton	Average cost of the total hull steel	400
Cst		Coefficient for stewards department	1.25
C_{stern}		Stern shape coefficient	0
C_w		Water plane coefficient	
D	m	Molded depth of the ship	
D_0	m	Depth of container	2.44
D_b		Container number below deck along the depth direction	
DBH	m	Double bottom height	1.83
Drt	day	Total round trip time	
D_s	m	Increased depth taking account of the shear and hatchway volume	1.008D
DST	nm	Service range of the ship	7000
EHP	hp	Effective horsepower of the ship	
Fcost	$/ton	Average fuel cost	80
F_n		Froude number	
Fni		Froude number based on the immersion	
F_{nT}		Froude number based on the transom immersion	
g	m/s2	Gravity acceleration	9.81
GM	m	Metacentric height of the ship	
H	m	Vertical distance from the center of A to the center of the underwater lateral area or approximately to the one-half draft point.	
h_B	m	Vertical position of the center of A_{BT}	
HCH	m	Height of hatch coamings	1.83
i		Iteration number	
i_E	degree	Half angle of entrance	
Ins1	$	Insurance for protection and indemnity	
Ins2	$	Insurance for hull and machinery	
Ir		Interest rate	8%

Symbol	Unit	Definition	Default Value
KG	m	Vertical distance of the ship's gravity center from the base line	
KG_b	m	Gravity center of the containers below deck	
KG_f	m	Gravity center of the fuel weight	
KG_h	m	Gravity center of the hull steel weight	
KG_{light}	m	Gravity center of the total lightship weight	
KG_m	m	Gravity center of the machinery weight	0.47D
Kg_{misc}	m	Gravity center of the total miscellaneous weight	0.5D
KG_{oh}	m	Gravity center of the total outfit weight	
L, L_{wl}	m	Waterline length	
L_0	m	Length of container	6.1
lambda		Step length during the optimization	
L_b		Container number below deck along the length direction	
L_{bp}	m	Length between perpendicular	L_{oa}/1.05
Lc	$/man-hour	Labor cost per man-hour for steel hull, hull engineering, outfit and machinery	20
L_{cb}		Longitudinal position of the center of buoyancy forward of 0.5L as a percentage of L	
L_{con}	m	Effective length for carrying containers	0.75L_{oa}
L_d		Container number above deck along the length direction	
Lhe	$	Labor cost for hull engineering	
Lhs	$	Labor cost for steel hull	
Lm	$	Labor cost for machinery	
Lo	$	Labor cost for outfit	
L_{oa}	m	Length overall	
L_R	m	Length of the run of the ship	
L_s	m	Length of superstructure within for and after perpendiculars	0.25L_{bp}
Lut	day	Time for loading and unloading containers per round trip	
Mathe	$	Material cost for hull engineering	
Mato	$	Material cost for outfit	
Mats	$	Material cost for steel hull	
Mhhe	man-hour	Man-hour for hull engineering	
Mhm	man-hour	Man-hour for machinery	
Mhm	$	Material cost for machinery	
Mho	man-hour	Man-hours for outfit	
Mhs	man-hour	Man-hours for steel hull	
Miscc	$	Miscellaneous cost	
Mrh	$	Maintenance and repair cost for hull	

Symbol	Unit	Definition	Default Value
Mrm	$	Maintenance and repair cost for machinery	
NBH		Number of basis hulls	
NCON		Number of constraints	
Ncrane		Number of crane available for the loading/unloading work	
Ncrew		Number of crew of the ship	
NDV		Number of design variables	
NT		Annual round trip number	
Ot	day	Annual operation time of the ship	350
Ovhc	$	Overhead cost	
Owc	$	Owner cost	
Owe	$	Owner expense	
P_B		Coefficient measuring for the emergence of the bow	
Pr	$	Yard profit	
Pwt	day	Port waiting time per round trip	2
R_A	N	Model-ship correlation resistance	
R_{APP}	N	Resistance of appendages	0
R_B	N	Additional pressure resistance of bulbous bow nears the water surface	
R_F	N	Frictional resistance	
RFR	$/t/nm	Required freight rate	
RFR0	$/t/nm	Required freight rate at the initial design point	
R_n		Reynolds number based on the waterline length L	
R_{total}	N	Total resistance of a ship	
R_{TR}	N	Additional pressure resistance of immersed transom stern	
R_W	N	Wave-making and wave-breaking resistance	
R_{W-A}	N	Wave resistance for the speed range of $F_n < 0.4$	
R_{W-B}	N	Wave resistance for the speed range of $F_n > 0.55$	
S	m^2	Projected wetted surface of the ship	
S		Search direction during the optimization	
S_b		Storage factors for containers below deck	
S_d		Storage factors for containers above deck	
SFC	g/hp/hour	Specific fuel consumption of the main engine	225
SHP	hp	Required shaft power of the ship	
SI	year	Ship life	20
Ss	$	Cost for stores and supplies	
St	day	Time spent at sea	
T	m	Molded draft of the ship	
TEU		Total number of containers (Twenty-foot Equivalent Unit)	

Symbol	Unit	Definition	Default Value
TEU_b		Container number below deck	
TEU_d		Container number above deck	
T_F	m	Forward draft of the ship	
TN_d		Tier number for containers above deck	
TSLU	TEU/day	Loading/unloading speed per crane	1440
V	m/s	Ship's speed	
Vk	knot	Ship's speed	
WB	m	Breadth of the wing tank	1.83
W_{con}	ton	Container weight	
W_{fuel}	ton	Fuel weight	
W_{fw}	ton	Fresh water weight	280 lton
W_h	ton	Hull steel weight	
W_{hc}	ton	Miscellaneous weight for the machinery being idle	
W_{he}	ton	Hull engineering weight	
W_{light}	ton	Lightship weight	
W_{lo}	ton	Lubricate oil weight	50 lton
W_m	ton	Machinery weight	
W_{misc}	ton	Miscellaneous weight	
W_o	ton	Outfit weight	
W_{oh}	ton	Outfit and hull engineering weight	
WPC	ton	Weight per container	12
W_{total}	ton	Total weight of the ship	
$\mathbf{X}$		Vector of design variables	
$\mathbf{X}^{\mathbf{0}}$		Initial design point	
X_i^L		Lower bounds on the design variables	
X_i^U		Upper bounds on the design variables	
Ybc	$	Yard building price	
Ytc	$	Yard cost	

Chapter 1 Introduction

For a long time, the ship design process has been an iterative procedure, which is known as the "Ship Design Spiral." The major characteristic of the Ship Design Spiral concept is that the design process is sequential and iterative. The iterative processes may be conceived as moving in a spiral fashion to a balanced conclusion with all features compatible. The process is arranged in a sequential manner because each design stage depends on the output of the preceding ones. Although the "Ship Design Spiral" concept is generally accepted, it is unable to provide the designers with an overview of the design and may obstruct the exploration of the optimum design.

With the end of the cold war, the defense budget for both the United States and European countries has been cut a lot. Therefore, many shipyards previously depending on naval shipbuilding have had to transfer their main goal to the commercial market. Nowadays, more and more countries participate in the global shipping market. Undoubtedly, these, among many other reasons, make the international commercial ship building market that is already full of competitiveness even tougher, not only for shipbuilders and for designers, but also for ship owners. It is generally accepted that initial design is the most important part of the ship design process. It is the most crucial phase in determining the overall configuration of the ship. It is also the initial design that decides whether the ship designer or shipbuilder can get the contract. Therefore, it is well motivated to develop a new tool for initial design. Not only should this tool give an initial design in a short period, but also should give the best design.

Fortunately, some developments enable us to achieve this goal in the last quarter of the century. First, we have seen dazzling growth in the computer technology, including their application to the ship design process. A number of Computer Aided Design (CAD) programs have been developed, including FlagShip, FORAN, TRIBON, etc. Ship designers now can create a mathematically defined ship hull on the computer screen, calculate hydrostatics and stability, predict resistance and powering, and analyze structure using the finite element method. More important, taking advantage of the great calculation speed and correctness of the computer, a great development in the application of mathematical theories into the technical world has been achieved. Representing the complex ship hull form with the B-spline surface and the numerical optimization techniques are two important aspects among them that give a lot of improvement on ship design. B-spline curve and surface have been used to define a ship hull form extensively because of their useful characteristics, such as local support, convex hull, variation-diminishing properties and easy incorporation of slope discontinuities. Numerical optimization techniques have been well investigated for application to the real technical world. A number of algorithms, as well as computer programs, have been developed for both the unconstrained and the constrained problem. Using the optimization technique gives users the best solution they can get while satisfying all the constraints within the design space. There is a hope that the ship designer can break the traditional "Ship Design Spiral" and get the "best" design on the computer.

To develop a computer tool that will give the best ship design using an optimization technique is one of the objects of the FIRST project funded by MARITECH. The task is assigned to the Department of Aerospace and Ocean Engineering at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. Choosing a containership design as a test case, the Design Optimization Tools (DOT) package from Vanderplaats Research and Development, Inc. is used as the optimization tool. The problem is tackled from the ship owner's point of view. The required freight rate is chosen as the objective function because the most important thing that concerns the ship owner is whether the ship will make a profit or not, and if so, how much profit it can make.

DOT, as well as any other numerical optimization tool, only gives an approximation of the optimum design and uses numerical approximation during the optimization. For example, it uses the finite difference method to calculate the gradient of the objective function and the constraints. It is very important for the users to formulate carefully the optimization problem so that it will give a stable and reasonable solution. Development of a geometric module and choosing suitable empirical formulas for performance evaluation are also major issues of the project.

Chapter 2 Literature Review

2.1 Introduction

To get a clear view of the recent technical developments relative to the ongoing project, science literature has been searched. The search is mainly directed to the aspects as follows:

- B-spline curve and surface used to define ship hull form
- Development of ship CAD system and container ship design
- Optimization technique used on ship design

2.2 B-spline Curve and Surface Used to Define Ship Hull Form

2.2.1 Bardis and Vafiadou [1]

Bardis and Vafiadou used a series of B-spline surface patches to approximate the hull surface. The task was to approximate a given hull form using B-spline surface patches. Although a single B-spline patch is suitable for initial design based on form parameters, it may give poor representation to a hull surface that is described through discrete points. Therefore, multiple B-spline surface patches were used in their task. The method involved three steps. First, lines along the length direction, such as waterlines, were approximated by B-spline curves. Then, transverse sections and the first parametric derivative in the length direction were approximated by B-spline curves. Finally, B-spline surface patches were constructed between each pair of transverse sections. The program was applied to represent the hull surface of a passenger ship successfully.

2.2.2 Huang et al [2]

Huang et al used the B-spline surface and the Levenberg-Marquardt algorithm to determine the bow surface according to the given pressure distribution. It was referred to as "the inverse geometry design problem" in contrast to the direct problem that involves calculation of the pressure distribution for a given surface. The bow surface was described by a B-spline surface. The inverse problem was solved by minimizing the sum of difference between desired pressure distribution and estimated pressure distribution at each control point. The program applied quite well to two different parent hull forms, a series-60 ship and a container ship.

2.2.3 Knowledge Learned

These two works, among many other works done, show that the B-spline surface is a good expression for a ship hull form. Some characteristics of the B-spline curve and surface, such as local support, convex hull, variation-diminishing properties and easy incorporation of slope discontinuities, enable it to well represent various kinds of complicated hull form. The ship hull form can be represented by as many as B-spline surface patches as necessary. We can approximate a ship hull form using B-spline surface through discrete data points, and also can construct a B-spline surface that gives us expected form parameters. In the MDO project, the hull form will be changed from iteration to iteration. Using B-spline surface definition of the "parent ship," it is very convenient to deform the "parent ship" to a desired ship form through moving the control point. Also, NURB (Non-Uniform Rational B-Spline) surface, which is more flexible in representing hull form than general B-spline surface, is used as the basis of the geometric module in the project.

2.3 Development of Ship CAD System and Container Ship Design

2.3.1 Development of Ship CAD System

There are several large integrated systems available for ship designers and ship builders, such as FORAN and TRIBON in Europe. In the United States, Proteus Engineering introduced FLAGSHIP, an integrated ship design package [3]. It includes FastShip hull design system and MAESTRO structural modeling analysis software. For performance calculation, it has GHS for stability, NavCAD for resistance and powering, and ESTIMATE for ship construction prices and contract quotation. It also offers a number of complementary software suites described as Flagship's "Backplane". These are used to provide additional ship design (such as finite element analysis), manufacturing and production management capabilities.

Taking Flagship as an example, we can see that the integrated ship design system not only provides ship designers computer software to calculate ship performance, but also provides ship builders the manufacturing and management information. It integrates different modules to deal with different disciplines, such as hydrostatics, hydrodynamics, structure and economics. It also should be noticed that although optimization is getting increasing attention today, it is not a part of the integrated system.

2.3.2 Container Ship Design

Since the project uses container ship design as the test case, information about several recent container ship designs has been collected. Main parameters of four container ships designed by European countries are listed in Table 2-1. There are reports that a 8000 TEU container ship is under consideration [8].

From these recent container ship designs, we can see that:

- There is not as much variation in the parameter ratios as there is in the parameter’s.
- The speed increases as the length increases. The speed range of container ship, in terms of Froude Number, is surely faster than that of other commercial ships, such as bulk carriers and tankers.
- There are more containers on the deck than in the hold.
- Containerships are going to be bigger and bigger. Since a container ship is a kind of commercial ship, we can say that from an economic point of view, the bigger the ship, the better it is.

Table 2-1 Recent Container Ship Design

Container Ship		Europe Feeder [4]	Sea Baltica [5]	CV2900 [6]	Post-Panamax [7]
Year		1993	1997	1996	1993
L_{oa} (m)		121.00	143.00	209.58	296.50
L_{bp} (m)		113.30	135.00	197.10	283.00
Breadth (m)		18.60	23.28	32.20	37.20
Depth (m)		9.20	11.70	19.40	21.70
Draught (m)		6.60	8.78	11.00	11.20
L_{bp} / B		6.09	5.80	6.12	7.61
B / D		2.20	1.99	1.66	1.71
T / D		0.72	0.75	0.57	0.52
L_{bp} / D		12.32	11.54	10.16	13.04
Deadweight (t)		6124	13300	30454	47000
TEU	In Holds	180		1218	2264
	On Deck	314		1672	2538
	Total	494	1050	2890	4802
Speed (kn)		16.8	19.0	22.5	24.5
F_n		0.2593	0.2687	0.2633	0.2393

2.4 Optimization Techniques Used on Ship Design

2.4.1 Ray et al [9]

Ray et al tackled the optimization problem of ship design as a multi-criterion constrained multivariable nonlinear optimization process and aimed at a global optimum solution of the problem. The model included three parts: a global optimization tool (simulated annealing), a decision system handler based on the analytic hierarchy process, and several naval architectural calculation methods. A containership design was chosen as an example. A unique characteristic of this model is that a unit approach was used to get the design variables. In the unit approach, each unit was an independent equation that had several inputs and outputs. The outputs of one unit could be used as an input to the subsequent units. The optimum inputs required for all the units were the necessary design variables by a proper ordering of these units. Such a unit approach had identified L, B, T, D, C_b, C_m and C_w as the design variables. The side constraints contained those on variables and on variable ratios (including L/B, L/D, L/T, B/D, B/T and T/D). The system constraints were classified into three groups. The first group is the constraints specified by the owner (speed, number of containers to be carried, and range). The second one is the performance requirements (weight should balance the buoyancy, stability requirements and freeboard requirements). The last group of constraints involved the design relations specified by the designer (relation between C_b and C_w, C_b and C_p, C_p and C_w). The objectives were to minimize building cost, power required and/or steel weight. The objectives were modeled as fuzzy membership functions to overcome the incommensurable units. The fuzzy membership functions were multiplied by their respective weight factors as calculated by multi-attribute decision making (MADM) techniques. The results showed that the use of a nonlinear multi-variable constrained optimization tool could only provide a local optimum. Solutions from the process of simulated annealing successfully identified the main cluster that was very close to the reported global optimum predicted by pure random methods and genetic algorithms.

2.4.2 Sen [10]

Sen demonstrated that a multiple criteria decision making (MCDM) approach is useful in modeling design synthesis and design selection situations. Ship design involves multi-criteria and both "hard" and "soft" constraints. Classical optimization methods can only deal with a single criterion and "hard" constraints. MCDM problems are classified to MODM (multiple objective decision making) problem and MADM (multiple attribute decision making) problem. There are generally three basic approaches to the solution of MCDM problem: weighting methods, prioritizing methods and efficient solution methods. Goal programming formulation combines all these three methods. It uses deviational variables, but does not guarantee to achieve all goals. Using deviational variables, all objective functions and constraints can be written in the same form. In the general sense, the solution from goal programming will not represent an "optimum", but a "compromise" solution. The objective functions should be normalized for numerical stability. The preliminary design of a ro-ro vessel was presented as an example to illustrate the goal programming method. Sequential linear programming, sequential quadratic programming and Powell's direct search method were used as the basic nonlinear optimization modules. Eleven design variables were chosen. The constraints either set limits on the permissible dimensional ratios, or reflected the requirements of freeboard, permissible C_b values, limiting KG values and other technical requirements. The goal constraints were obtaining required ship capacity, minimizing required freight rate, attaining displacement balance and minimizing the weight of water ballast. The problem was solved by using the generalized goal programming method including several linear and nonlinear MCDM models. Goal programming method can be used to deal with both MODM and MADM problems. There are also several methods that specifically handle MADM problems, such as multi-attribute utility theory (MAUT), fuzzy sets and Analytic Hierarchy Process (AHP).

2.4.3 Keane et al [11]

Keane et al described an integrated computational approach to ship concept design using optimization techniques. The method incorporated accepted naval architectural tools, a sophisticated data base handler and several optimization procedures. The system consisted of a design control module, an optimizer, some design theory modules, a data base handler and some auxiliary routines. However, some fundamental design aspects were not represented, such as cost, sea keeping, structures, etc., due to lack of published data.

The design control module (CONSST) formed the heart of the system, which controlled the order and choice of the design theory modules and auxiliary routines. It could be used in one of two modes: manual mode and automated mode with optimization. Using the automated mode for the whole process was not practicable for a number of reasons. First, it was time consuming. Second, it was difficult to verify that the optimum found by the optimizer was the true global optimum. Finally, not all of the optimization methods were suitable for the ship concept design. Therefore, a more sophisticated strategy was required. First, select an objective function and as many constraints as can be found on a realistic ship. A set of design variables was then chosen. The list of design variables was next reduced to two since it was desirable to produce a 3-D contour mapping of the function. Then, optimize for just these two variables. The results from different optimization strategies were fully studied. Finally, proceed to the N-dimensional problem.

Failures during optimization could arise when very wide limit settings were given for the trial vector that allowed the optimizer to reach unpredicted singularities. These were usually caused by the optimizer selecting inconsistent hull-form parameters. Therefore, monitoring and interaction were very important during this combined manual and automatic design process. Usually, interleaved sequences of interacting and optimization were found most appropriate when developing a design. A number of different optimization strategies were available within the system. The suite contained seven main methods of unconstrained nonlinear optimization with four-associated penalty functions, together with two constrained nonlinear methods.

The design theory modules formed a basic set of naval architectural routines. They comprised hull-form creation and drawing, hydrostatics generation, enclosed volume estimation, condition displacement and CG estimation, resistance calculation using Holtrop and Mennen's power prediction method and stability evaluation. The hull-form creation routine defined a simple hull form from a set of nineteen parameters. Default parameters were available for three types of ships, i.e., passenger ships, bulk carriers, and frigates. The method had limitations when dealing with certain types of ships, i.e., chined ones and some extreme forms, but most ship types could be handled. It was ideal for the concept design phase where great precision in representing minor form details was not warranted. The choice of Holtrop and Mennen's method was because it is acceptably accurate for concept design purposes and covers a wide range of types and sizes of ships.

As an example, a frigate was designed manually as a starting point for optimization, with the goal set as minimum resistance at design speed within the usual constraints. In two variables optimization, most methods gave a successful optimum point while random exploration technique failed to reach the true optimum due to the shrinkage mechanism. When moved on to the full problem involving five parameters, only successive linear approximation failed to cope with geometrically impossible ships. Other various optimization processes led to approximately the same optimum design. The process tended to produce a longer and more slender ship. The most rapid optimization was achieved by the Hooke and Jeeves direct search with a one-pass external penalty function. It revealed that the use of optimizers without some care could give rise to problems.

2.4.4 Knowledge Learned

These works show us the recent development on ship design optimization. We can learn several things from their works, and these optimization principles are well incorporated in our MDO project:

1. The optimization problem should be carefully formulated with different optimization tools used.
2. The objective function usually includes minimizing building cost, required freight rate and resistance. It should be normalized to achieve stable results.
3. Design variable should be chosen carefully. A unit approach can be used to identify design variables for a big optimization problem such as ship design.
4. The constraints include that displacement should be equal to weight, minimum container numbers, minimum stability requirement and freeboard requirement. Side constraints on parameter ratios should be considered. Side constraints on form coefficient should also be considered if we do not have a surface description for the hull form.
5. Holtrop and Mennen's method is a commonly used method to predict resistance.

Chapter 3 Overview of Project

3.1 Introduction

3.1.1 Background

This MDO project is a part of an integrated system called FIRST (A First Principles Approach for Shipbuilding Integrated Process and Product Development) sponsored by DARPA/Maritech Research Program. Intergraph Corporation, Proteus Engineering, Spar Associates, Inc., Virginia Tech, Newport News Shipbuilding and American Bureau of Shipping take part to develop the system.

The MDO project is developed by a team composed of the professors and graduate students in the Department of Aerospace and Ocean Engineering of Virginia Polytechnic Institute and State University at Blacksburg, Virginia. Table 3-1 gives the organization of the MDO project at Virginia Tech. The goal of the project is to develop a software package to optimize the performance of a ship. A containership design is chosen as the test case. The objective function for optimization is the required freight rate of the containership.

Table 3-1 Organization of MDO Project

Person	Title	Duty
Dr. Wayne Neu	Associate Professor	Project Manager, Principle Investigator
Dr. Owen Hughes	Professor	Principle Investigator
Dr. Bernard Grossman	Professor Department Head	Advisor
Dr. William Mason	Professor	Advisor
Dr. Shaoyu Ni	Visiting Scholar	Supervisor Software organization
Mr. Sivaramakrishna Tumma	Graduate Student (Ph.D.)	Formulating weight and stability calculation module
Mr. Zhiyi Lin	Graduate Student (M.S.)	Geometry operation
Mr. Vikram Ganesan	Graduate Student (M.S.)	Formulating container number and weight calculation
Mr. Ying Chen	Graduate Student (M.S.)	Problem organization

3.1.2 Component Module

The package includes three modules: an optimization module, a geometric module and a performance evaluation module. The function of the optimization module is to give the minimum value of the objective function subject to constraints. The designed containership is subjected to some constraints so that it satisfies several regulations while giving a reasonable performance both technically and economically. The geometric module gives a smooth ship hull form based on a NURBS surface expression. It also calculates the hydrostatic performance of the ship. The performance evaluation module calculates the technical and economical performance of the designed containership. The technical performance includes resistance, stability, container capacity and ship weight. The economical performance includes the building cost, operation cost, and the required freight rate of the ship.

Figure 3-1 gives the flow chart of the MDO project.

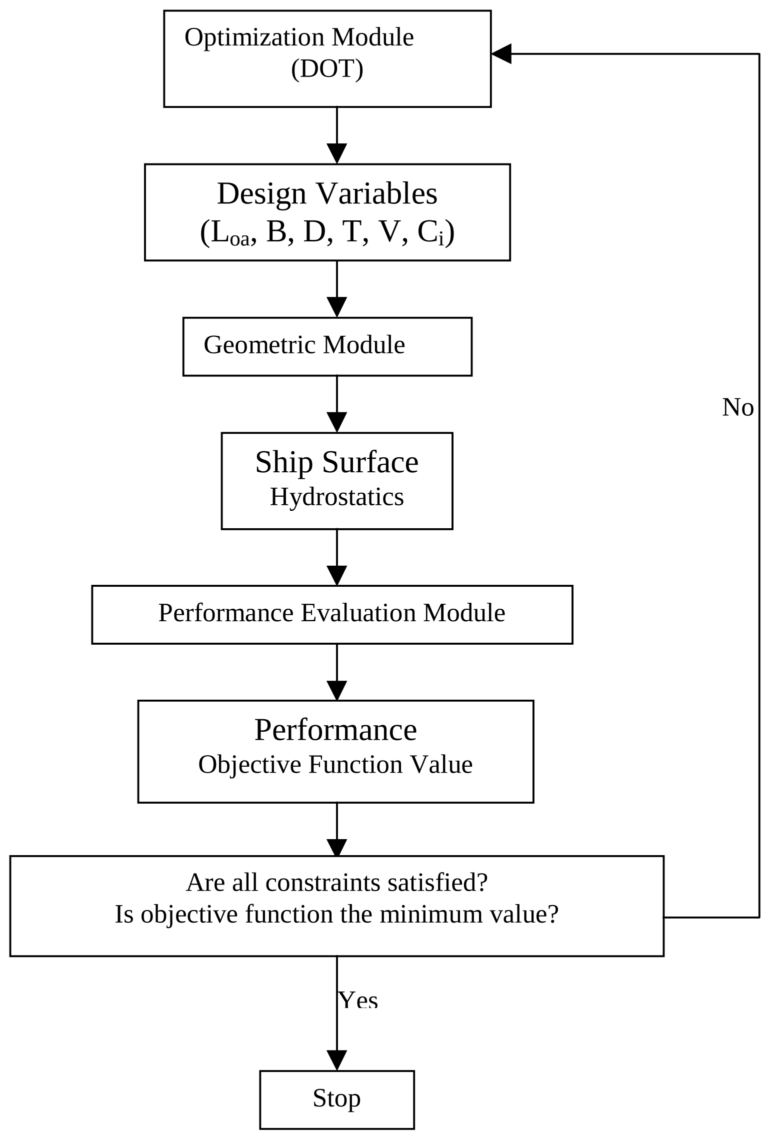


Figure 3-1 Flow Chart of the MDO Project

3.2 Optimization Module

3.2.1 Overview of Optimization Problem

3.2.1.1 General Formulation of Optimization Problem

In an optimization problem, the value of a certain objective function is maximized or minimized while satisfying the constraints. The optimization problem is formally stated as follows:

Minimize or maximize:

$\mathbf{F(X)}$		Objective Function

Subject to:

$\mathbf{g_j(X) \le 0}$	j = 1, NCON	Inequality Constraints
$\mathbf{X_i^L \le X_i \le X_i^U}$	i = 1, NDV	Side Constraints

Where X is the vector of design variables, NCON is the number of constraints, NDV is the number of design variables, X_i^L and X_i^U are the lower and upper bounds on the design variables.

3.2.1.2 Algorithm for Optimization Problem

To solve an optimization problem, it is usually started with an initial design point, $\mathbf{X^0}$. Then, the next design point is determined by:

$$\mathbf{X}^{i+1} = \mathbf{X}^{i} + \lambda\, \mathbf{S}^{i}$$

Where *i* is the iteration number, λ is the step length and **S** is the searching direction.

During iteration, the step length λ and the searching direction **S** should be determined to give the new design variable for the next iteration. The searching direction determines the direction of the next design point and the step length λ determines how far it should be taken along this direction. The searching direction **S** should be both usable and feasible. It should be usable so that the value of objective function will be decreased (or increased) along this direction. It should feasible so that the constraints will not be violated. The searching direction

S is usually determined by the gradient of the objective function and the gradient of the constraints. Having determined the searching direction **S**, the step length λ will be determined using a one-dimension search technique. This procedure is repeated until the optimum design point is reached, i.e., no searching direction can be found to improve the objective function while still satisfying the constraints.

3.2.2 Optimization Tool

DOT (Design Optimization Tools), developed by Vanderplaats Research & Development, Inc., has been chosen as the optimization tool. It uses numerical search methods to seek the searching direction and step length so that the minimum value of objective function is reached. The source code of DOT is written in FORTRAN. DOT contains several different mature optimization methods to deal with unconstrained and constrained optimization problems. Table 3-2 gives a brief description of these methods, after the DOT User's Manual [12].

Table 3-2 Methods Used by DOT

Method	Description
	Unconstrained Minimization
0, 1*	Broydon-Fletcher-Goldfarb-Shanno (BFGS) variable metric method
2	Fletcher-Reeves (F.R.) conjugate gradient method
	Constrained Minimization
0, 1*	Modified Method of Feasible Directions (MMFD)
2	Sequential Linear Programming (SLP)
3	Sequential Quadratic Programming (SQP)

* Default Method in DOT

3.3 Geometric Module

The goal for the geometric module is to give a smooth ship hull form and calculate its hydrostatic performance. FastShip, from Proteus Engineering, and NURBS (Non-Uniform Rational B-Spline) surface are the basis for the geometric module. During the project, the construction of the geometric module has involved three phases: FastGen macro, Containership Wizard and Geometric Blending Technique.

3.3.1 FastGen Macro

At first, a FastGen macro from FastShip was used to give the geometry of the ship form. FastGen uses a series of parametric "handles" to control the hull shape. Using the FastGen macro, a "parent hull", which is an existing NURBS surface model, can be deformed to a new ship hull according to a set of input parameters. These parameters include length, breadth, draft, mid-ship section coefficient, prismatic coefficient, block coefficient, longitudinal center of buoyancy and the length of parallel mid-body. That is, the input of the FastGen macro is the ship parameters while the output is a ship hull form that satisfies these parameters. The required parameters of the ship will be given by the optimization tool. Unfortunately, several disadvantages of the FastGen macro were found to prevent it from being used in the project. One disadvantage of FastGen is that it can not be implemented with DOT. We can not run DOT within the FastGen environment. The FastGen macro, like all the other FastShip macro, is written in Perl (Practical Extraction and Report Language). The version of Perl used in the FastGen macro is an old version that can not call C routine or Fortran routine. DOT, the optimization tool used in the MDO project, is written in Fortran. Therefore, the geometry of the ship hull can only be viewed after the optimization. The danger of that is the hull form may go crazy during the optimization. Another problem is that the FastGen macro does not have a function to change the water plane coefficient of the ship. This enforces an additional constraint of keeping the water plane coefficient as a constant, which decreases the freedom of the optimization. Using FastGen macro to give the NURBS surface of the ship is an iterative process. It can not give a unique solution. In addition, it takes a lot of computer time to get a required hull form using the FastGen macro.

3.3.2 Containership Wizard

Having found that the FastGen macro is unusable in the project, a new function called Containership Wizard was provided by Proteus Engineering. It is also a parametric tool deforming the "parent hull". The input of the Containership Wizard is the length, breadth, depth, length of parallel mid-body, length of flat of side, etc., of the container ship. The output is a ship hull form expressed as a NURBS surface. The version of Perl used in the Containership Wizard, named Perl5, is improved from that used in the FastGen macro. Although we still can not directly call Fortran routine from Perl5, now we can call C routine from Perl 5. A new wrapper called PCFDOT is developed for this transfer purpose. The PCFDOT enables us to call C routine from Perl5 routine then call Fortran routine from C routine, and vise versa. In this way, we now can run DOT within the Containership Wizard. Figure 3-2 shows the function of PCFDOT.

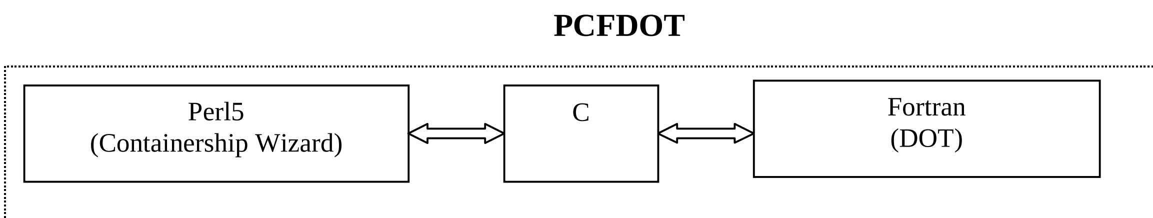


Figure 3-2 Function of PCFDOT

Using the Containership Wizard along with DOT, the ship hull form can be examined on the screen during optimization. There are also some flaws in the Containership Wizard. Among those, the original Containership Wizard macro does not include draft as an input parameter. Therefore, the hydrostatics can not be calculated using the original Containership Wizard. This problem is fixed by the team members. There is only one "parent ship" provided with the Containership Wizard, which greatly limits the freedom of the optimization. Another problem is that a new version of FastShip is needed using Perl5, and not all of the necessary functions included in the old version of FastShip are enabled in this new version of FastShip.

3.3.3 Geometric Blending Method

Both the FastGen macro and Containership Wizard are functions within the FastShip software. They can not be used without FastShip. During the development of FIRST, Proteus Engineering, developer of FastShip, decided not to support the Perl5 version of FastShip. Under this situation, it is better to develop a new geometric module that runs outside of FastShip. The geometric blending technique is considered in the new module. The new geometry module using blending technique is the one currently used in the MDO project.

The basic idea of the geometric blending technique is that the design ship hull form is derived by blending the net points of several basis hull forms. The basis hull forms are different from each other. The resulting hull form is determined by the blending factors and the diversity of basis hull forms.

If we use two different basis hulls, the expression of the result ship hull is as follows:

$$C_1 \text{BasisHull}_1 + C_2 \text{BasisHull}_2 = \text{Resultant Ship Hull} \tag{1}$$

$$C_1 + C_2 = 1 \tag{2}$$

$$0 \le C_1 \le 1 \tag{3}$$

$$0 \le C_2 \le 1 \tag{4}$$

Where C_1 and C_2 are the blending factors of the basis hull.

The blending equation (1) is applied to the mesh points of the basis hull defined as a NURBS surface. It is a linear function. The hydrostatics of the result ship hull may or may not be linear to the hydrostatics of the basis hulls. The hydrostatics of the result ship hull is calculated directly from the result surface. The constraints of (2), (3) and (4) guarantee the result ship hull is within the limit set by the basis hulls. Figure 3-3 illustrates the geometric blending technique for the mid-section of two basis ships.

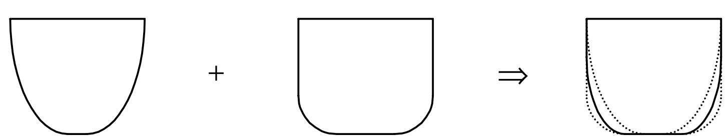


Figure 3-3 Illustration of Geometric Blending Technique

In general, the geometric blending technique used in MDO project can be expressed as follows with multiple basis hulls:

$$\Sigma C_i BasisHull_i = \text{Resultant Ship Hull}$$

$$\Sigma C_i = 1$$

$$0 \le C_i \le 1$$

$$i = 1, 2, \ldots NBH$$

Where NBH is the number of basis hulls

There are two ways to treat the blending factor C_i in the optimization. One is using all the C_is as the design variables. In this case, the equality constraint upon the C_is should be applied in the optimization to ensure that the sum of all blending factors is one. The other way, which is used in the MDO project, is to use (NBH-1) blending factors as the design variables. The value of the last blending factor C_{NBH} is determined by the fact that the sum of all blending factors should be equal to one. Using this formulation, not only is the number of design variables, along with the side bounds on the design variable, decreased by one, the equality constraint for the blending factors is also diminished from the optimization.

3.4 Performance Evaluation Module

The goal for the performance evaluation module is to calculate the technical and economical performance of the ship. Several well-accepted formulas have been used in this module. Holtrop and Mennen’s method is used for the resistance estimate. A new method for estimating the number of containers carried by the ship is developed by the team members. The wind heel criteria from the US Coast Guard is used for an initial stability check. Some empirical formulae are used for weight and cost calculation.

3.4.1 Resistance Calculation

Holtrop and Mennen’s method [15] is used to predict the resistance of the ship. The total resistance of a ship is divided into components as follows:

$$R_{total} = R_F (1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

Where:

R_{total} = total resistance of a ship

R_F = frictional resistance according to the ITTC-1957 friction formula

$1+k_1$ = form factor describing the viscous resistance of the hull form in relation to R_F

R_{APP} = resistance of appendages

R_W = wave-making and wave-breaking resistance

R_B = additional pressure resistance of bulbous bow nears the water surface

R_{TR} = additional pressure resistance of immersed transom stern

R_A = model-ship correlation resistance

3.4.1.1 Frictional Resistance and Form Factor

The frictional resistance is calculated as follows:

$$R_F = 0.5\,\rho\,V^2\,C_F\,S$$

In which ρ is the mass density of the water, V the speed, C_F the coefficient of frictional resistance, S the projected wetted surface.

The coefficient of frictional resistance is determined using the ITTC-1957 formula:

$$C_F = 0.075 / (\log R_n - 2)^2$$

With the Reynolds number, R_n based on the waterline length L.

The projected wetted surface of the bare hull can be provided from the hydrostatics of the ship or calculated using the following statistical formula provided by Holtrop and Mennen:

$$S = L(2T + B)\sqrt{C_m}\,(0.453 + 0.4425C_b - 0.2862\,C_m - 0.003467\,B/T + 0.3696\,C_w)$$
$$+ 2.38\frac{A_{BT}}{C_b}$$

In this formula C_m is the Midship-section coefficient, T the average molded draft, B the breadth, C_b the block coefficient, C_w the water plane coefficient and A_{BT} the transverse sectional area of the bulb at the position where the still-water surface intersects the stem.

The formula for the form factor of the hull is:

$$1+k_1 = 0.93 + 0.487118\, c_{14}\, (B/L)^{1.06806}\, (T/L)^{0.46106}\, (L/L_R)^{0.121563}\, (L^3/\nabla)^{0.36486}\, (1 - C_p)^{-0.60247}$$

In this formula ∇ is the molded displacement volume, C_p the prismatic coefficient based on the waterline length.

L_R is a parameter reflecting the length of the run. It can be estimated using the following formula:

$$L_R = L\, [1 - C_p + 0.06\, C_p\, L_{cb} / (4\, C_p - 1)]$$

Where L_{cb} is the longitudinal position of the center of buoyancy forward of 0.5L as a percentage of L.

The coefficient c_{14} accounts for the stern shape and depends on the stern shape coefficient C_{stern}.

$$c_{14} = 1 + 0.011\, C_{stern}$$

In MDO project, the value of C_{stern} is taken as zero for normal stern.

3.4.1.2 Appendage Resistance

The appendage resistance is ignored in MDO project.

3.4.1.3 Wave Resistance

The following wave resistance formula is used for the speed range of Froude number $F_n > 0.55$:

$$R_{w-B} = \nabla\, \rho\, g\, c_{17}\, c_2\, c_5\, \exp\, [\, m_3\, F_n^{\,d} + m_4 \cos\, (\lambda_R\, F_n^{-2})\,]$$

Where:

$c_{17} = 691.3\, C_m^{-1.3346}\, (\nabla/L^3)^{2.00977}\, (L/B - 2)^{1.40692}$

$c_2 = \exp\, (-1.89 \sqrt{c_3})$

$c_3 = 0.56\, A_{BT}^{1.5} / [\, B\, T\, (0.31 \sqrt{A_{BT}} + T_F - h_B)\,]$

$c_5 = 1 - 0.8\, A_T / (B\, T\, C_m)$

$m_3 = -7.2035\, (B/L)^{0.326869}\, (T/B)^{0.605375}$

$d = -0.9$

$m_4 = c_{15}\ 0.4 \exp(-0.034\ F_n^{-3.29})$

$c_{15} = -1.69385$	when $L^3/\nabla < 512$
$c_{15} = -1.69385 + (L/\nabla^{1/3} - 8) / 2.36$	when $512 < L^3/\nabla < 1726.91$
$c_{15} = 0$	when $L^3/\nabla > 1726.91$

$\lambda_R = 1.446\ C_p - 0.03\ L / B$	when $L / B < 12$
$\lambda_R = 1.446\ C_p - 0.036$	when $L / B > 12$

In this formula A_T is the transverse immersed transom area at rest, T_F the forward draft of the ship, h_B the vertical position of the center of $A_{BT.}$ The value of h_B should not exceed the upper limit of 0.6 T_F.

The following formula for wave resistance is used for the speed range of $F_n < 0.4$

$$R_{w\text{-}A} = \nabla\ \rho\ g\ c_1\ c_2\ c_5 \exp[m_1\ F_n^{d} + m_4 \cos(\lambda_R\ F_n^{-2})]$$

Where:

$c_1 = 2223105\ c_7^{3.78613}\ (T/B)^{1.07961}\ (90 - i_E)^{-1.37565}$

$c_7 = 0.229577\ (B/L)^{0.33333}$	when $B / L < 0.11$
$c_7 = B/L$	when $0.11 < B / L < 0.25$
$c_7 = 0.5 - 0.0625\ (L/B)$	when $B / L > 0.25$

$i_E = 1 + 89 \exp[-(L/B)^{0.80856}\ (1-C_w)^{0.30484}\ (1-C_p-0.0225Lcb)^{0.6367}\ (L_R/B)^{0.34574}$
$(100\ \nabla / L^3)^{0.16302}]$

$m_1 = 0.0140407\ L/T - 1.75254\ \nabla^{1/3}/L - 4.79323\ B/L - c_{16}$

$c_{16} = 8.07981\ C_p - 13.8673\ C_p^2 + 6.984388\ C_p^3$	when $C_p < 0.8$
$c_{16} = 1.73014 - 0.7067\ C_p$	when $C_p > 0.8$

For the speed range $0.40 < F_n < 0.55$, the following interpolation formula is used:

$$R_w = R_{W\text{-}A0.4} + (10\ F_n - 4)\ (R_{W\text{-}B0.55} - R_{W\text{-}A0.4}) / 1.5$$

Here $R_{W\text{-}A0.4}$ is the wave resistance prediction for $F_n = 0.40$ and $R_{W\text{-}B0.55}$ is the wave resistance for $F_n = 0.55$ according to the respective formulae.

3.4.1.4 Resistance of a Bulbous Bow

The additional resistance due to the presence of a bulbous bow near the surface is determined from the following formula:

$$R_B = 0.11 \exp(-3\ P_B^{-2})\ F_{ni}^3\ A_{BT}^{1.5}\ \rho\ g / (1 + F_{ni}^2)$$

Where the coefficient P_B is a measure for the emergence of the bow and F_{ni} is the Froude number based on the immersion:

$$P_B = 0.56\ A_{BT}^{0.5} / (T_F - 1.5\ h_B)$$

And

$$F_{ni} = V / [g\ (T_F - h_B - 0.25\ A_{BT}^{0.5}) + 0.15\ V^2]^{0.5}$$

3.4.1.5 Resistance of the Immersed Transom

The additional pressure resistance due to the immersed transom is determined from the following formula:

$$R_{TR} = 0.5\ \rho\ V^2\ A_T\ c_6$$

The coefficient c_6 is related to the Froude number based on the transom immersion:

$c_6 = 0.2\ (1 - 0.2\ F_{nT})$ when $F_{nT} < 5$

$c_6 = 0$ when $F_{nT} \geq 5$

F_{nT} is defined as:

$$F_{nT} = V / [2\ g\ A_T / (B + B\ C_w)]^{0.5}$$

3.4.1.6 Model-Ship Correlation Resistance

The model-ship correlation resistance R_A is determined from the following formula:

$R_A = 0.5\ \rho\ V^2\ S\ C_A$

The following formula for the correlation allowance coefficient C_A is used:

$$C_A = 0.006\ (L + 100)^{-0.16} - 0.00205 + 0.003\ (L/7.5)^{0.5}\ C_b^4\ c_2\ (0.04 - c_4)$$

$$c_4 = T_F / L \qquad \text{when } T_F / L \le 0.04$$
$$c_4 = 0.04 \qquad \text{when } T_F / L > 0.04$$

3.4.1.7 Effective Horsepower and Shaft Horsepower

The effective horsepower of the ship, EHP, is determined by:

$$EHP = \frac{R_{total} V}{746.0}$$

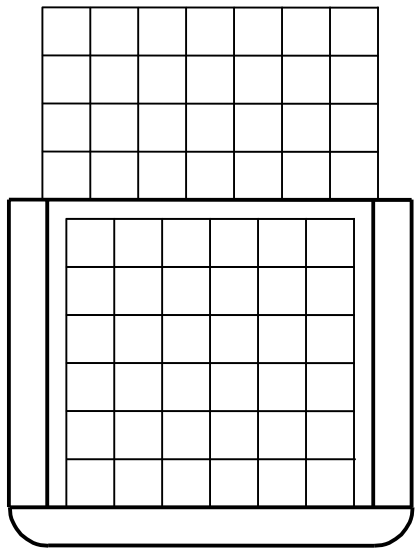
Where EHP is in horsepower, R_{total} in N, and V in m/sec.

We do not choose a propeller for the ship but rather simply assume a propulsive efficiency of 0.65. The required shaft power, SHP, is then to be:

$$SHP = \frac{EHP}{0.65}$$

3.4.2 Container Number Calculation

Although there are several approximation equations available for container number estimate, they are either out-dated or without the corresponding value of the gravity center of the containers. Therefore, a new method for estimating the container number carried by the ship is developed.



a. Section View

b. Profile View

Figure 3-4 Container Number Calculation

The total container number carried by a ship can be expressed as follows:

$$TEU = TEU_b + TEU_d$$

$$TEU_b = S_b \times L_b \times B_b \times D_b$$

$$TEU_d = S_d \times L_d \times B_d \times TN_d$$

Where TEU is the total number of containers (Twenty-foot Equivalent Unit), TEU_b is the container number below deck and TEU_d is the container number above deck. L_b is the container number below deck along the length direction, B_b is the container number below deck along the beam direction and D_b is the container number below deck along the depth direction. L_d is the container number above deck along the length direction and B_d is the container number above deck along the beam direction. All the values of L_b, B_b, D_b, L_d and B_d are integer numbers. In Figure 3-4, L_b is six, B_b is six, D_b is six, L_d is six and B_d is seven. S_b and S_d are the stowage factors for containers below deck and above deck respectively. TN_d is the tier number for container above deck. It is not necessarily an integer number.

From Figure 3-4, we can see that the container numbers along the three dimension of the ship below and above deck can be expressed as:

$$L_b = L_d = \mathrm{int}(\frac{L_{con}}{L_0})$$

$$B_b = \mathrm{int}(\frac{B - 2 \times WB}{B_0})$$

$$D_b = \mathrm{int}(\frac{D - DBH}{D_0})$$

$$B_d = \mathrm{int}(\frac{B}{B_0})$$

Where L_{con} is the effective length for carrying containers, WB the breadth of the wing tank, D the depth of the ship, DBH the double bottom height and L_0, B_0, D_0 are the length, breadth and depth of container, respectively. L_{con} is assumed a fraction of the overall length of the ship, L_{oa}.

The tier number of container above deck TN_d can be determined by the designer or using the following approximation where B is in meter:

$TN_d = 4$ when $B < 32.2$ m

$$TN_d = 4 + \frac{B - 32.2}{7.8} \quad \text{when } 32.2 \text{ m} \le B \le 40 \text{ m}$$

$$TN_d = 5 + \frac{B - 40}{3} \quad \text{when } 40 \text{ m} \le B \le 43 \text{ m}$$

$TN_d = 6$ when $B > 43$ m

The above approximation formulae will not be suitable for ships with small beams. In that case, the designer can specify an appropriate value for TN_d. As we will see in the results of the optimization, the result ship always tends to hit the upper bounds of the breadth. Therefore, the above approximation formulae is used in the MDO project for the tier number of container above deck.

The stowage factors S_b and S_d are determined from the data of twelve existing container ships. The following expressions for S_b and S_d are used:

$$S_b = 0.8479 \times C_b - 0.0918$$

$$S_d = 0.7534$$

Because the container numbers along the three dimensions of the ship should be integer, the container number that could be carried by the ship is a step-like function with respect to the dimension of the ship. Figure 3-5 illustrates this effect.

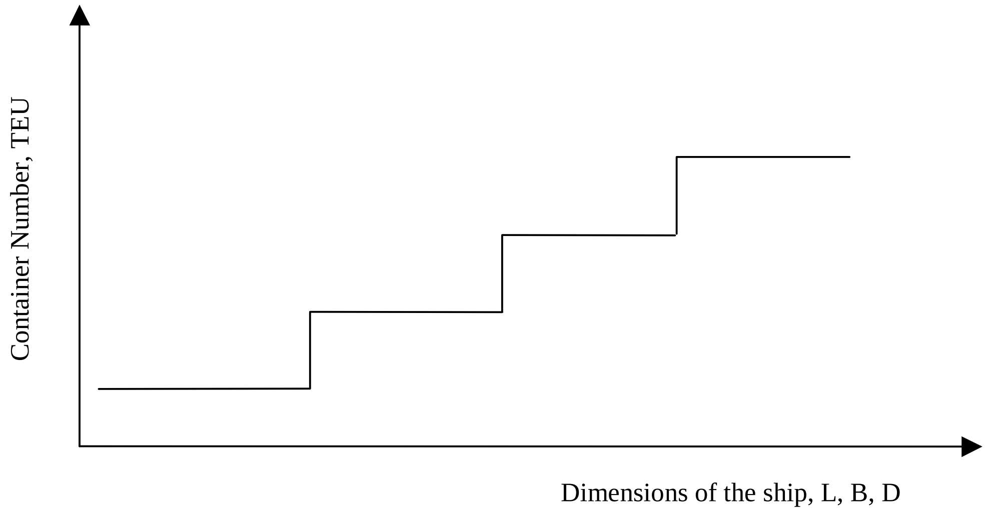


Figure 3-5 Container Number as a Function of Dimensions of the Ship

The step-like behavior of the container number function has a big influence on the optimization, since it prevents the optimizer to calculate the gradients of the objective and the constraints functions. Therefore, it can lead the optimizer to the local minimum points. To overcome this difficulty, the least square fitting method is used to give a smooth function of the container number that could be carried by a specified ship. The values of WB and DBH are assumed to be 1.83 meters. The smooth functions derived using least square fitting method are as follows:

$$TEU_{b\_float} = S_b \times (0.0196 \times L_{oa} \times B \times D - 148.6129)$$
$$TEU_{d\_float} = 0.050117 \times L_{oa} \times B \times TN_d - 82.6702$$

Where L_{oa} is the overall length of the ship. The units for L_{oa}, B and D in the above equation are meters.

These floating numbers of container will be used during the optimization. The actual number of container that could be carried by the ship is the integer number. The difference between the floating and integer numbers of container is usually less than one percent.

The gravity center of the containers below deck is determined from the following formula:

$$KG_b = DBH + C_{kgb} \times D_b \times D_0$$

Where C_{kgb} is the form factor of gravity center of containers below deck.

$C_{kgb} = 1/2$ when $C_b = 1.0$, corresponding to a rectangular section

$C_{kgb} = 2/3$ when $C_b = 0.5$, corresponding to a triangular section

When $0.5 < C_b < 1.0$, the value of C_{kgb} is linearly interpolated between the value of 1/2 and 2/3.

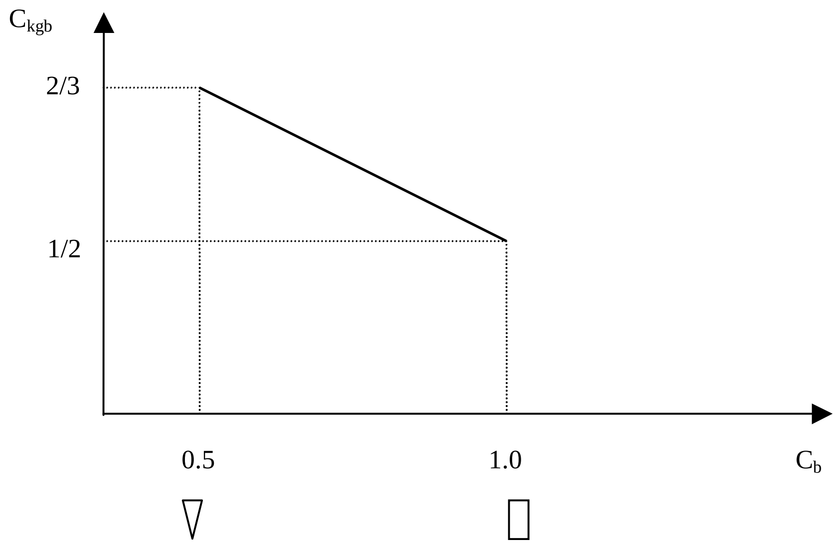


Figure 3-6 Form Factor of Gravity Center of Containes Below Deck

The gravity center of the containers above deck is determined from the following:

$$KG_d = D + HCH + TN_d \times D_0 / 2$$

Where HCH is the height of hatch coamings.

A secondary optimization is used to further investigate the influence of using a smooth function of the container number which actually is an integer number and improve the optimization results. The idea of this secondary optimization is that we have got an optimum point using that smooth function of container number in the first optimization process. But the actual behavior of the container number, which has a big influence on the objective function of required freight rate, will be the same within a certain vicinity of the dimensions of the optimum ship. As in Figure 3-5, the container number will be the same within certain range of L, B and

D. The secondary optimization will focus on that "Plateau" on which the container number will be the same as that of the optimum point derived from the first optimization. Some performance of the ship, such as displacement and building cost, will change with respect to the change of ship dimensions while the container number will keep the same on that plateau. The second optimization will be used to find an improved optimum point within that plateau. We may need to go to another plateau if the secondary optimum point is at the corner of the plateau. The detail of this secondary optimization is beyond the scope of this thesis.

3.4.3 Weight Estimate

The total weight of the ship is divided into components as follows:

$$W_{total} = W_{con} + W_{light} + W_{fuel} + W_{misc}$$

Where:

W_{total} = total weight of the ship

W_{con} = container weight

W_{light} = lightship weight

W_{fuel} = fuel weight

W_{misc} = miscellaneous weight

3.4.3.1 Container Weight

The container weight is determined by the container number and the weight per container:

$$W_{con} = TEU \times WPC$$

Where WPC is the weight per container.

The gravity center of container is calculated by the method described in Section 3.4.2.

3.4.3.2 Lightship Weight

The lightship weight is further divided into sub-components as follows:

$$W_{light} = W_h + W_{oh} + W_m$$

Where:

W_h = hull steel weight

W_{oh} = outfit and hull engineering weight

W_m = machinery weight

Hull structure [14] includes the main hull structure, superstructure, deck houses and all internal divisional bulkheads over one eight inch thick. It also includes masts, king posts and foundations.

$$W_h = C_s \times CL_1 \times CL_2 \times CL_3 \times \left[\frac{CN}{1000}\right]^{0.9} \qquad \textit{ton}$$

Where:

$C_s = 8550$

$CL_1 = 0.675 + 0.5 \times C_b$

$$CL_2 = 1 + 0.36 \times \frac{L_s}{L_{bp}}$$

L_s is the length of superstructure within fore and aft perpendiculars. L_{bp} is the length between perpendiculars. The ratio of L_s/L_{bp} is approximated as 0.25 in the MDO project.

$$CL_3 = 0.00585 \times (\frac{L_{oa}}{D} - 8.3)^{1.8} + 0.939$$

$$CN = \frac{L_{oa} \times B \times D}{100}$$

In the above equation for CN, the units for L_{oa}, B and D are meters.

The vertical center of gravity for the hull steel weight, expressed as a percentage of the depth, is estimated using the following formula [13]:

$$KG_h = [48 + 0.15 \times (0.85 - C_b) \times (\frac{L_{oa}}{D})^2] \times \frac{D_s}{D}$$

Where Ds is the increased depth taking account of the shear and hatchway volume. The ratio of D_s/D is approximated as 1.008 in the MDO project.

Outfit constitutes hull insulation, joiner bulkheads, hawse pipes, deck fittings, cargo booms, hatch covers, anchors, rudder and stock and gallery equipment [14].

$$W_o = 2412 \times (\frac{CN}{1000})^{0.825} \qquad \textit{ton}$$

Hull engineering constitutes non-propulsion mechanical equipment such as deck machinery, steering engine, generators, ventilation systems, refrigeration systems, hull piping systems, pumps, and electrical systems [14].

$$W_{he} = 1196 \times (\frac{CN}{1000})^{0.825} \qquad \textit{ton}$$

The total outfitting weight is the sum of the outfit weight and the hull engineering weight:

$$W_{oh} = W_o + W_{he}$$

The vertical center of gravity for the total outfit weight is estimated using the following approximation formula [16]:

$$KG_{oh} = (1.005 - 0.000689 \times L_{oa}) \times D$$

The propulsion machinery weight [14] is determined by the shaft horsepower of the main engine:

$$W_m = 215 \times C_f \times (\frac{SHP}{1000})^{0.72} \qquad \textit{ton}$$

Where C_f is the conversion factor from long tons to metric tons. The value of C_f is 1.016. The unit for SHP is horsepower.

The vertical center of gravity for the machinery weight is approximated as 47% of the depth [14].

A three-percent allowance is taken to give the total lightship weight as:

$$W_{light} = 1.03 \times (W_h + W_{oh} + W_m)$$

A 0.3-meter allowance is taken to give the gravity center of the total lightship weight as:

$$KG_{light} = \frac{W_h \times KG_h + W_{oh} \times KG_{oh} + W_m \times KG_m}{W_h + W_{oh} + W_m} + 0.3$$

3.4.3.3 Fuel Weight

The fuel weight [16] is determined by the shaft horsepower SHP, the service range Dst, the speed of the ship V and the specific fuel consumption SFC of the engine with an additional ten-percent allowance.

$$W_f = 1.1 \times \frac{SHP \times Dst \times SFC}{V}$$

The vertical center of gravity for the fuel weight is approximated as follows [16]:

$$KG_f = \frac{6.1}{3385} \times W_f$$

Where the unit for W_f is ton and for KG_f is meter.

3.4.3.4 Round Trip Time [17]

Time for loading and unloading containers per round trip can be determined from the following formula:

$$Lut = 4 \times \frac{TEU}{TSLU \times Ncrane}$$

Where TSLU is the loading/unloading speed of the crane and Ncrane is the crane number available for the loading/unloading work.

The number of crane can be calculated based on the assumption that we will have one crane in each interval of 135 feet over 75 percent of the ship length.

$$Ncrane = int(\frac{0.75 \times L_{oa}}{41.175} + 1)$$

Because the number of crane should always be an integer number, the function of crane number is again a step-like function, as the function of the container number. The least square fitting method is used to give the following smooth function of the crane number:

$$\text{Ncrane\_float} = 0.0187 \times L_{oa} + 0.3572$$

The time spent at sea by the ship is determined by the range and the speed of the ship:

$$St = \frac{Dst}{V}$$

Therefore, the total round trip time, Drt, can be calculated as:

$$Drt = Lut + Pwt + St$$

Where Pwt is the port waiting time.

The round trip number, NT, during each year of the ship life can be determined from the following:

$$NT = \frac{Ot}{Drt}$$

Where Ot is the annual operation time of the ship.

3.4.3.5 Miscellaneous Weight

The weight for the crew and provisions is approximated as follows [18]:

$$W_{cp} = (6 \times Drt + 50) \times C_f \qquad \textit{ton}$$

The weight for fresh water is approximated as follows [18]:

$$W_{fw} = 280 \times C_f \qquad \textit{ton}$$

The weight for lubricate oil is approximated as follows [18]:

$$W_{lo} = 50 \times C_f \qquad \textit{ton}$$

The miscellaneous weight for the machinery being idle is approximated as follows [18]:

$$W_{hc} = 5 \times Pwt \times C_f$$

Therefore, the total miscellaneous weight is:

$$W_{misc} = W_{cp} + W_{fw} + W_{lo} + W_{hc}$$

The vertical center of gravity of the total miscellaneous weight is chosen as a half of the depth [16].

3.4.4 Cost Estimate [14] [18] [19]

3.4.4.1 Building Cost

The building cost comprises the cost for shipbuilding, including machinery, steel hull, hull engineering and outfit. The general idea for building cost calculation is to calculate man-hours required based on the weights of the related components and use the man-hour estimate to determine the labor cost. The material cost is calculated as a function of the weight.

Throughout the MDO project, the labor cost, Lc is chosen as $20 per man-hour. Overheads are 70 percent of the labor cost. Further since the formulae were developed in 1962, the following modifications are made to make the formulae suitable to the present day situation: reduce man-hours by sixty percent to account for automation, increase material costs by 40 percent to account for inflation.

In all the following formulae, the unit for weight is ton; the unit for cost is dollar.

Steel Hull

Man-hours: $\text{Mhs} = \text{Cmhs} \times \left(\frac{W_h}{1000}\right)^{0.85}$

Where Cmhs is a coefficient depending on the effectiveness of the yard. We assume an average value of 3160.

Labor Cost: $\text{Lhs} = \text{Mhs} \times \text{Lc}$

Material Cost: $\text{Mats} = \text{Csh} \times W_h$

Where Csh is the average cost of the total hull steel.

Outfit

Man-hours: $\text{Mho} = \text{Co} \times \left(\dfrac{W_o}{100} \right)^{0.9}$

Where Co is a coefficient with a value of 8000.

Labor Cost: $\text{Lo} = \text{Mho} \times \text{Lc}$

Material Cost: $\text{Mato} = \text{Cof} \times W_o$

Where Cof is the average cost of the outfit.

Hull Engineering

Man-hours: $\text{Mhhe} = \text{Chhe} \times \left(\dfrac{W_{he}}{100} \right)^{0.75}$

Where Chhe is a coefficient with a value of 20400.

Labor Cost: $\text{Lhe} = \text{Mhhe} \times \text{Lc}$

Material Cost: $\text{Mathe} = \text{Chull} \times W_{he}$

Where Chull is the cost of the hull engineering.

Machinery

Man-hours: $\text{Mhm} = \text{Chm} \times \left(\dfrac{\text{SHP}}{1000} \right)^{0.6}$

Where Chm has a modified value of 6773.

Labor Cost: $\text{Lm} = \text{Mhm} \times \text{Lc}$

Material Cost: $\text{Matm} = \text{Cmm} \times \left(\dfrac{\text{SHP}}{1000} \right)^{0.6}$

Where Cmm is a coefficient with a modified average value of 38867.

Miscellaneous Cost

This involves cost that is not concerned with any of the weight categories. It includes drafting, purchasing, blueprints, scheduling, model tests, material handling, cleaning, launching, staging, dry-dock, tests and trials, classification, etc. It is chosen as ten-percent of the subtotal of the material costs.

$$\text{Miscc} = 0.10 \times (\text{Mats} + \text{Mato} + \text{Mathe} + \text{Matm})$$

Accommodation Cost

It is approximated as a function of the number of crew.

$$\text{Accoc} = 180{,}000 \times \text{Ncrew}^{0.56}$$

Overhead Cost

It includes all costs that can not be directly charged to any one contract, such as the officers' salaries, taxes, depreciation, watchmen, utilities, etc. It is chosen as seventy- percent of the total labor cost.

$$\text{Ovhc} = 0.70 \times (\text{Lhs} + \text{Lo} + \text{Lhe} + \text{Lm})$$

Yards Total Cost

It is the sum of all the above components.

$$\text{Ytc} = \text{Mats} + \text{Mato} + \text{Mathe} + \text{Matm} + \text{Miscc} + \text{Accoc} + \text{Ovhc}$$

Yard Profit

It is five percent of the yards total cost.

$$\text{Pr} = 0.05 \times \text{Ytc}$$

Yards Building Price

It is the sum of the yards total cost and the yard profit.

$$\text{Ybc} = \text{Ytc} + \text{Pr}$$

Owner Expense

This accounts for the costs involved in surveying and inspection, and is five percent of the yards building price.

$$\text{Owe} = 0.05 \times \text{Ybc}$$

Owner Cost

This is the sum of the yards building price and the owner expense.

$$\text{Owc} = \text{Ybc} + \text{Owe}$$

Annual Building Cost

For uniform annual cost, we use a capital recovery factor, Cr, which is defined as:

$$\text{Cr} = \frac{(1+\text{Ir})^{\text{Sl}} \times \text{Ir}}{(1+\text{Ir})^{\text{Sl}} - 1}$$

Where Ir is the interest rate and Sl is the ship life.

Therefore, the annual building cost can be calculated as follows:

$$\text{Abc} = \text{Owc} \times \text{Cr}$$

3.4.4.2 Operating Cost

Wages

First we estimate the number of crew as follows:

$$\text{Ncrew} = \text{Cst} \times \left[\text{Cdk} \times \left(\frac{\text{CN}}{1000} \right)^{1/6} + \text{Ceng} \times \left(\frac{\text{SHP}}{1000} \right)^{1/5} \right]$$

Where:

Cst = Coefficient for stewards department = 1.25

Cdk = Coefficient for the deck department = 15.4

Ceng = Coefficient for the engine department = 10

$$\text{Wage} = 37800 \times \text{Ncrew}^{4/5}$$

Stores and Supplies

$$\text{Ss} = 112 \times \left(\frac{\text{Ncrew}}{10} \right)^{4} \qquad \text{if the number of crew is less than 50}$$

Or

$$\text{Ss} = 70{,}000 + 5600 \times (\text{Ncrew} - 50)$$

Insurance

Protection and Indemnity:

$$\text{Ins1} = 1351 \times \text{Ncrew}$$

Hull and Machinery:

$$\text{Ins2} = 14000 + 0.0098 \times (Mathe + Mats + Mato + Matm + Lm + Lhs + Lo + Lhe)$$

Maintenance and Repair

Hull: $\text{Mrh} = 151200 \times \left(\frac{\text{CN}}{1000}\right)^{2/3}$

Machinery: $\text{Mrm} = 14000 \times \left(\frac{\text{SHP}}{1000}\right)^{2/3}$

Port Expenses

$$\text{Port} = \left[20 + 290 \times \left(\frac{\text{CN}}{1000}\right)\right] \times \text{Pwt} \times \text{NT}$$

Annual Fuel Cost

$$\text{Afc} = W_f \times \text{Fcost} \times \text{NT}$$

Where Fcost is the average fuel cost in dollars per ton.

Annual Operating Cost

$$\text{Aoc} = \text{Wage} + \text{Ss} + \text{Ins1} + \text{Ins2} + \text{Port} + \text{Afc}$$

3.4.4.3 Required Freight Rate

Annual Average Cost

$$\text{Aac} = \text{Abc} + \text{Aoc}$$

Required Freight Rate

$$\text{RFR} = \frac{\text{Aac}}{\text{NT} \times \text{W}_{\text{con}} \times \text{Dst}}$$

3.4.5 Initial Stability, Freeboard and Rolling Period

3.4.5.1 Initial Stability

The wind heel criteria from US Coast Guard [20] is used for an initial stability check. The minimum value of GM, in meters, is determined from the following formula:

$$\text{GM}_{\text{min}} = \frac{\text{P} \times \text{A} \times \text{H}}{\Delta \times \text{tg}\theta}$$

Where:

$$P = 0.055 + \left(\frac{L_{bp}}{1309}\right)^2$$

The unit for P is tons/m^2. The unit for L_{bp} is meter.

A is the projected lateral area in square meters of the portion of the ship and deck cargo above the waterline. It can be approximated using the following formula:

$A = L_{oa} \times (D\text{-}T) + TN_d \times D_0 \times L_{oa}$

H is the vertical distance in meters from the center of A to the center of the underwater lateral area or approximately to the one-half draft point. It can be approximated using the following formula:

$$H = \frac{\frac{1}{2} \times L_{oa} \times (D - T)^2 + \frac{1}{2} \times L_{oa} \times (TN_d \times D_0)^2}{A} + \frac{1}{2} \times T$$

Δ is the displacement of the ship, in metric tons.

θ is the lesser of either 14 degrees or the angle of heel in degrees to the deck edge.

3.4.5.2 Freeboard

The minimum freeboard, unit in meters, is determined using the following approximate formula:

$$FreeBoard_{min} = c \times a + b$$

Where:

$c = 0.025633 \times L_{oa}^{0.9146}$

The unit for L_{oa} is meter.

When $C_b > 0.68$:

$a = \frac{C_b + 0.68}{1.36}$

Otherwise, a = 1.0

When $L_{oa}/D < 15.0$:

$b = 0.25 \times (D - \frac{L_{oa}}{15.0})$

Otherwise, b = 0

3.4.5.3 Rolling Period

The rolling period of the ship is calculated using the following formula from “Principles of Naval Architecture” [21]:

$$RollingPeriod = 0.58 \times \sqrt{\frac{B^2 + 4 \times KG^2}{GM}}$$

Chapter 4 Optimization Formulation

4.1 Introduction

Having the general formulation for optimization, each specific optimization problem must be formulated carefully since a numerical algorithm, such as that in DOT, is used to solve the problem. Different formulations to the same problem will give different results. A good formulation should give a stable and reasonable solution. The formulation of the optimization problem includes three parts: selection of the design variables, formulation of the objective function and formulation of the constraints.

4.2 Objective Function

4.2.1 Using Required Freight Rate as Objective Function

The goal of the MDO project is to develop a tool to help the designer find the best ship design. A container ship design is chosen as the test case. The problem is tackled from the standpoint of a shipping company. The objective is to minimize the required freight rate with a fixed range between two ports. The freight rate is the money charged by the shipping company per unit weight of cargo and per unit distance the cargo to be carried. Schneekluth [13] gives the definition of required freight rate. "The required freight rate for a given rate of utilization produces net profits which exactly cover the operating costs inclusive of calculated interest on the invested capital; i.e. profit and rate of return are nil." Simply put, there will be no profit for the shipping company if it charges the required freight rate. Surely in real life, the asked freight rate charged by the shipping company is higher than the required freight rate, so it can make profit from carrying the cargo. For a given asked freight rate which is determined by many other factors besides required freight rate, the lower the required freight rate, the more profit the shipping company can make. Therefore, the required freight rate is an important economic index of the ship from the standpoint of the shipping company. In the commercial ship market, the economic performance of a ship is the most important thing that concerns the ship owner. All the other technical performance of the ship must be judged based upon whether they can bring profit to the ship owner. Therefore, the required freight rate has been chosen as the objective function for the MDO problem. The required freight rate is also used as the objective function by other optimization works [10].

4.2.2 Algorithm to Calculate Required Freight Rate

The required freight rate is derived from solving the equation that the annual income the ship makes is equal to the cost. The income per voyage is calculated for a given ship whose cargo capacity can be determined. The annual number of trips is determined by the service speed of the ship. The annual income is the product of the income per trip and the number of annual trips. The annual cost of the ship contains building cost and operation cost. The total building cost of the ship depends on the ship size, ship type and the building location. That cost is spread over the expected life of the ship using an assumed interest rate to give the annual building cost. The operation cost includes the fuel cost, crew's wage, cost for stores and supplies, insurance, maintenance and repair cost, port expenses and cargo handling cost. The fuel cost is calculated based upon the resistance of the ship, its speed and the assumed specific fuel consumption of the main propulsion engine. By equalizing the annual income to the annual cost, the solved freight rate is the required freight rate by definition.

4.2.3 Normalization of Objective Function

The required freight rate can be expressed as the money charged either per unit cargo weight per unit distance, or per unit cargo weight alone, since the distance is pre-determined in the MDO project. Consequently, the magnitude of the objective function can differ largely as the distance is usually thousands of nautical miles. More important, the magnitude of the gradients of the objective function, which has a large influence on the searching direction vector, will differ a lot. As a numerical optimization tool, DOT seeks the searching direction vector based upon the sign and the magnitude of the gradients of the objective function and the constraints. DOT does not normalize the searching direction vector during the optimization process. The optimization process will stop when the largest component of searching vector is very small in magnitude. Therefore, we will be told by DOT that the optimization process has converged using one kind of definition for required freight rate, while it has not converged using another definition. This causes the optimization result to be unstable. In fact, we are mostly concerned with the relationship between the gradients rather than the magnitude of the gradients. To get a stable formulation for the objective function avoiding changing the source code of DOT, a normalized objective function has been used in the project. There are many ways to normalize the objective function. In the project, the value of the required freight rate is normalized by the initial value of the required freight rate. After all, it is well accepted that normalizing the objective function will do no harm to the optimization and always give a better solution.

4.2.4 Formulation of Objective Function

The objective function for the MDO project is formulated as follows:

Objective function:

$$\textbf{Minimize} \quad F(x) = \frac{RFR}{RFR0}$$

Where:

RFR: Required freight rate

RFR0: Required freight rate at the initial design point

4.3 Constraints

4.3.1 Selection of Constraints

There are two kinds of constraints used in the project: constraints on the parameter ratios and constraints concerning the performance requirements. The first kind of constraints includes constraints that are only raised from the technical concern. To take full advantage of the optimization technique which may produce non-traditional results, other constrains that are raised from ship design experience, such as L/B, are not included in the MDO project. One of the constraints that should be concerned is that on the ratio of L_{oa}/D. L_{oa} is the length overall of the ship. D is the ship's depth. The constraint on L_{oa}/D results from the empirical formula [14] to be used to calculate the hull steel weight of the ship. The formula is valid only when L_{oa}/D is greater or equal to 8.3. There are several constraints concerning the performance requirement. The ship weight should be equal to the displacement. The GM value should be greater than the minimum value set by the US Coast Guard. The freeboard should be greater than the minimum requirement. The rolling period of the ship should be greater than a certain value to make the ship comfortable for the crew. The ship should be able to carry a minimum number of containers required by the shipping company. There also might exist an upper bound for the container number due to the market situation.

4.3.2 Equality Constraints

DOT recognizes only inequality constraints, which require a set of function g_j (X) to be less than or equal to zero. To specify that a function (or functions) must be equal to zero at the optimum, two separate inequality constraints must be defined. One constraint requires the function to be less than or equal to zero and the other constraint requires the function to be greater than or equal to zero (in standard form, the negative of the function be less than zero). The only function value that satisfies both constraints is zero, which is just what an equality constraint requires. Table 4-1 gives the formulation of equality constraints before normalization in DOT.

Table 4-1 Formulation of Equality Constraint

Equality Constraint	Formulation
$A = B$	$A - B \le 0$ $-(A - B) \le 0$

4.3.3 Normalization of Constraints

In an optimization problem, there are different constraints involving different parameters. They usually contain various class of information with different magnitude. DOT, as a numerical optimization tool, uses a consistent criterion to judge whether a constraint is violated and whether a constraint is active (close to being violated). DOT will give a searching direction that pulls the violated constraints back to be inviolate and keeps the active constraints from being violated. Different magnitude of constraints will also give the different constraints' gradient, which has a great influence on the search direction vector. To keep the constraint violation and active criteria to be consistent for all different constraints, and to give a stable searching direction, all constraints should be normalized in the same manner. Table 4-2 gives the formulation of constraints after normalization for DOT.

Table 4-2 Normalization of Constraint for DOT

Constraint	Formulation for Optimization	Normalization for DOT
$A \le B$	$A - B \le 0$	$1 - \frac{B}{A} \le 0$

4.3.4 Formulation of Constraints

Table 4-3 gives the formulation of constraints used in the MDO project.

Table 4-3 Formulation of Constraints in MDO Project

No	Constraint	Expression	Formulation
1	L_{oa}/D	$\frac{L_{oa}}{D} \geq 8.3$	$1 - \frac{L_{oa}/D}{8.3} \leq 0$
2	Displacement and Weight	$Displacement = Weight$	$1 - \frac{Dispalcement}{Weight} \leq 0$ $-\left(1 - \frac{Dispalcement}{Weight}\right) \leq 0$
3	GM	$GM \geq GM_{\min}$	$1 - \frac{GM}{GM_{\min}} \leq 0$
4	Freeboard	$Freeboard \geq Freeboard_{\min}$	$1 - \frac{Freeboard}{Freeboard_{\min}} \leq 0$
5	Rolling Period	$RollingPeriod \geq RollingPeriod_{\min}$	$1 - \frac{RollingPeriod}{RollingPeriod_{\min}} \leq 0$
6	Container Number (TEU)	$TEU_{\min} \leq TEU \leq TEU_{\max}$	$1 - \frac{TEU}{TEU_{\min}} \leq 0$ $\frac{TEU_{\max}}{TEU} - 1 \leq 0$

4.4 Design Variables

4.4.1 Selection of Design Variables

There are several principles for choosing the design variables in an optimization problem. First, a design variable should have direct influence on the objective function and constrains. Second, the number of design variables should be kept as small as possible. Third, the design variables should be kept as independent as possible. The design variables to be used in the MDO project should be chosen after careful inspection of the input and output parameters of every module. Table 4-4 gives the input and output information of different modules. From Table 4-4, it can be seen that there are only five independent parameters plus the blending factor's vector C_i

that need to be adjusted during the optimization. The five independent parameters are Length overall, L_{oa}, Breadth, B, Depth, D, Draft, T and Speed, V. All the other parameters can be calculated from these independent parameters and blending factors. Table 4-5 gives the design variables to be used in the MDO project.

Table 4-4 Input and Output of Different Modules

No	Module	Input	Output
1	Geometry (using blending technique)	L_{oa}, B, D, T, C_i	Hydrostatics Information L_{wl}, C_b, C_p, C_m, C_w, L_{cb}, V_{cb}, S, A_{BT}, h_B, ∇, BM
2	Resistance (using Holtrop Mannen method)	L_{wl}, B, T, V, C_b, C_p, C_m, C_w, L_{cb}, S, ∇	EHP
3	Propulsion	EHP	SHP
4	Container Number	L_{oa}, B, D, C_b	TEU, Cargo Weight
4	Weight	L_{oa}, B, D, SHP, V	Weight components
5	Cost	Weight component, L_{oa}, B, D, SHP,	Cost components Required Freight Rate
6	Stability GM (using US coast guard's requirement)	KG, V_{cb}, BM, L, D, T	GM, GM_{min}
7	Freeboard	D, T, L_{oa}	Freeboard, $Freeboard_{min}$
8	Rolling Period	B, KG, GM	Rolling Period

Table 4-5 Design Variables Used in MDO Project

No	Design Variables	Description
1	L_{oa}	Length Overall
2	B	Breadth
3	D	Depth
4	T	Draft
5	V	Speed
6	C_i	Blending Factor

4.4.2 Scaling of Design Variables

Care should always be taken in scaling the design variables of the optimization. The design variables of the optimization problem may be in different categories with different units. Their magnitudes may differ a lot. Efforts should be made trying to scale the design variables so that they are within the same general order of magnitude.

There are many ways to scale the design variables. Table 4-6 gives the scaling factor for design variables used in DOT where Value After Scaling = Original Value × Scaling Factor. From Table 4-6, it can be seen that DOT does not scale the design variables with very small magnitude, i.e., far less than 1.0. Fortunately, the design variables used in the MDO project that are less than 1.0 are usually the blending factors whose values are generally range between 0.1 to 1.0. Therefore, it is fine to use the scaling factor defined by DOT. If we have some design variables whose value are far less than 1.0, it would be better for us to define our own scaling factor to keep the design variables in the general order of magnitude.

Table 4-6 Scaling Factor for Design Variables Used in DOT

	Original Value	Scaling Factor	Value after Scaling
1	Largest (in the order of 10^n)	10^{-n}	1.0 ~ 10.0
2	Larger than 1.0	Reciprocal of the original value	1.0
3	Less than 1.0	1.0	Same as the original value

DOT also has a controlling parameter named ISCAL that controls how frequently DOT re-calculates the scaling factor. The default value for ISCAL is equal to the number of design variables. It means that DOT does not re-calculate the scaling factors in each single iteration, but only does so after a certain number of iterations. This number is equal to the number of design variables by default. The reason for doing a scaling factor calculation only after a certain number of iterations is that DOT assumes the magnitude and relationship between design variables will not change drastically within these iterations. This is true if the number of design variables is not very large, which is just the case in the MDO project. However, the scaling factor calculation should be accelerated if we have a large amount of design variables.

Chapter 5 Optimization Results and Discussion

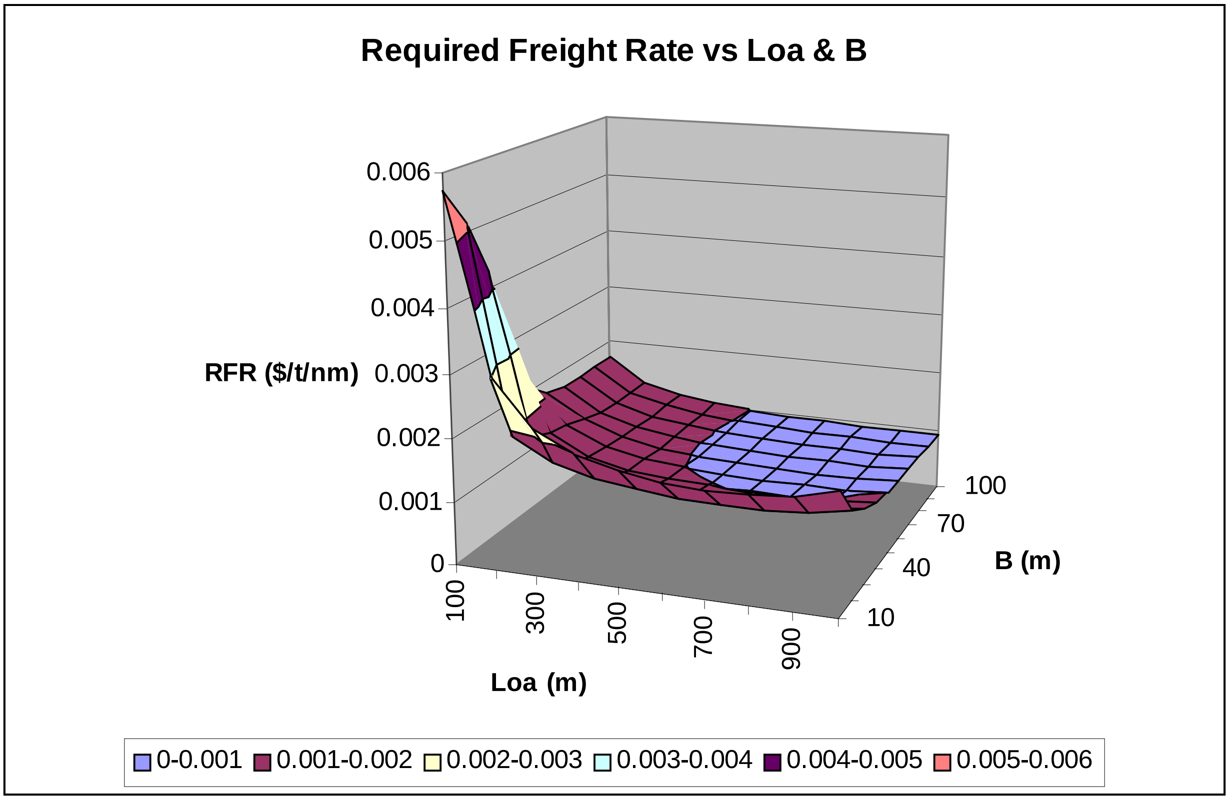
5.1 One Global Minimum

To check whether we have several local minimum points or just one global minimum point, the optimization process is started from different initial design points. The intervals between the upper and lower bounds of the design variables are set to be very large to ensure that the optimum value of the design variable will not be at the bounds. SLP (Sequential Linear Programming) is used in the optimization. Only two basis ships are used, namely basis14 and basis22. Table 5-1 shows the results of the optimization. The value of C_1 in Table 5-1 is the geometric blending factor for basis14. The value of the blending factor for basis22 is calculated from:

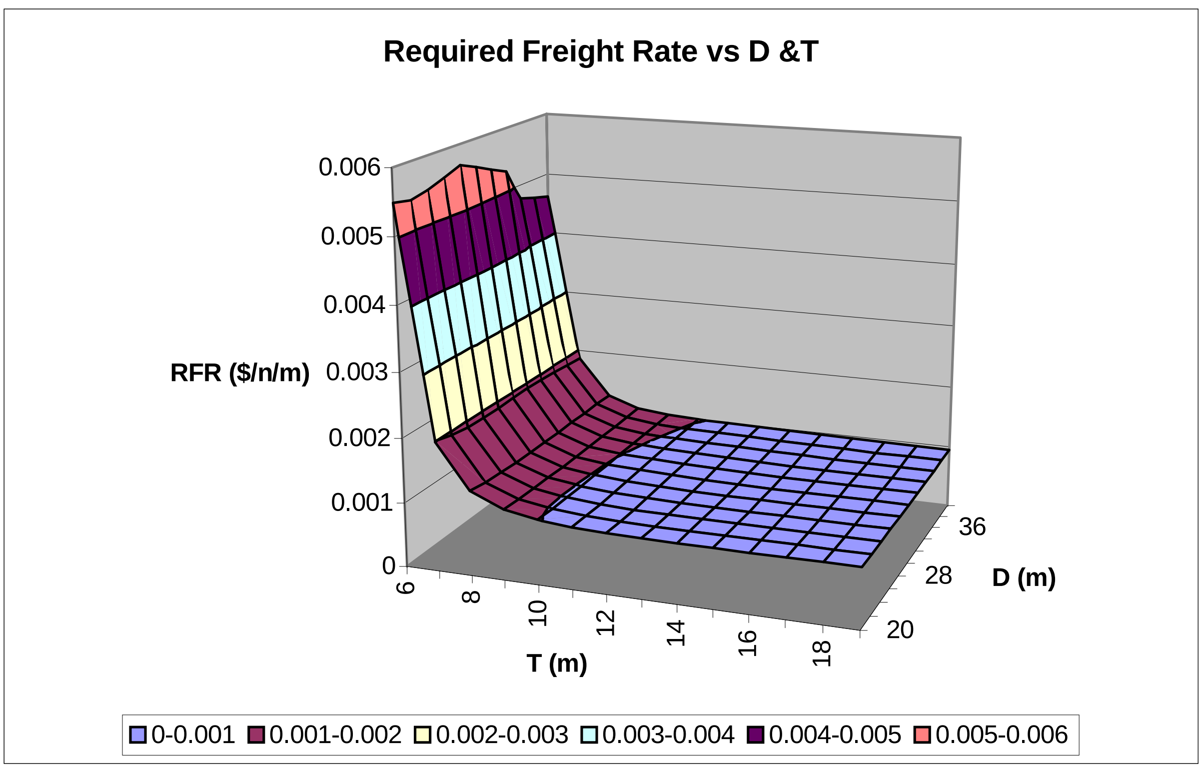
$$C_2 = 1 - C_1$$

Table 5-1 Optimization Results with Different Starting Points

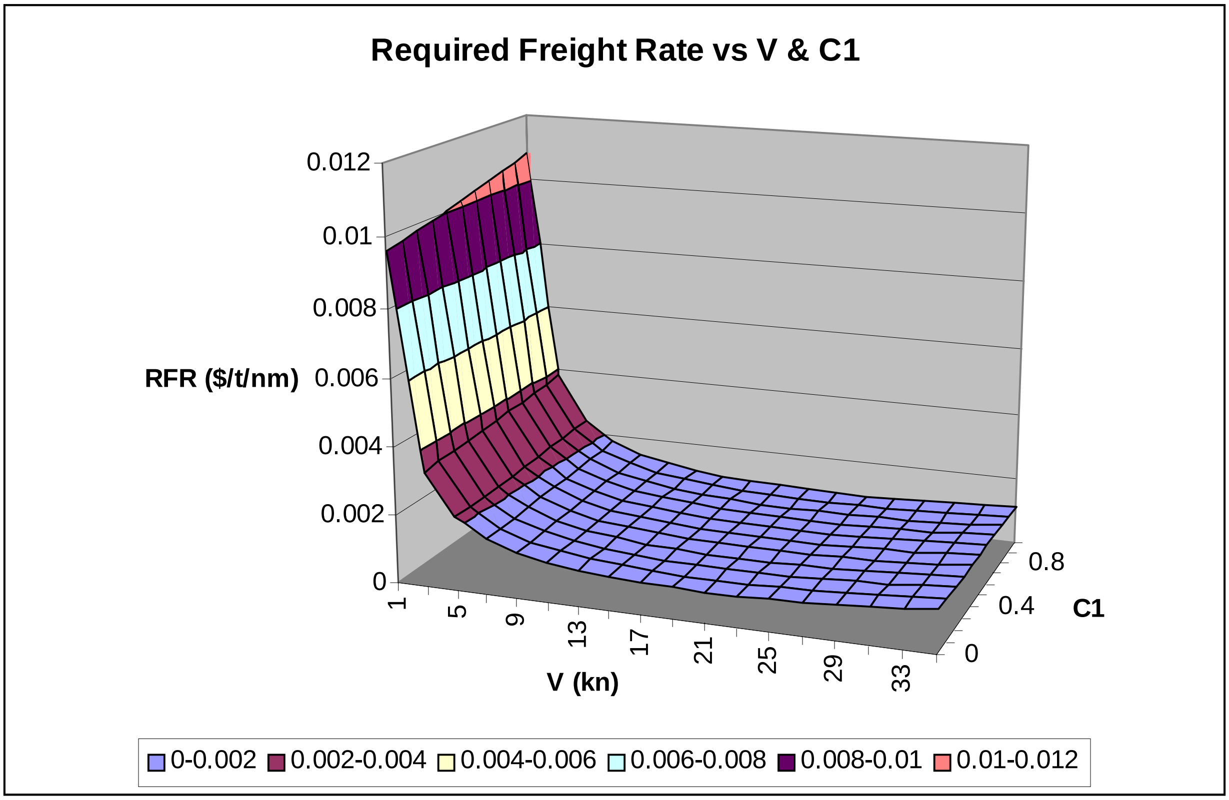
	1000RFR ($/t/nm)	L_{oa} (m)	B (m)	D (m)	T (m)	Vk (kn)	C_1
Lower Bound	21.6005	100	20	10	6	1	0
Upper Bound	1.1354	1000	100	40	34	35	1
1. Starting from the lower bound	0.9133	832.994	68.565	27.187	14.178	20.999	0.1443
2. Starting from the upper bound	0.9131	819.339	67.740	26.412	13.974	20.652	0.1850
3. Starting from the middle point	0.9130	806.491	67.275	26.785	13.965	20.550	0.1136
Average Value	0.9131	819.608	67.860	26.795	14.039	20.734	0.1476



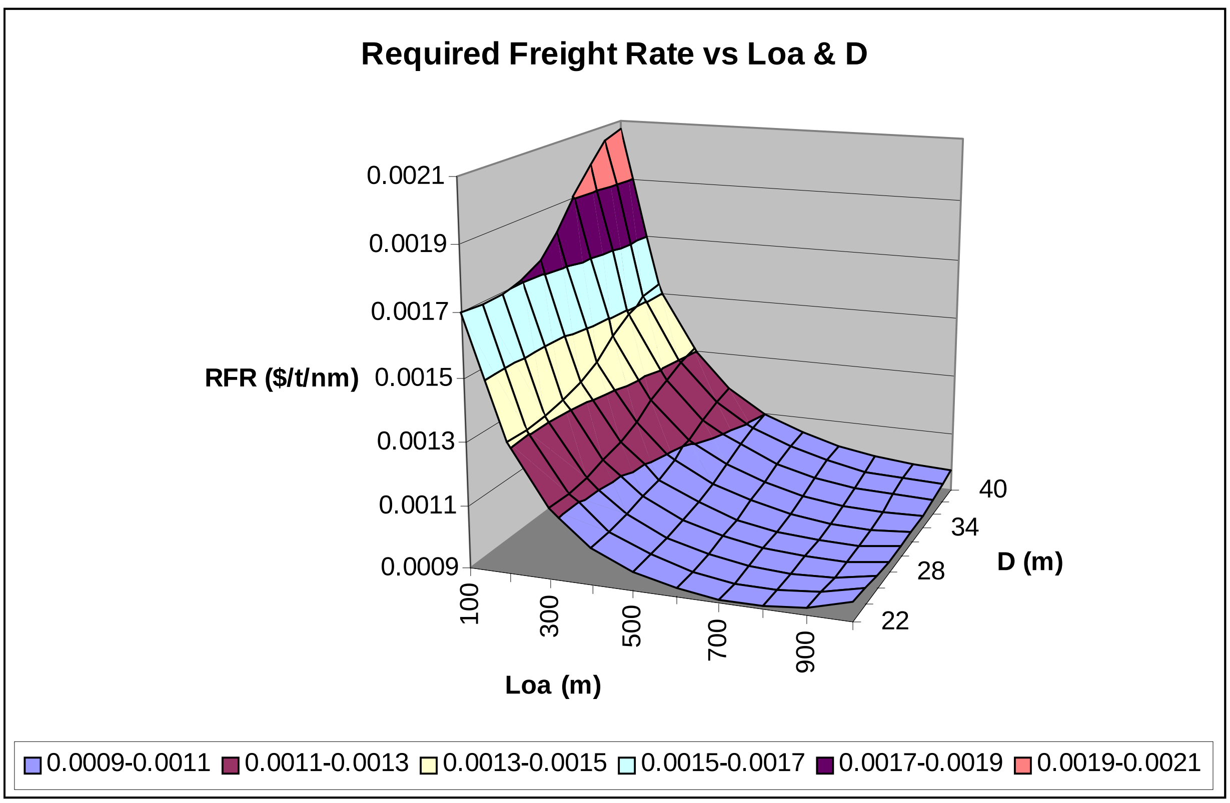
Required Freight Rate vs Loa & B
RFR ($/t/nm)
0.006
0.005
0.004
0.003
0.002
0.001
0
100
300
500
700
900
Loa (m)
10
40
70
100
B (m)
0-0.001
0.001-0.002
0.002-0.003
0.003-0.004
0.004-0.005
0.005-0.006



Required Freight Rate vs D &T
RFR ($/n/m)
0.006
0.005
0.004
0.003
0.002
0.001
0
6
8
10
12
14
16
18
T (m)
20
28
36
D (m)
0-0.001
0.001-0.002
0.002-0.003
0.003-0.004
0.004-0.005
0.005-0.006



Required Freight Rate vs V & C1
RFR ($/t/nm)
0.012
0.01
0.008
0.006
0.004
0.002
0
V (kn)
1
5
9
13
17
21
25
29
33
C1
0
0.4
0.8
0-0.002
0.002-0.004
0.004-0.006
0.006-0.008
0.008-0.01
0.01-0.012



Required Freight Rate vs Loa & D
RFR ($/t/nm)
0.0021
0.0019
0.0017
0.0015
0.0013
0.0011
0.0009
Loa (m)
100
300
500
700
900
D (m)
22
28
34
40
0.0009-0.0011
0.0011-0.0013
0.0013-0.0015
0.0015-0.0017
0.0017-0.0019
0.0019-0.0021

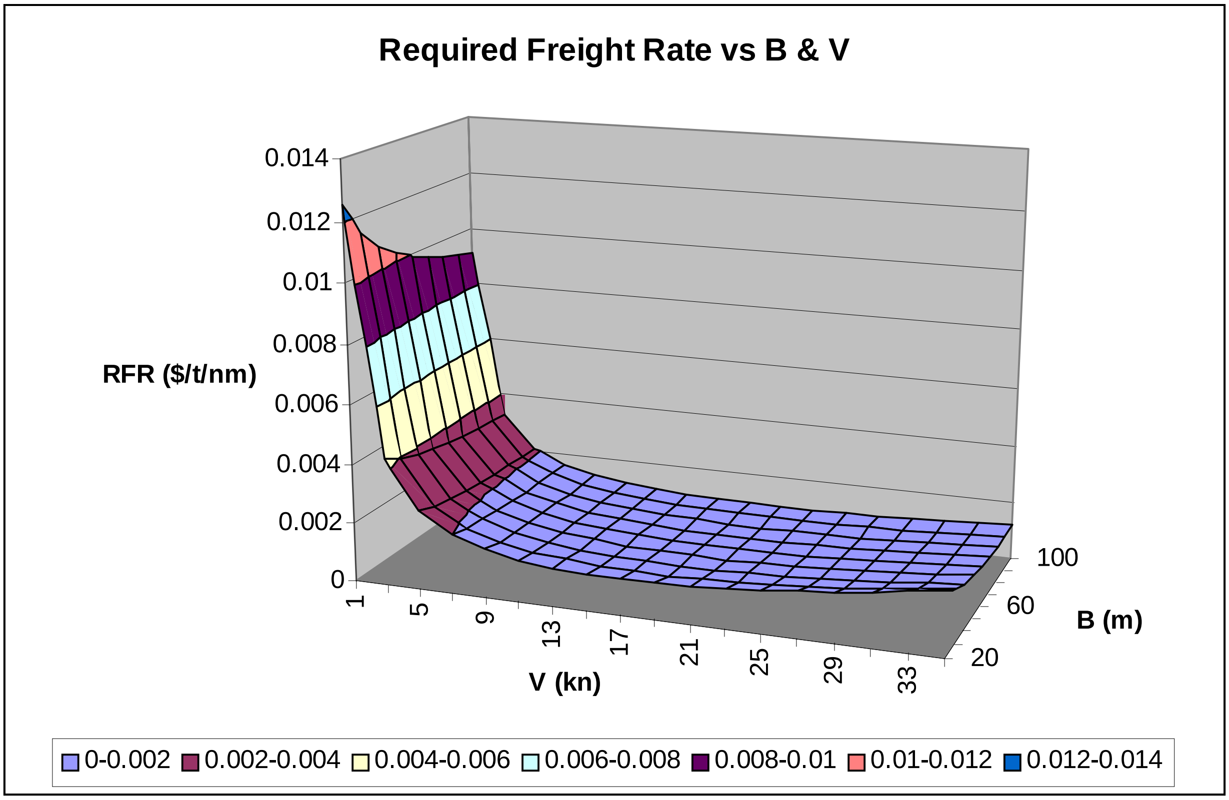


Figure 5-1 Two Dimensional Surface of Required Freight Rate

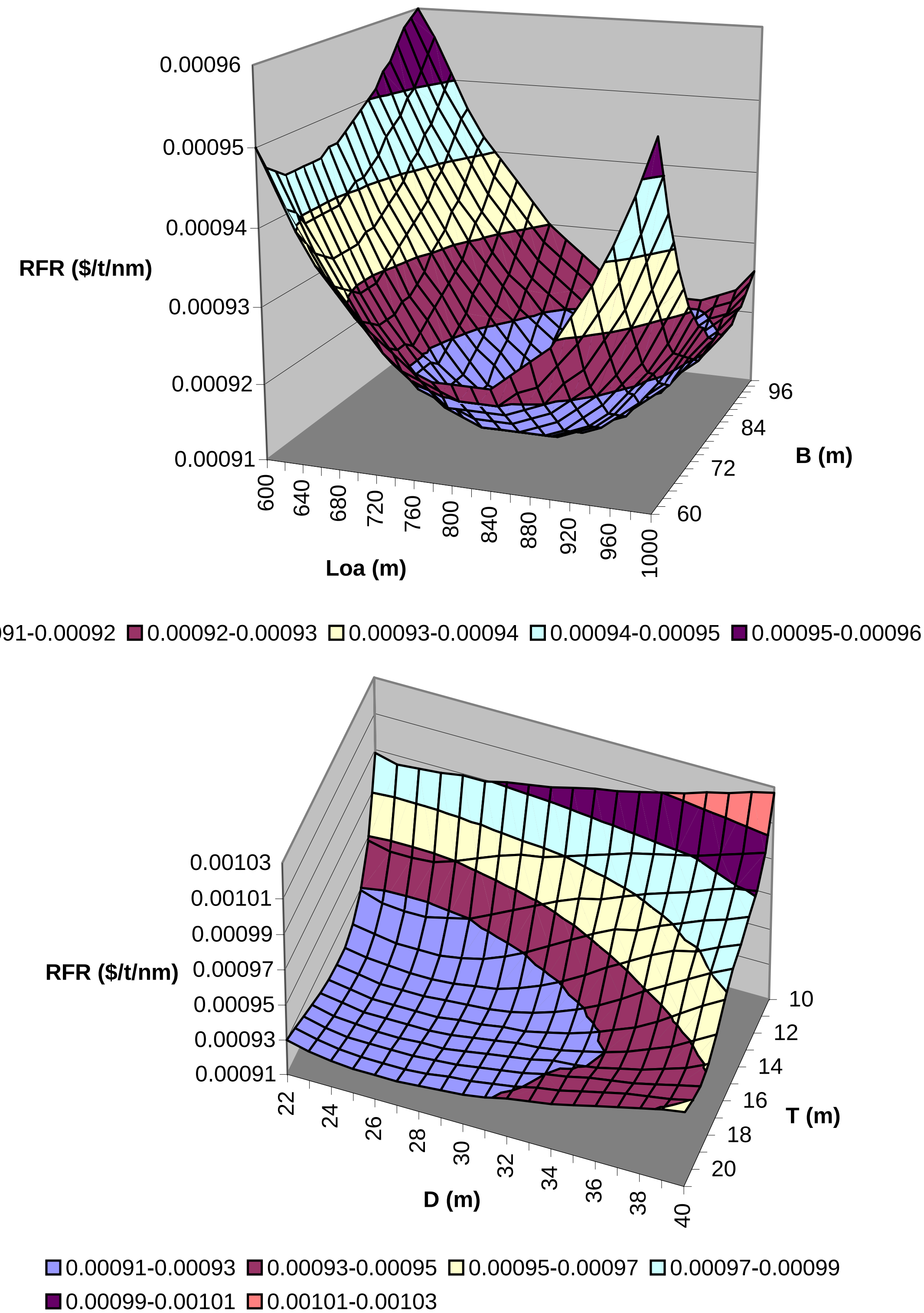


Figure 5-2 Refined Objective Surface around Reference Point

Taking the average value of the design variable as the value for the reference point, further calculation shows that we have a very flat objective surface around the reference point. Because the surface of the objective function, the normalized required freight rate, is a multi-dimensional surface with respect to the design variables, in this case, six design variables, it is very difficult to visualize the surface. To get a better understanding about the behavior of the objective function, several two-dimensional surfaces are plotted with the other design variables that besides the independent variables keeping the same as those of the reference point. From Figure 5-1, we can see that the surface of the required freight rate around the reference point is a very smooth convex surface. Figure 5-2 refines the surface around the reference point. The fact that the objective surface is a convex surface ensures that there is only one local minimum point within the design space. Therefore, that local minimum point is the global minimum point within the design space.

The deviation is caused by the fact that we are using a numerical optimization tool that rarely gives a true accurate optimum point. The range of deviation is within the engineering allowance, except for the blending factor C_1. The divergence of C_1 at the optimum point will be further discussed in the next section.

5.2 Sensitivity of Objective Function to Design Variables

To investigate the sensitivity of the objective function to the design variables, we calculate the relative value of the objective function with respect to its reference value, at the vicinity of the reference point. The idea is similar to that for the surface plot in Section 5.1. Here, instead of using two independent variables, we use only one independent variable while keeping the other five design variables the same as those for the reference point.

Figure 5-3 shows the sensitivity of the objective function to each design variable at the reference point. The horizontal axis in Figure 5-3 is the relative value of the independent variables with respect to its reference value. The vertical axis in Figure 5-3 is the non-dimensional required freight rate with respect to the reference value of the required freight rate.

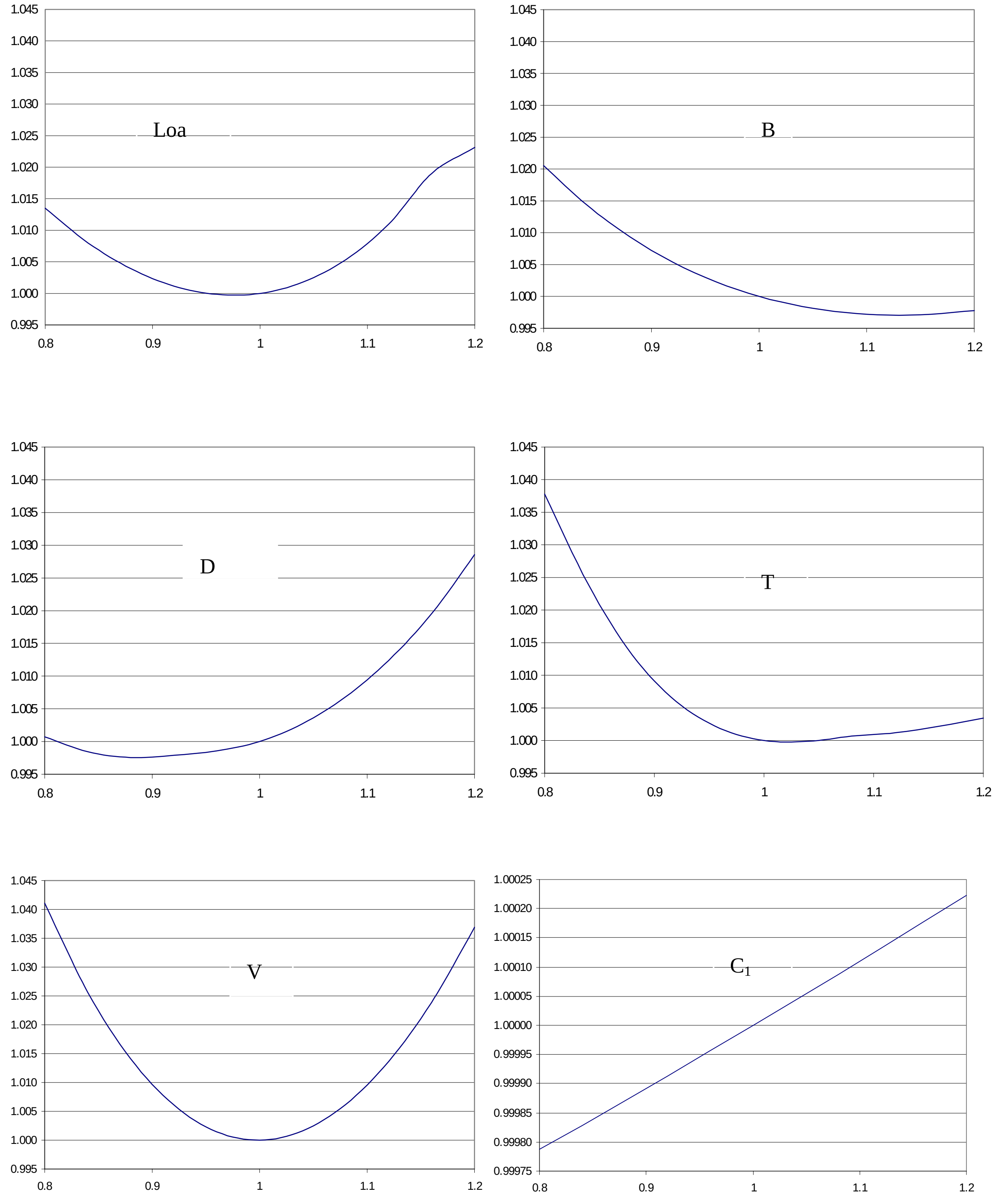


Figure 5-3 Required Freight Rate at Vicinity of Reference Point

From Figure 5-3, we can see that the objective function, required freight rate, has similar sensitivity to the design variables of L_{oa}, B, D, T and V. However, it is very insensitive to the blending factor C_1, notice the different scale of the vertical axis for C_1 from the other design variables. With C_1 changing from $0.8C_{10}$ to $1.2C_{10}$, where C_{10} is the reference value for C_1, the value of the objective function only changes about less than 0.05% of RFR_0, where RFR_0 is the reference value for the required freight rate. In the meantime, the value of objective function changes about 4% of the reference value when the other design variables change from $0.8X_0$ to 1.2 X_0, where X_0 is the reference value for the corresponding design variable.

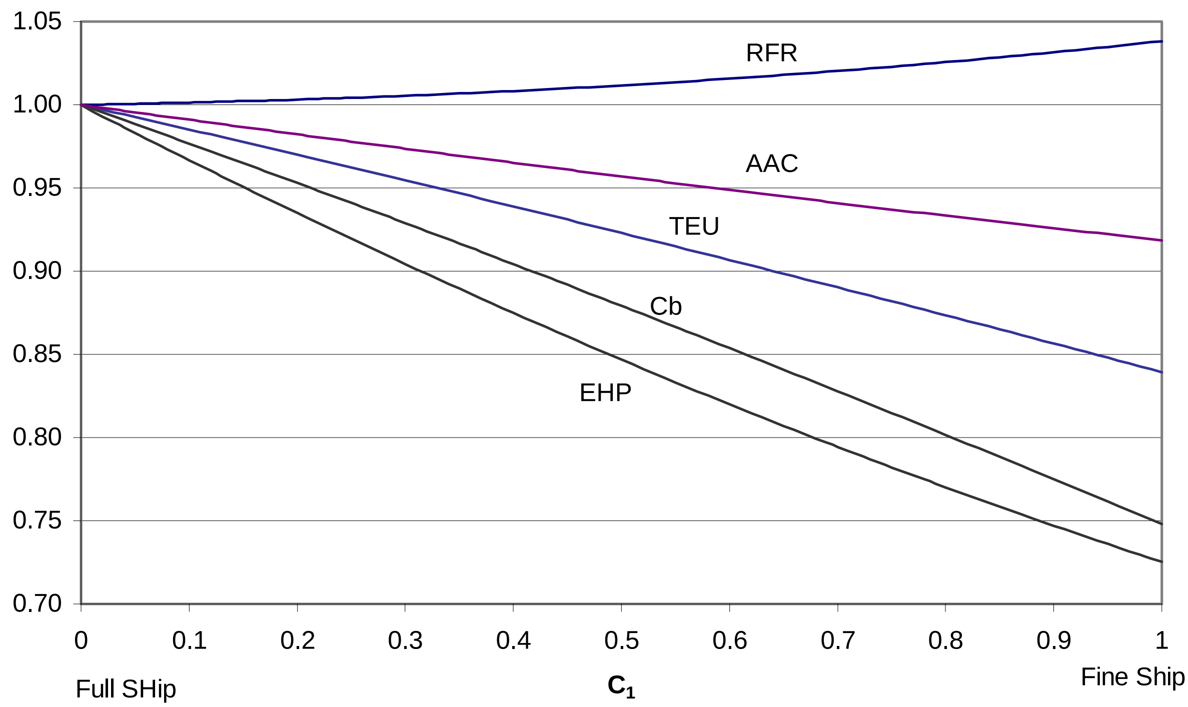


Figure 5-4 Influence of C_1 on Required Freight Rate

To get a better understanding of why the geometric blending factor C_1 is so insensitive to the objective function, we should investigate the influence of C_1 on the required freight rate. In Figure 5-4, RFR is the required freight rate, AAC is the annual total cost, TEU is the container capacity of the ship, C_b is the block coefficient, EHP is the effective horsepower. All these values are normalized with respect to their corresponding values at C_1 equals zero. All other dimensions of the ship, including Loa, B, D, T and V, are kept the same during the calculation. At C_1 equals zero, the block coefficient is about 0.7 corresponding to a full ship, while it is about 0.57 when C_1 equals one, corresponding to a fine ship.

Using Holtrop and Mennen's method [15] for resistance prediction, the fine ship has less resistance than the full ship. The fine ship has less container capacity than the full ship since the stowage factor for containers under deck is relative to C_b. The decrease for TEU is less than the decrease for C_b because the container capacities above deck for both ships are the same as they have the same gross dimensions. The total annual cost for a fine ship is less than that for a full ship, but the decrease is less that that for the container capacity. The required freight rate is proportional to the total annual cost and inversely proportional to the container capacity. Therefore, the required freight rate for a fine ship is slightly bigger than that for a full ship by about four-percent.

Since our objective is to minimize the normalized required freight rate, the optimization should go to the lower bound of C_1 in theory with another set of other design variables including L_{oa}, B, D, T and V. The noise of optimum C_1 value, as indicated by Table 5-1, is caused by the difference between the objective function's gradient of C_1 and other design variables. Because the objective function's gradient of C_1 is much less than that of other design variables, such as L_{oa}, C_1 has much less influence on the searching direction during the optimization than the other design variables. During the optimization, C_1 takes very small step in each iteration towards the optimum point. The relative and absolute convergence criteria for optimization have already been met before C_1 goes to the true optimum value of zero. As we are using a numerical optimization tool, the difference between the optimum value of C_1 can be very large.

5.3 Big Ship

From Table 5-1, we can see that the optimum ship given by the optimization is a very big ship. The dimensions of the ship are well beyond the conventional range of the general commercial ship, especially for L_{oa} and B. It shows that with the simple formulation of the required freight rate which only considers the fundamental constraints such as displacement equals buoyancy, initial stability requirement, etc., and without a structural analysis, a bigger ship is equal to a better ship. A bigger ship means it can carry more containers so it can make more money for the ship owner. The results from the optimization that the optimum ship is much bigger than the conventional container ship is coincident to the fact that the container ship is getting bigger and bigger nowadays.

The dimensions of the ship will be further constrained by the followings:

- Maximum L_{oa}, constrained by structure strength, available berth, turning radius, etc.
- Maximum B, constrained by channel, crane reach, etc.
- Maximum Draft, constrained by the water depth at port
- Minimum Speed, constrained by the time requirement for the delivery of the containers to the destination port
- Maximum Container Capacity, constrained by the market situation

Table 5-2 shows the optimization result using more realistic lower and upper bounds on the design variables. The maximum container capacity of the ship is set to be 10000 TEUs. The optimization starts from the middle of the design space using the SLP method. Figure 5-5 shows the iteration history of the objective function (normalized required freight rate), the required freight rate and the design variables. The horizontal axis in Figure 5-5 is the iteration number. Using these more realistic bounds, the optimum value of Loa hits the upper bound while B is very near the upper bound. The optimum value of B is constrained by the requirement of the minimum rolling period, which is set to be 15 seconds. The value of D and T are constrained by the fact that the displacement must be equal to the weight of the ship. Still, the optimization gives us a container ship as big as possible.

Table 5-2 Optimization Using Realistic Bounds

	L_{oa} (m)	B (m)	D (m)	T (m)	Vk (kn)	C_1	RFR ($/t/nm)	TEU*
Lower Bound	100	20	10	6	15	0		2000
Upper Bound	300	43	40	20	35	1		10000
Starting Point	200	30	25	13	25	0.5	0.002043	2740
Optimum Point	300.000	41.553	15.483	9.830	17.315	0.1313	0.001106	4940

* TEU: Container capacity of the ship for twenty-foot equivalent units. It is not a design variable.

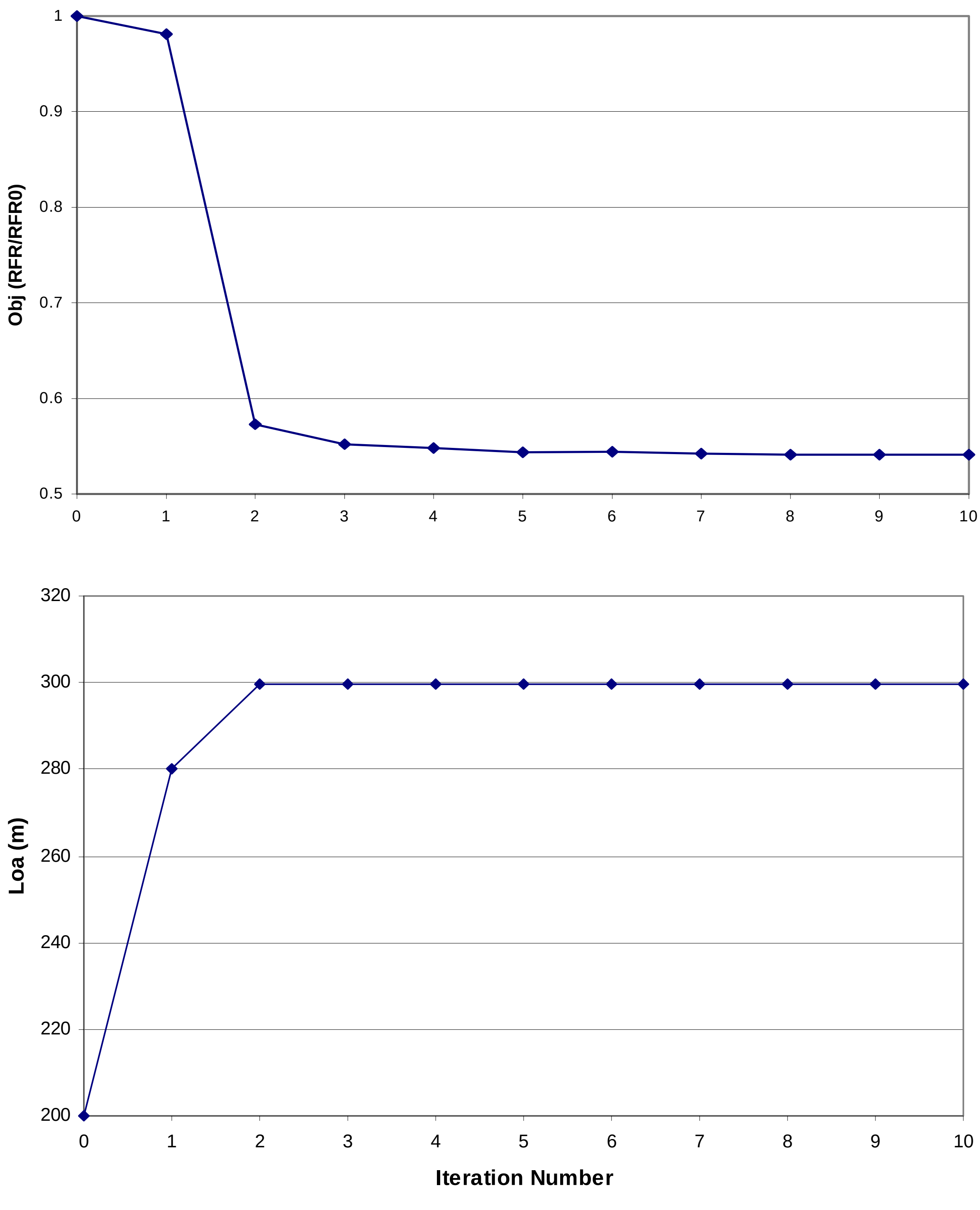
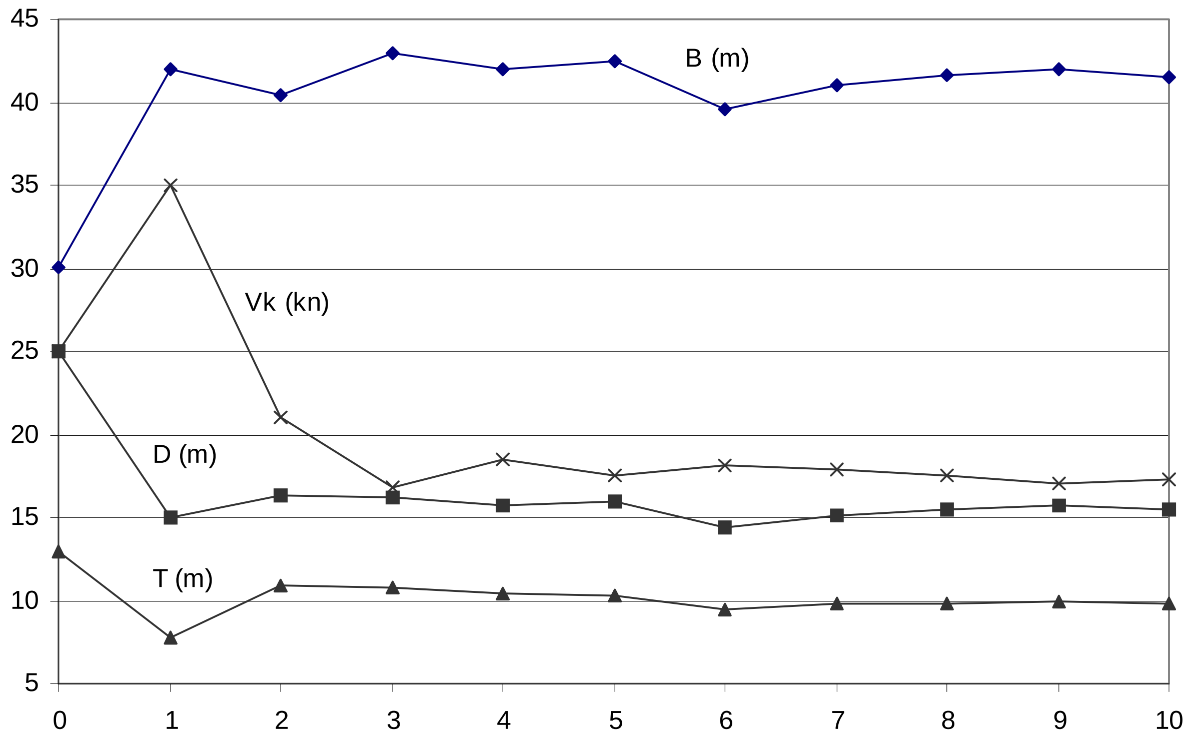


Figure 5-5 Iteration History of Objective Function and Design Variables



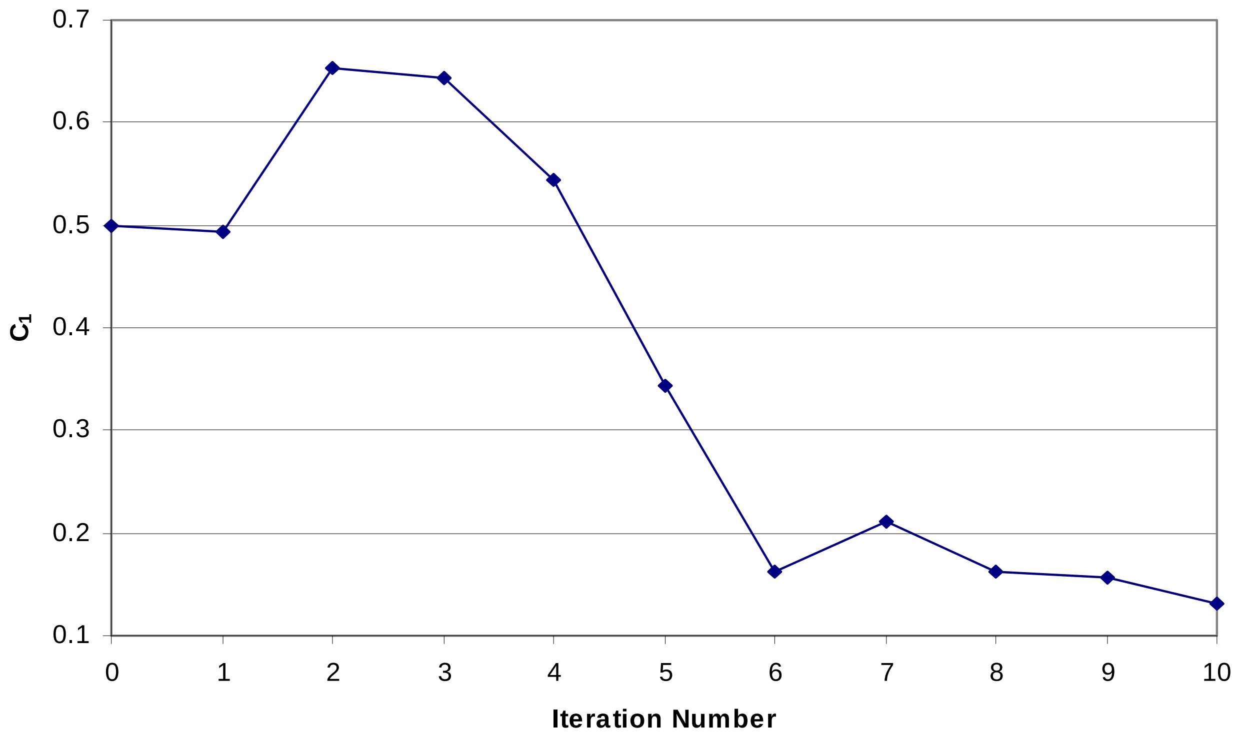


Figure 5-5 (continue) Iteration History of Objective Function and Design Variables

5.4 Different Optimization Method

DOT, used in the MDO project as our optimization tool, provided three optimization methods for the constrained optimization problem:

- MMFD: Modified Method of Feasible Direction
- SLP: Sequential Linear Programming
- SQP: Sequential Quadratic Programming

All these methods are usable in the project. To investigate the efficiency of each method, we should first have a look at the termination criteria used in DOT to terminate the optimization process. As mentioned before, DOT is a numerical optimization tool. The termination of the optimization process in DOT is determined by the numerical behavior of the objective function and the searching direction vector.

There are several termination criteria used by DOT:

1. Convergence Criteria:

The optimum is usually approached asymptotically during the optimization process. Therefore, continued iterations are not justified while some small progress of the objective function is still being made. Two criteria are used for this case. The first is that the relative change in the objective function between iterations is less than a specified tolerance, DELOBJ. Thus, the criterion is satisfied if:

$$\frac{\left|F(X^{i}) - F(X^{i-1})\right|}{\left|F(X^{i-1})\right|} \leq \text{DELOBJ}$$

Where i indicates the iteration number. The default value for DELOBJ is 0.001.

The second criterion is that the absolute change in the objective function between iterations is less than a specified tolerance, DABOBJ. This criterion is satisfied if:

$$\left|F(X^{q}) - F(X^{q-1})\right| \leq \text{DABOBJ}$$

The default value for DABOBJ is the maximum of $0.001|F(X^0)|$ and 0.0001, where $F(X^0)$ is the value of the objective function at the starting point.

2. Gradient of Objective Function

An important criterion to judge whether a point is a local optimum for a constrained optimization problem is to check whether it satisfies the Kuhn-Tucker necessary condition. The Kuhn-Tucker condition states that the gradients of the objective function should vanish at the local optimum. Considering the Kuhn-Tucker necessary condition, DOT terminates the optimization process if all components of the gradient of the objective function are less than 0.001.

3. Feasible Solution

If the initial design is infeasible, the first step in the optimization is to find a feasible solution. However, this may not be possible if there are conflicting constraints. Therefore, if a feasible design has not been achieved in 20 iterations, the optimization process is terminated in DOT.

4. Maximum Iterations

Since the optimization problem is solved by an iterative process using a numerical optimization tool, a maximum iteration counter is included in the control parameters of DOT. The default value is 100 iterations.

The most common termination criteria that are met in the MDO project are the convergence criteria. This means that most of the time, the optimization process is terminated just because the objective function is making little progress at the stopping point. It can not ensure that we have reached a local minimum point. The best way to check whether the stopping point is a true local optimum point is to start the optimization process again from the stopping point. If it remains at the same point as it stopped last time, it is a local minimum point.

Based upon this, the efficiency of the different optimization methods is judged on whether it always gives us a true local minimum point. Table 5-3 shows the result from the three different optimization methods used by DOT. The upper and lower bounds for the design variables are the same as the realistic bounds shown on Table 5-2.

Table 5-3 Optimization Using Different Methods

Method	RFR ($/t/nm)	L_{oa} (m)	B (m)	D (m)	T (m)	Vk (kn)	C_1
Case 1 Starting from the middle of the design space							
MMFD	0.001109	300.000	41.822	15.112	10.092	17.263	0.4461
SLP*	0.001105	300.000	41.527	15.569	9.775	17.236	0.0639
SQP	0.001112	300.000	42.309	15.182	10.410	17.716	0.6298
Case 2 Starting from the stopping points by different method in Case 1							
Case 2.1 Starting from the stopping points given by MMFD							
MMFD	0.001108	300.000	41.491	15.016	9.967	17.173	0.3824
SLP	0.001106	299.963	42.136	15.653	10.015	17.642	0.2257
SQP	0.001108	300.000	41.678	15.071	10.080	17.560	0.4384
Case 2.2 Starting from the stopping points given by SLP							
MMFD	0.001105	300.000	41.722	15.707	9.808	17.185	0.0531
SLP	0.001106	300.000	42.544	16.232	9.987	17.782	0.0500
SQP	0.001105	300.000	41.552	15.606	9.781	17.237	0.0586
Case 2.3 Starting from the stopping points given by SQP							
MMFD	0.001107	299.994	40.089	14.370	9.651	17.147	0.3023
SLP	0.001106	299.982	40.767	14.967	9.659	16.964	0.1454
SQP	0.001106	300.000	40.045	14.545	9.537	17.110	0.1606

*: Local minimum point

From Table 5-3, we can see that the first stopping point using SLP starting from the middle of the design space is the local minimum point. Actually, as pointed out in Section 5.1, this local minimum point is the global minimum point within the design space. Starting the optimization from this point again, the value of the objective function, required freight rate, stays the same using MMFD and SQP. The values of the design variables only change a little bit.

When using SLP again starting from that point, the value of the required freight rate increases a little. The starting point is a feasible point where all constraints are satisfied. When the optimization moves away from the starting point, it goes into an infeasible design point where the equality constraint for displacement and weight is violated. The optimization can not go back to the starting point when it adjusts the design variables to satisfy this equality constraint. It ends at another feasible point whose value of objective function is slightly bigger than that of the starting point. Again, it proves that the starting point is a true local minimum point.

Using a different starting point gives similar results. Therefore, SLP is the most efficient method to be used in the MDO project.

5.5 Basis Ships

Basis ships are the "parent hulls" used in the geometric blending method. They have a great influence on the resultant ship hull. Six basis ships are chosen in the MDO project. To evaluate the performance of every basis ship, we run the optimization process using each single basis ship. The results are shown in Table 5-4 where RFR is the required freight rate. The lower and upper bounds of the design variables are the same as those used in Table 5-1. The unrealistic bounds of the design variables enable us to fully investigate the behavior of the different basis ships. From the results, we can see that basis1 is the best ship and basis14 is the worst ship in the eyes of the optimizer.

The fact that the optimizer favors basis22 over basis 14 agrees with the discussions in the previous sections. In the previous section where we only use two basis ships, basis14 and basis22, the optimum value of C_1, the geometric blending factor for the first basis ship, which is basis14, tends to go to zero. This means that the optimizer favors the second basis ship, basis22. Therefore, the optimizer considers basis22 is a better ship than basis14.

Table 5-4 Evaluation of Basis Ships

Basis Ship	1000RFR ($/t/nm)	Loa (m)	B (m)	D (m)	T (m)	Vk (kn)
Basis1	0.900778	868.369	73.822	27.898	14.598	21.813
Basis11	0.903265	802.521	67.742	25.866	13.707	20.985
Basis22	0.912946	797.410	66.382	27.162	13.912	20.398
Basis142	0.923945	821.260	70.054	26.410	14.762	21.700
Basis2	0.930341	810.693	68.883	26.240	14.804	21.167
Basis14	0.939383	805.551	81.623	27.579	16.123	23.295

Table 5-5 Optimization Using Different Methods

No	Basis Ships			1000RFR ($/t/nm)	Geometric Blending Factor for Basis Ship					
	I	II	III		1	11	22	142	2	14
1	1	11	22	0.900509	0.7494	0.2506	0	----	----	----
2	1	11	142	0.900729	0.6854	0.3146	----	0	----	----
3	1	11	2	0.901804	0.6271	0.3729	----	----	0	----
4	1	11	14	0.901663	0.9285	0.0715	----	----	----	0
5	1	22	142	0.901341	0.8038	----	0.1958	0.0004	----	----
6	1	22	2	0.901294	0.9996	----	0.0004	----	0	----
7	1	22	14	0.901435	0.9951	----	0.0049	----	---	0
8	1	142	2	0.900094	0.9993	----	----	0.0007	0	----
9	1	142	14	0.900256	1	----	----	----	0	0
10	1	2	14	0.900231	1	----	----	0	----	0
11	11	22	142	0.904374	----	0.8169	0.1831	0	----	----
12	11	22	2	0.902886	----	0.9963	0.0037	----	0	----
13	11	22	14	0.903510	----	0.9566	0.0434	----	----	0
14	11	142	2	0.903210	----	1	----	0	0	----
15	11	142	14	0.903252	----	0.9225	----	0.0266	----	0.0509
16	11	2	14	0.902730	----	0.9753	----	----	0	0.0247
17	22	142	2	0.913165	----	----	0.9889	0.0111	0	----
18	22	142	14	0.912956	----	----	0.9920	0	----	0.0080
19	22	2	14	0.913405	----	----	0.8010	----	0.0370	0.1620
20	142	2	14	0.923886	----	----	----	0.6189	0.1045	0.2766

To investigate the influence of different basis ships on the final optimum ship, different combinations of three basis ships are used in Table 5-5. From the optimization results, we can see that the optimizer always favors the best basis ship. For example, in Case No 8, we use basis1, basis142 and basis2 as our three basis ships, in which basis1 is the best basis ship. For the final optimum ship using these three basis ships, the geometric blending factors are 0.9993 for basis1, 0.0007 for basis142 and zero for basis14. This shows that the shape of the final optimum ship is mostly controlled by basis1. This shows that the behavior of the optimization agrees with the idea of the geometric blending method. We want the optimization to give us the best combination of the different basis ships.

On the other hand, we also can see that the optimum ship using three different basis ships is not better than that using one single basis ship, shown in Table 5-4. The slight decreases in the objective function value of some cases from those of using only one single basis ship are caused by the numerical noise. These slight improvements of the objective function do not demonstrate that using different basis ships is better than using only one basis ship. The reason this happens is that the differences in basis ships are not big enough to let the optimizer take full advantage of the different shapes of the basis ships. The optimum basis ship may be better than any one of the basis ships if we have much more difference between the basis ships.

Chapter 6 Summary and Future Work

6.1 Summary

The goal of the MDO project is to develop a software package that gives the best ship design using the optimization technique. The task is assigned to the Department of Aerospace and Ocean Engineering at Virginia Polytechnic Institute and State University. A container ship design is chosen as a test case. The objective function for optimization is to minimize the required freight rate of the ship. Science literature has been searched to get a clear view of the recent technical developments.

The package includes an optimization module, a geometric module and a performance evaluation module. The Design Optimization Tools (DOT) from Vanderplaats Research and Development, Inc. is chosen as the optimization module. The geometric blending technique is used to give a smooth ship hull form using NURBS expression based on basis ship hulls. The performance evaluation module calculates resistance, stability, container capacity, ship weight, building cost, operation cost and the required freight rate of the ship. Holtrop and Mennen's method is used for the resistance estimate. A new method for estimating the container capacity is developed. The wind heel criteria from the US Coast Guard is used for the initial stability check. Some empirical formulae are used for weight and cost calculation.

The optimization problem has been carefully formulated to give a stable solution. The design variables are chosen after careful inspection of every module. The constraints are based on the performance requirements. The objective function is normalized with respect to its initial value. The design variables are scaled using the scaling factor defined by DOT.

From the results of the optimization, we have conclusions as follows:

- We have only one global minimum point within our design space.
- The required freight rate is very insensitive to the geometric blending factor
- The optimum container ship tends to be as big as possible.
- SLP is the most efficient optimization method to be used in the MDO project.

- The optimizer favors the best basis ship.

6.2 Future Work

- Use more different basis ships
- Add structural analysis into the optimization
- Use NAVCAD for resistance calculations
- Apply strip method for seakeeping calculations
- Develop a graphical user interface
- Integrate the MDO project into the FIRST system

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