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Spreadsheet Modeling to Determine Optimum Ship Main Dimensions and Power Requirements at Basic Design Stage

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The objective of this paper is to describe and evaluate a scheme of engineering-economic analysis in determining optimum ship main dimensions and power requirements at the basic design stage. An optimization model designs the problem and is arranged into five main parts, namely, Input, Equation, Constraint, Output and Objective Function. The constraints, which are the considerations to be fulfilled, become the director of this process and a minimum and a maximum value are set on each constraint so as to give the working area of the optimization process. The outputs (decision variables) are optimized in favor of minimizing the objective function. Microsoft Excel-Premium Solver Platform (PSP), a spreadsheet modeling tool is utilized to model the optimization problem. The first part of this paper contains a description on general optimization problems, followed by model construction of the optimization program. A case study on the determination of ship main dimensions and its power requirements for a tanker is introduced with the main objective being to minimize the economic cost of transport (ECT). After simulating the model and verifying the results, it is observed that this method yields considerably comparable results with the main dimensions and power requirement database of the real operated ships (tanker). It is also believed that this process needs no painful and exhaustive efforts to produce the programming code, if the problem and optimization model have been well defined.

1. Introduction

THE design process of ships and their machinery is a highly intensive task. Frequently, during this design process, different design configurations have to be calculated before an "optional" one is found. Prompted by higher demands on effective use of resources in general, it is thus very convenient to have access to an optimization program that allows a quick, simple, as well as reliable calculation in designing a ship's main dimensions and power requirements, and at the same time obtain an estimation of the associated costs.

The problem in designing optimum ship and marine machinery, however, appears to be due to the great number of considerations that must be taken into account. This problem becomes even heavier with the development of the machinery systems on board, in terms of the complexity and number of components. This condition clearly increases the capital cost and the complexity of the design option. Consequently, the decision on a ship's design and its selected machinery must guarantee that the ship and its machinery will operate with a low level of failure, safely and efficiently, with high level of availability and at the end of the time will deliver an optimum rate of return on the capital being employed. In more general terms, precision in designing a ship's main dimensions and its marine machinery would, therefore, be one of the most critical points in achieving reliable ship operation [1,2].

The techno-economic evaluations are often used to assess the suitability of alternative technical solutions of marine machinery for ships. An extensive review of such research has been proposed by Thorp & Armstrong [3]. They utilized a comprehensive method in selecting the machinery arrangement for a Panamax-size bulk carrier of 70 000 dwt and the assessment is focused on the two general alternatives of slow-speed diesel installation and medium-speed diesel installation. Some of the parameters included in their study will also be taken in this study. One main distinguishing difference with this study is that it takes the design problem at the basic design process, which allows the optimization process to determine the optimum ship's main dimensions and its related machinery characteristics within the given constraints.

Suich & Patterson [4] delivered an interesting report concerning the method on minimizing the cost by choosing the optimal subsystem on a general machinery system using the expected value concept. This probability approach has a weakness in how much we can guarantee that the selected assumptions will be exactly consistent with the real condition. For that reason, the optimization scheme presented here is developed to be able to accommodate input from real data analysis and empirical formula.

This paper addresses an alternative process in optimizing marine design, particularly on the determination of a ship's main dimensions and its power requirements at the basic design stage. Spreadsheet modeling is adopted here and nonlinear programming (NLP) expresses the problem. The optimization will be performed using Premium Solver Platform (PSP), and the generalized-reduced gradient (GRG) method is chosen to work in conjunction with the NLP problems. The next part of this paper is organized as follows. Section 2 describes the PSP and the basic optimization model, while Section 3 presents the description of the optimization problem along with a way to convert the problem into a spreadsheet model. Description is then drawn to the analysis of the model including the sensitivity analysis in Section 4. The end of this paper delivers conclusions and some general comments on the proposed method.

2. The PSP and the basic optimization model

General design problems involve more than one criterion, some or all of which may be in conflict and constrained by scarce resources and some functional requirements. The determination of the ship's main dimensions and its machinery

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power requirements also encounters many constraints and considerations in its synthesized process [5]. The main idea of the optimization of ship design and its machinery is then to resolve the conflicts of a decision situation in such a way that the variables under the control of the decision-maker take their best possible value, and the optimum value is achieved when the working area of the optimization problem is satisfied.

A number of methods are available to solve the multi-constraints and multi-variables optimization problem as summarized by Rao [6]. This paper will not discuss in length the mathematical background behind the optimization program; however, the main purpose here is to introduce an alternative optimization process, which could be used during the basic design stage of ships and marine machinery.

Generally, a classic multiple constrained optimization problem can be represented as follows.

$$\text{find } X = \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{Bmatrix}, \text{ which minimize/maximize } f(X) \quad (1)$$

Subject to constraints

$$g_{(lb)i} \leq g_i\,(X) \leq g_{(ub)i} \quad \text{for } i = 1,2,3,\ldots\ldots.,m \quad (2)$$

$$X_{(lb)j} \leq X_j \leq X_{(ub)j} \quad \text{for } i = 1,2,3,\ldots\ldots.,p \quad (3)$$

where lb and ub stand for lower bound and upper bound, respectively, X is a vector of j variables and the function $g_i, \ldots g_m$ all depend on X.

As mentioned before, this paper will employ the Microsoft Excel-PSP software to deal with the above general expression of the optimization problem. The PSP combines the function of a Graphical User Interface (GUI), an algebraic modeling language and optimizer for linear, nonlinear, and an integer program. Each of these functions is integrated into the host spreadsheet program, which allows us to specify an objective function and constraints and other supporting features interactively. Moreover, because of the architecture of spreadsheet programs, it is easy to create spreadsheet models that contain discontinuous functions of even nonnumeric values. These models usually cannot be solved with classical optimization methods. The model construction process is eased with the existence of a rich variety of operators and several hundred built-in functions, as well as user-written functions within the PSP. The PSP then analyzes the complete optimization model and produces the matrix form required by the optimizers. The optimizers themselves employ the simplex (for LP model), generalized-reduced gradient (for NLP), and branch and bound methods to find an optimal solution and sensitivity information. For the LP problem, the focus of the model representation is the LP coefficient matrix. This is the Jacobian matrix of partial derivatives of the objective function and constraints with respect to the decision variables. In LP problems, the matrix entries are constant and need to be evaluated only once at the start of the optimization. On the other hand, in NLP problems, the Jacobian matrix entries are variable and must be recomputed at each new trial point.

For an LP, the PSP uses a straightforward implementation of the simplex method with bounded variables to find the optimal solution. In the case of an NLP, as particularly adopted in this paper, the PSP utilizes the generalized-reduced gradient method (GRG), as implemented in the GRG2 code [7,8]. This requires function values and the Jacobian matrix, which is not constant for NLP models. The PSP approximates the Jacobian matrix using the finite difference method.

The GRG algorithms, introduced by Abadie & Carpentier [9] are widely used to solve small- to medium-sized problems, mainly through the FORTRAN codes GRG2 [7] and OPT [10], and the interpretive PC-based system GINO [11]. Optimization problems that can be solved by using GRG algorithm, are usually written in the following form:

$$\begin{array}{ll} \text{Minimize} & g_{m+1}(X) \\ \text{subject to} & \\ g_i(X) = 0 & i = 1,\cdots, neq \\ 0 \leq g_i(X) \leq ub(n+i) & i = neq+1,\cdots, m \\ lb(i) \leq X_i \leq ub(i) & i = 1,\cdots, n \end{array} \quad (4)$$

where X is a vector of n variables. The number of equality constraints, neq, may be zero. The function g_i is assumed differentiable. Equations (4) are then converted to the following equality form by adding slack variables $X_{n+i}, \cdots, X_{n+m}$, and the new equation would be:

$$\begin{array}{ll} \text{Minimize} & g_{m+1}(X) \\ \text{subject to} & \\ g_i(X) - X_{n+1} = 0 & i = 1,\cdots, m \\ lb(i) \leq X_i \leq ub(i) & i = 1,\cdots, n+m \\ lb(i) = ub(i) = 0 & i = n+1,\cdots, n+neq \\ lb(i) = 0 & i = n+neq,\cdots, n+m \end{array} \quad (5)$$

These last two equations are the bounds for the slack variables. The variables $X_i, \ldots X_n$ are called natural variables. Let $\overline{X}$ satisfy the constraints of equation (4), and assume that nb (basic variable) of the g_i constraints are binding at $\overline{X}$. A constraint g_i is taken as binding if

$$|g_i - ub(n+i)| < \in \quad \text{or} \quad |g_i - lb(n+i)| < \in \quad (6)$$

The tolerance $\in$ is one of the most critical parameters and it usually takes a value of 10^{-4}. Let y be the vector of nb basic variables and x the vector of n non-basic variables, with their values corresponding to $\overline{X}$ denoted by $(\overline{y},\overline{x})$. Then the binding constraints can be written

$$g(y,x) = 0 \quad (7)$$

where g is the vector of nb binding constraint functions. The basic variables must be selected so that the nb-by-nb basis matrix B $= (\partial g_i/\partial y_i)$ is nonsingular at $\overline{X}$. Then the binding constraints (7) may be solved for y in terms of x, yielding a function $y(x)$ valid for all (y, x) sufficiently near $(\overline{y},\overline{x})$. This reduces the objective to a function of x only

$$g_{m+1}(y(x),x) = F(x) \quad (8)$$

and reduces the original problem to a simpler reduced problem

$$\begin{array}{ll} \text{Minimize} & F(x) \\ \text{subject to} & l \leq x \leq u \end{array} \quad (9)$$

where l and u are the bound vectors for x. The function $F(x)$ is called the reduced objective and its gradient, $\nabla F(x)$, the reduced gradient. Eventually, the original problem (4) can be solved by a sequence of reduced problems using the gradient method [7]. We can see that the optimization problem, which is represented by equations (1–3), has the same structure as equation (9), and can be solved by using the GRG algorithm.

The basic format of the offered optimization model is given as shown in Fig. 1. The model consists of five folders namely Input, Equation, Constraint, Output, and Objective function. The Input folder consists of all parameters that are used in the entire optimization process. Those parameters can be classified into several directories to make the fault identification easier and the relationship between each directory understandable.

All basic calculations of the optimization process are located in the Equation folder. The results of each equation are continuously updated since the process in the Constraints

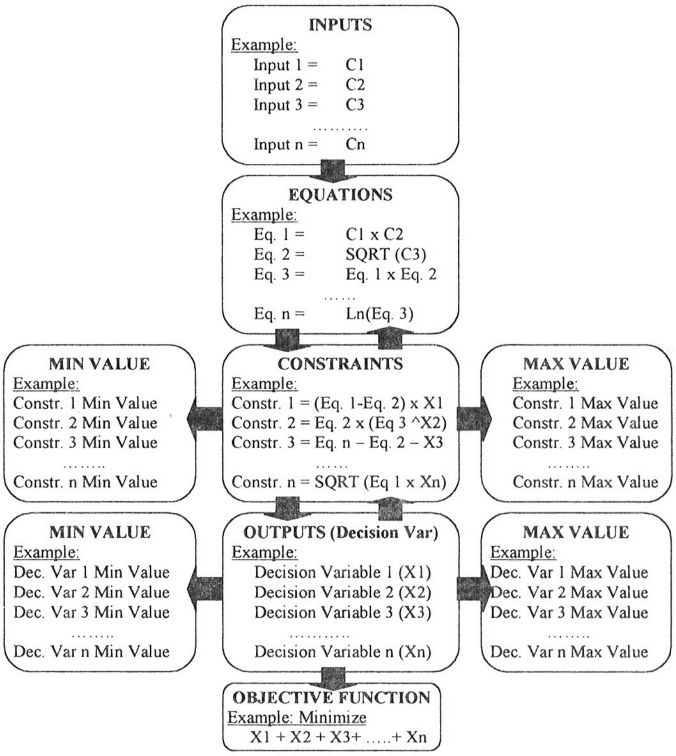


Fig. 1 Basic format of optimization process

folder and the Output folder always affect the variables employed in the Equation folder.

The Constraints folder, which is the collection of considerations to be fulfilled, becomes the director of this optimization process. A minimum and a maximum value are set to each constraint to give the working area of the optimization process and the optimum values are located in the center of the form. Determination of the minimum or maximum value absolutely depends on the characteristics of the constraints. Some of them can be logically adopted from the "rules of thumb," such as the range of the length-beam ratio of a tanker for a specific capacity range, or the power allowance factor of the main engine for a certain route.

The Output folder in many respects has nearly the same characteristics as the Constraint folder, except that each output is composed by a decision variable (optimization result); on the other hand the constraints consists of equations that employ parameters from the Input folder. The maximum and minimum values are also set on each output to guide the optimization process.

All optimization methods have the same pattern in which they are formed to find either a maximum or a minimum solution of the objective function. The goal of this optimization program is to minimize the economic cost of transport (ECT) of the ships, while fulfilling the constraints. There are several strategies for transferring the model into spreadsheet form. Ragsdale [12] and Monahan [13] can be referred to for detailed information on this matter.

3. Basic design optimization process for tanker with specified throughput

Problem statement

At the basic design stage, it is required to design a certain number of identical ships (tanker), which have optimum main dimensions and optimum specified power, and then are used to serve a crude oil delivering contract of a certain throughput. The outcome of the minimum ECT is utilized as the objective function of the optimization problem. In other words, the minimum ECT must be obtained to guarantee that the optimum design is achieved. The tanker will be used to serve a certain route having a distance of 1600 (optional) nautical miles with no intermediate port. Port characteristics require such constraints as the ship must not exceed a length of 200 m and a draft of 11 m. The general scheme of the conceptual problem is shown in Fig. 2. Some economic data inputs that are employed during the optimization process are shown in Table 1.

Model structure

As mentioned in Section 2, in favor of making the optimization problem easier, it is suggested to divide the input and equation folder into several directories. In this particular optimization problem, the Input folder covers: ship data, machinery data, reliability data, voyage data, economic data, annual adjustment factor, cargo unloading data, and cargo loading data. Each directory represents a collection of parameters to be used in the calculation process.

The Equation folder consists of several directories such as ship coefficient, machinery, reliability (Weibull-based distribution for main engine only), loading and unloading, fuel, operating cost and economic considerations. The Constraint folder comprises expected replacement cost, reliability index, unloading pump capacity, SFOC for main engine (ME) and auxiliary engine (GE), cargo handling rate, percentage of the required BHP, required freight rate, L/B ratio, and maximum allowable ship length in port. The Output folder produces an optimum preventive maintenance interval, block coefficient, optimum design draft, optimum specified BHP, service speed, propeller rpm, number of shore connection units, B/T ratio, and number of required ships. These values are sought with the main objective to minimize the ECT of the ship that consists of several variables, namely required freight rate (RFR), inventory cost of cargo and annual tons of cargo carried (ATC) [14]. The optimum value of RFR itself depends on annual capital recovery of the vessel cost, annual

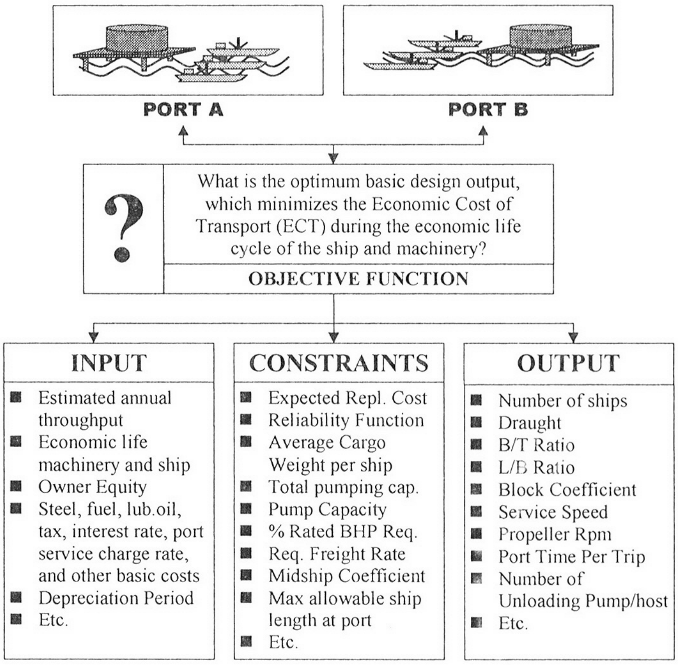


Fig. 2 Problem statement

Table 1 Economic data input

Input	Unit	Value
Economic life of machinery	Years	20.00
Loan repayment period	Years	20.00
Interest rate	%	0.10
Rate of return on equity	%	0.12
Economic life of ship	Years	20.00
Ship depreciation period	Years	15.00
Machinery depreciation period	Years	15.00
Tax rate	%	0.30
Annual inflation rate	%	0.01
Average fuel price (HFO/DO)	$/lb.	0.08
Average crew cost per month	$/month	1,250.00
Average LO price (ME/GE)	$/ton	750.00
Steel cost	$/ton	493.70
Labor rate	$/man-hours	16.67
Average port cost	$/GRT	25.00
Average insurance cost	$/ton	0.40

* source: mainly obtained from Ref.[14]

operating cost, and the annual throughput [15]. If we further trace the constituents of the ECT, then we can figure out the interdependency of the associated variables. One example is shown in Fig. 3. This figure shows that the relationship between each design consideration is very strict and, of course, the result of one process or sequence directly affects the results of the succeeding and foregoing process. Furthermore, it is obvious that an engineering design process becomes more and more difficult when economic factors are taken into account. For instance, it might not be a simple task to relate the optimum number of shore connections, which must be fitted on a tanker with the resulted RFR or outcome of the loan repayment scheme of a certain ship design. However, it is believed that those variables somehow interconnect and affect each other. Hence, the basic nature of a ship and its machinery design optimization process would lay on the ability of the designer to accommodate all of the design considerations, and the provision of adequate flexibility to alter the decision variables while fulfilling the main objective of the optimization process.

Figure 4 shows the general structure of this optimization program. First, the initial value of the decision variables is set. Using relevant basic parameters located in the Input folder, all calculations are executed in the Equation folder. The results are exported to the Constraint folder to calculate all constraints accordingly. After the maximum and minimum values of each constraint verify the result, the Objective function is executed and verified as to whether the new objective function value is less than or bigger than the previous one (depends on the maximization or minimization). This process is repeated until the global maximum or minimum value is obtained.

The optimization problems for the determination of optimum ship main dimensions and power requirements itself can be mapped as shown in Table 2. The objective function is to minimize $f(X)$, which is the ECT while determining the optimum value of X_1 to X_{12} subject to constraint $g_1(X)$ to $g_{16}(X)$. Around 278 basic and dependent equations including a number of polynomials composed the model through folders and directories as mentioned above. The basic ship design and ship resistance formulas are mainly taken from references [16–19] and the economic parameters and major assumptions related to cost calculation are taken from references [14 and 20]. The optimization results are obtained by solving each model several times with various decision variable's initial values, while keeping constant the maximum and minimum value of the constraints. If the optimization

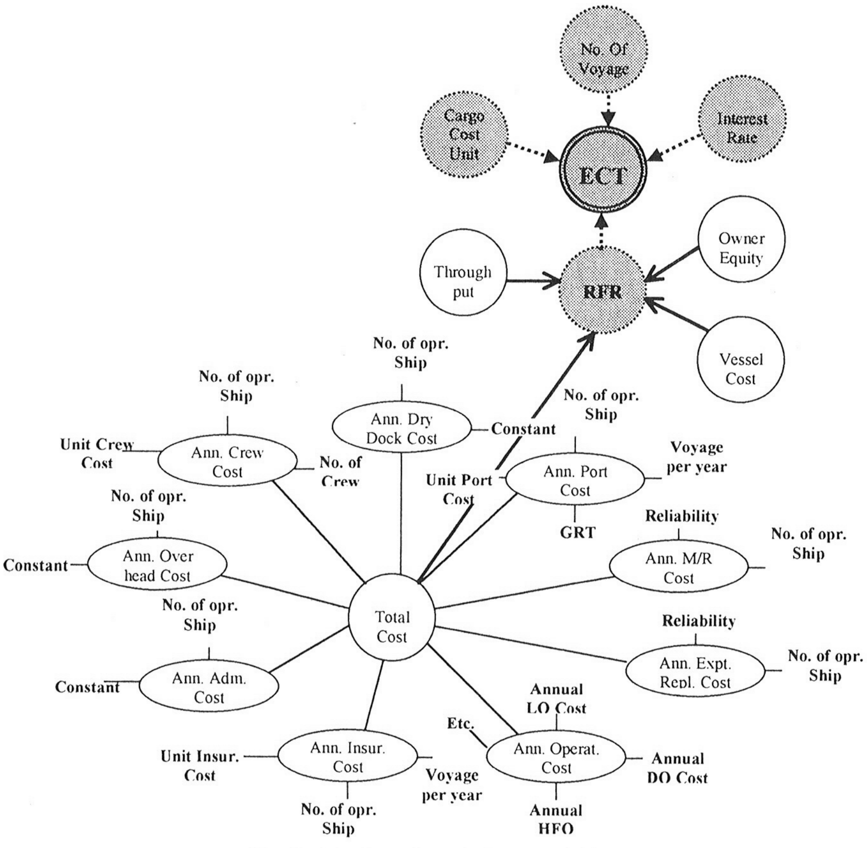


Fig. 3 Interdependency between variables

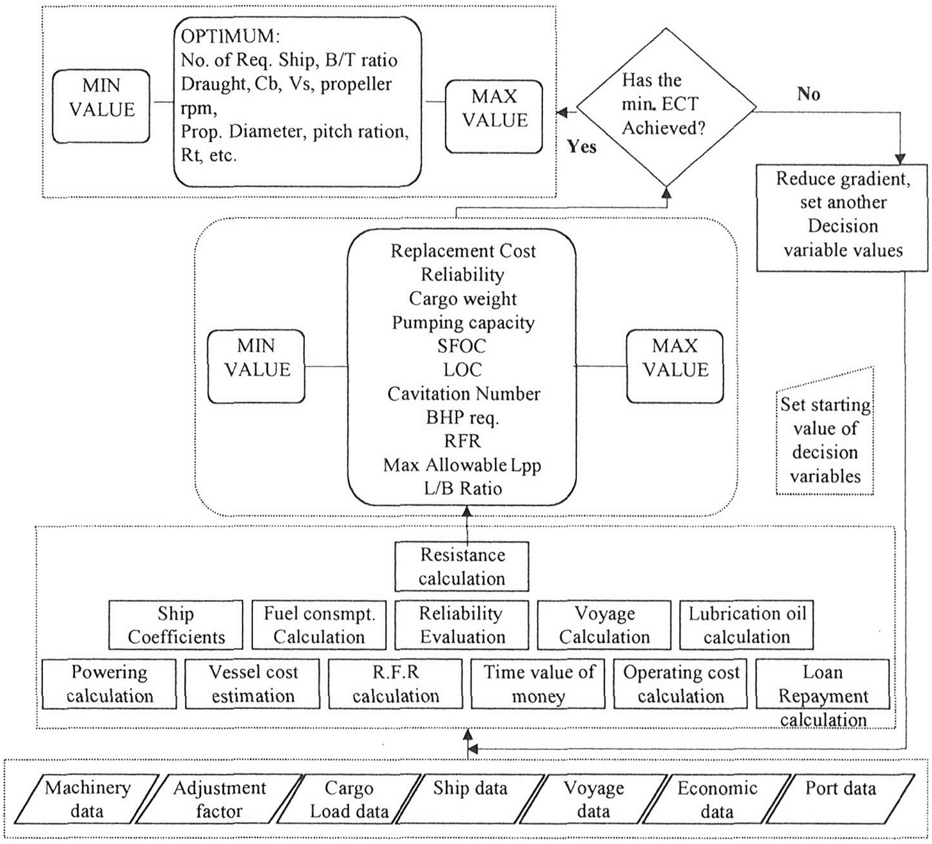


Fig. 4 Structure of optimization model

results remain the same, then we can consider that the optimization program is stable. When the first message, "Solver found a solution" appears, it means that the optimal solution has been found. This convinces us that there is no other set of values for the decision variables close to the current value, which yields a better value for the objective. In other words, we found a peak if maximization, or valley if minimization.

During model construction process, the most frequently encountered problem is the inability of the PSP software to execute the problem due to the existence of the cyclic equation (circular reference). This is probably a common phenomenon when a huge number of equations are employed in the model. The best way to solve such a problem is by tracing down each equation that forms the cyclic/circular calculation, and then, if possible, take one of the variables as the constraint or output of the model being optimized.

Further description of directories

The Input folder of the model consists of several given parameters that are grouped into different directories. The ship data directory takes the cargo density of 915 kg/m^3. The appendages factor, which influences the resistance calculation, is assumed to have value of 0.03. This directory also allocates the need to use a reduction gear for engine speed reduction. The Machinery Data directory allows the alternative of using either a single main engine or multiple main engines. The model also provides the flexibility of employing the number of generator sets. In terms of the machinery, this specific tanker design model is only focused on the determination of the main engine and the generator set. Their reliability model is assumed to be represented by the Weibull distribution, and its related parameters (γ, β, η) must be defined accordingly. Since the Weibull distribution is appropriate for the component/engine during its wear-out-period, Weibull analysis is used in order to find the best period/interval of carrying out the maintenance program. The cost of failure replacement and the cost of preventive replacement are also assumed before the optimization process can be executed [21,22]. Bearing in mind that the ships are still in the design process, then total knowledge of the reliability aspects of the main engine is not yet available. For that reason, some tangible aspects in the determination of the maintenance and replacement policy, such as MTBF, MTTR, failure rate, and reliability parameters, can be estimated only from failure data concerning machines working in other ships under more or less similar operating condition. In this particular paper, such data are obtained from reference [23]. The Voyage Data directory is one of the vital directories in the optimization model. Optional trip distance and number of intermediate ports make the model flexible. The assumed outbound and inbound load factors allow the model to be more realistic. Moreover, to determine the number of voyages per year, we must assume the duration required for annual docking days and unscheduled maintenance in advance.

The Economic Data directory and their related values, as shown in Table 1, are gathered from many different sources and play a very important role within the optimization model. The annual adjustment factor provides a more realistic calculation of the operating cost. This allows the annual increase of the operating cost component to be taken into account. The loading and unloading data are mainly used during the determination of port time and cargo pump capacity.

The Equation folder is also divided into several directories. The Coefficient and Ship directory collects all equations for determining the main dimensions of the ship. Since the related equations usually stand as empirical formulas, then the interpolation process comes into play when the required ship

Table 2 Optimization statement

Find					
X_1	Min value	≤	Time (t) independent variable	≤	Max. value
X_2	Min value	≤	Number of ships	≤	Max. value
X_3	Min value	≤	Draught	≤	Max. value
X_4	Min value	≤	B/t ratio	≤	Max. value
X_5	Min value	≤	Block coefficient	≤	Max. value
X_6	Min value	≤	Service speed	≤	Max. value
X_7	Min value	≤	Propeller rpm	≤	Max. value
X_8	Min value	≤	Diameter propeller	≤	Max. value
X_9	Min value	≤	Pitch ratio	≤	Max. value
X_{10}	Min value	≤	Time required for preventive replacement	≤	Max. value
X_{11}	Min value	≤	Port time per trip (loading)	≤	Max. value
X_{12}	Min value	≤	Number of unloading pump/host	≤	Max. value
Which minimizes: Economic Cost of Transport (ECT) (f(X))					
RFR	Total cost		Annual port cost *f* (unit port cost, grt, voyage per year, no. of operated ship)		
			Annual insurance cost *f* (voyage per year, weight of cargo, unit insurance, no. of ship)		
			Annual overhead cost *f* (constant, no of ship)		
			Annual crew cost *f* (unit of crew cost, no. Of crew, no. of ship)		
			Annual expected replacement cost *f* (reliability, no. of ship)		
			Annual M/R cost *f* (reliability, no. of ship)		
			Annual dry docking expenses *f* (constant, no of ship)		
			Annual administration cost *f* (constant, no of ship)		
			Annual operating cost *f* (lo cost, do cost, hfo cost, etc)		
	Owner equity		Constant		
	Throughput		Given		
Cargo cost unit			Constant		
Number of voyage			Operating day *f* (docking days, unscheduled maintenance days, time at port)		
			Turn round time		
Interest rate			Constant		
Subject to					
$g_1(X)$	Min value	≤	Expected replacement cost, *f*(Reliability index, Cost of fail. .rep, Cost of Prev. rep)	≤	Max. value
$g_2(X)$	Min value	≤	Reliability function, *f*(failure distribution parameters)	≤	Max. value
$g_3(X)$	Min value	≤	Ave. cargo weight per ship, *f*(throughput, No. of ship, voy. per year, Load factor)	≤	Max. value
$g_4(X)$	Min value	≤	Total pumping capacity, *f* (Pump capacity, No. of req. pump)	≤	Max. value
$g_5(X)$	Min value	≤	Pump capacity *f* (Cargo weight, Port time, Cargo density)	≤	Max. value
$g_6(X)$	Min value	≤	SFOC for full load ME *f* (DHP, engine rpm)	≤	Max. value
$g_7(X)$	Min value	≤	SFOC for full load GE *f*(DHP, diesel generator rpm)	≤	Max. value
$g_8(X)$	Min value	≤	Cavitation number *f*(THP, Projected Blade Area (Ap), dynamic pressure at tip radius)	≤	Max. value
$g_9(X)$	Min value	≤	Local cavitation number *f*(press. at the screw centerline, dyn.pressure at tip radius)	≤	Max. value
$g_{10}(X)$	Min value	≤	% Rated BHP requirement *f* (min. resulted SFOC at feasible region)	≤	Max. value
$g_{11}(X)$	Min value	≤	Required freight rate *f* (Ann. Vessel cost, total opr. Cost, throughput)	≤	Max. value
$g_{12}(X)$	Min value	≤	Midship coefficient *f* (Displacement, Breadth, Draught, Lpp)	≤	Max. value
$g_{13}(X)$	Min value	≤	L/B ratio *f* (Lpp/Breadth)	≤	Max. value
$g_{14}(X)$	Min value	≤	Max allowable ship length at port *f*(Vol. Displ, Breadth, Draught, Block coef.)	≤	Max. value
$g_{15}(X)$	Min value	≤	Length of water line (LWL) *f* (LOA)	≤	Max. value
$g_{16}(X)$	Min value	≤	Length between perpendicular (LPP) *f*(LWL)	≤	Max. value

lies beyond the original range [20]. Determination of ship resistance and power prediction calculations are carried out using Harvald's power prediction method. The estimation of the propeller data and its cavitation prediction are based on the Wageningen B-series propellers [16–18]. The Vessel Cost directory allows us to perform a basic hull cost, outfit cost, machinery cost and estimated overhead cost [14]. These calculations employ many constants taken from many related sources. The SFOC-Speed-Power directory estimates the optimum percentage of rated BHP to be used during the service condition. This estimation is only based on the objective to minimize the SFOC and the appropriate operation condition (speed) of the propeller. The Reliability directory of the equation element determines the failure rate and unreliability of the main engine based on given Weibull parameters. This directory also estimates the expected length of operating hours before failure cycle. The number of voyages per year, which strongly influences the economic cost of transport, takes part in the Trip Per Year directory. However, in order to find an integer number of operated ships, the calculation might generate a noninteger number of voyages per year. A decision must be made whether to accept the optimization results by rounding up or down the number of voyages per year, or simply by altering other parameters to find a more realistic value of the annual number of voyages. The Fuel and Lubricating Oil directory estimates the annual fuel and lubricating oil requirements per year. Since the model does not refer to any particular engine, the calculation is then made empirically. The Operating Cost directory determines the annual operating cost for all required ships. To deal with this estimation, some parameters such as unit of insurance cost, unit of port cost, unit of crew cost and others must be assigned in advance. In this case, the perplexity happens because the determination of precise operating cost constituents that play a major position in the determination of the ECT is quite difficult. The investment scheme also affects the value of optimized ECT. Therefore, the Loan Repayment directory and the Time Value of Money directory are allocated to give flexibility in determining the preferred investment scenario.

4. Analysis

The Appendix shows the summary of optimization results for five different throughputs for a specific distance of 1600 miles. The results of the optimization program provide us with the information concerning the optimum main dimensions and number of ships, operating cost constituents, the investment and loan repayment scheme, and the specified power for the main engine along with the maintenance and repairs scheme including their associated costs, etc.

The ship main dimensions for five different throughputs are obtained as shown in Fig. 5. Its associated cargo carrying capacity and number of voyages per year are also available in the Appendix. Along with them, the associated cost components are also brought about as shown in Figs. 6 and 7. Each combination for each throughput provides the minimum economic cost of transport (ECT) that indicates the competitiveness of the design. Figure 6 also shows that an increase in throughput significantly reduces the escalation of the total estimated annual cost and the operating cost and this is also the case for the ECT and RFR as shown in Fig. 7.

No specific constraint violation has occurred because of the wide range of the maximum and minimum value of the constraints and output. However, when the throughput is set to be 700 000 tons, the upper limit of the cargo carrying capacity is violated. Expanding this maximum value does not directly solve the problem because the maximum port time would then be broken. Increasing the allowable port time might be not a wise solution, since the ECR would also significantly increase. In this case, the remaining alternative is by increasing the maximum cargo pump capacity or adding to the number of cargo pumps. At a glance, the last option is also not a wise solution if there was a limitation on the available space for the additional pump, and moreover this addition would also increase the requirement for maintenance and spare parts.

This kind of trade-off process is a common phenomenon during the optimization process. Again, the sensibility of the design is mainly dependent on that of the input parameter values and correctness of the adopted equations, as well as the constraint range. Additional directories can also be set within the program; for instance, some specific machinery subsystem evaluation can be added within the optimization program.

The Appendix also shows the optimum specified BHP for each model as well as the specific fuel oil consumption for the main engine and the diesel generator. The optimization result also suggests the optimum percentage of rated BHP, in which the main engine preferably operates. Associated propeller main characteristics, i.e., rpm, diameter, and pitch ratio are also obtained. Figure 5 also shows that the existing limitation of draft and maximum allowable ship length at port determines the characteristics of the main dimensions and the number of required ships. These constraints make the optimum draft of the ship for transporting cargo of more than 300 000 tons always binding to the upper limit of 11 meters. By securing the upper limit of the draft, it generates the maximum cargo carrying capacity and eventually reduces the economic cost of transportation (ECT) as sought by the objective function.

Results verification

Considering that we can never be sure about the results of this optimization program, to verify the effectiveness and precision of the program, the optimization results are compared with the BHP, DWT, and T data of about 300 existing tankers. The results are shown in Figs. 8 and 9. We observe that the result of the simulation can gently conform to the real data. Though there is no assurance that the available real data are optimum designs, we can roughly take a point that the model structure can fit with real ship design.

At some points the optimization results drastically shift to a new point (marked by a white circle), and this is apparently caused by any adjustment to the optimization program. For instance, if the throughput is less than 300 000 tons, then we could set the maximum constraint of the cargo carrying capacity at the value of 25 000 tons. Once we increase the throughput, the optimization cannot produce optimum results until we increase the upper constraints of the cargo carrying capacity.

Furthermore, we also compare the optimum number of voyages, the ECT and the RFR, which are obtained from our optimization program, with the one obtained by using RFRSIM [14]. The RFRSIM is a compiled FORTRAN program, which calculates the RFR and ECT when input is expressed as normal or truncated-normal variants. There are 24 basic input parameters that must be employed within the RFRSIM. Several adjustments must be done prior to the optimization using RFRSIM. This adjustment enables the optimum results from the PSP to become the input parameter for the RFRSIM. The major difference between the RFRSIM with

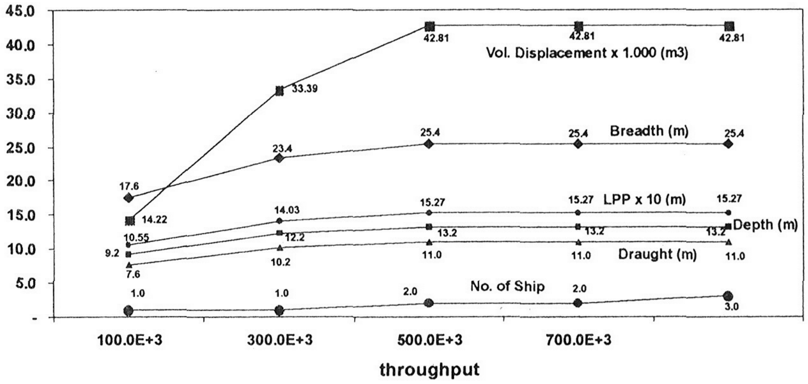


Fig. 5 Optimum ship dimension design for various throughputs

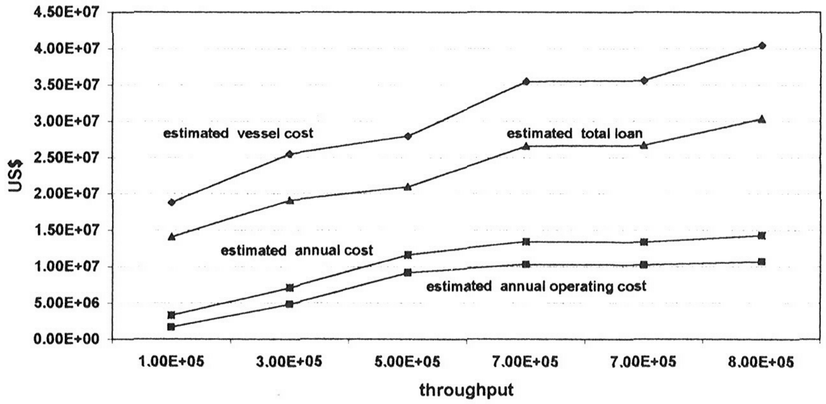


Fig. 6 Optimum composition of cost component for various throughputs

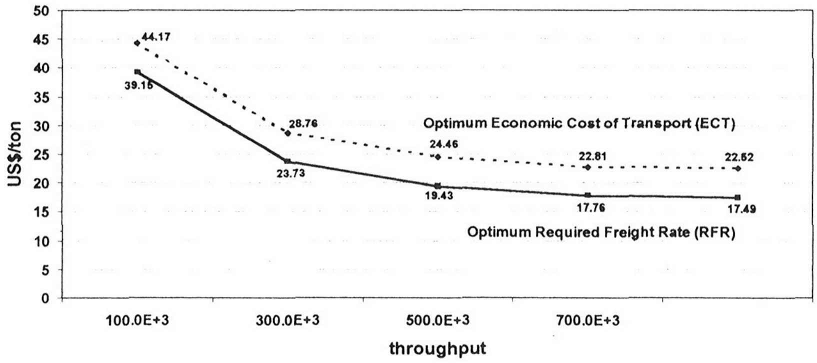


Fig. 7 Optimum RFR and ECT for various throughputs

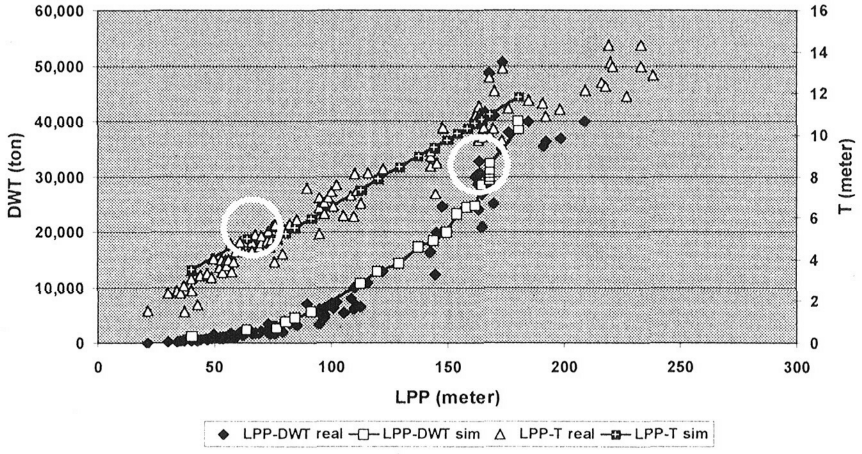


Fig. 8 LPP-DWT and LPP-T verification

our optimization model is that the RFRSIM is using predefined unit capacity of a vessel in order to obtain the ECT and the RFR, instead of using throughput as used in our optimization model.

The comparison between the results obtained from RFRSIM and PSP is shown in Fig. 10. VPY stands for the number of voyages per year. The RFRSIM results use extension 0.99, which means the values that are obtained using the Monte Carlo simulation in 250 trials are with a 99% confidence degree. The result that is obtained from the spreadsheet model uses extension PSP. The figure shows that the PSP results are nearly identical from that of the RFRSIM. The discrepancies of the results between these two methods are caused by the difference in the value of the unit costs and the cost element composition.

5. Concluding remarks

In this paper, a spreadsheet model has been developed and used to determine the optimum ship main dimensions and power requirements at the basic design stage in the framework of a NLP problem. The PSP is employed to simulate five models with different throughput, and the optimal design is defined as the one that minimizes the ECT. This optimization process needs no exhaustive effort in producing programming codes, especially when the problem and the optimization model have been well defined.

Some other significant points can be drawn as summarized below.

First, for the basic design stage or feasibility study purposes, this method might be employed before commencing

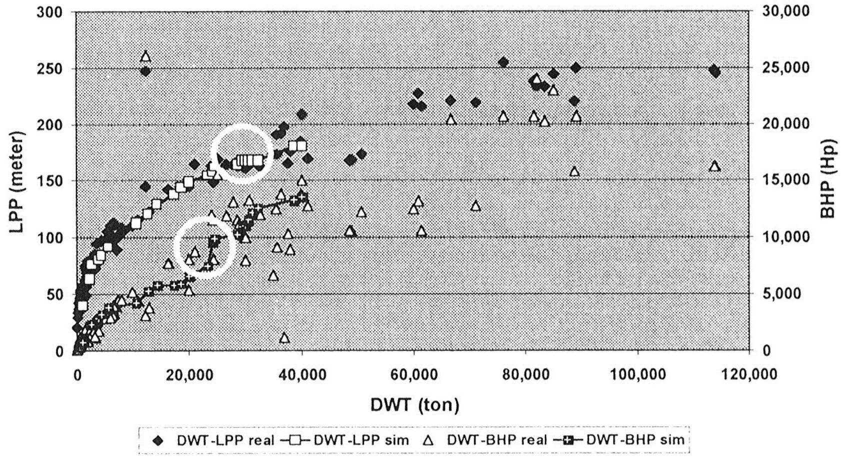
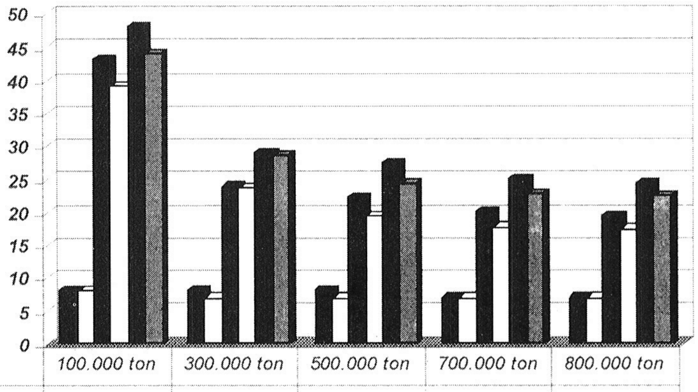


Fig. 9 DWT-BHP and DWT-T verification



	100.000 ton	300.000 ton	500.000 ton	700.000 ton	800.000 ton
VPY-0.99	8	8	8	7	7
VPY-PSP	8	7	7	7	7
RFR-0.99	43.13	23.9	22.36	19.98	19.35
RFR-PSP	39.15	23.73	19.43	17.78	17.49
ECT-0.99	48.15	28.92	27.38	25	24.37
ECT-PSP	44.17	28.76	24.46	22.81	22.52

Fig. 10 Annual voyage-RFR-ECT verification

any further design stage. The case study presented here shows how this optimization program can be effectively and precisely consistent with the real ship's design. The most tedious difficulty, however, is the way to construct all of the equations in the model, especially for a very complicated model with a huge number of required data.

Second, as a common procedure in the basic stage of ship and machinery design, the ship main dimensions and its power requirements obtained through the method offered in this paper can be further traced down into a more detailed analysis in designing the machinery system on board. Additional tasks can easily be added within the optimization program, simply by inserting a new directory within the Input and the Equation folder. Associated constraints and expected output can be attached with the objective either to minimize or maximize the Objective function. This kind of optimization process can also be utilized to select marine machinery from a certain number of available alternatives or further to determine the maintenance management scheme as utilized by authors in references [24 and 25].

Finally, the difficulties of using a spreadsheet model to optimize ship design are not manifested in the spreadsheet's construction viewpoint. Instead, the model is a way to express the design problem in mathematical expressions which can be executed by a spreadsheet.

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Appendix

Summary of optimization results for five models

throughput		100,000,000	300,000,000	500,000,000	700,000,000	800,000,000	
Breadth	m	17.6	23.4	25.4	25.4	25.4	
Depth	m	9.2	12.2	13.2	13.2	13.2	
Volume Displacement	m3	14,218.3	33,386.5	42,805.9	42,805.9	42,805.9	
Specified BHP	hp	3,740.0	6,587.3	7,773.8	7,773.8	7,773.8	
estimated vessel cost	US$	19,302,653.7	34,010,809.1	40,500,780.1	40,500,780.5	40,500,780.5	
Number of Voyage per Year (round Trips)		8	7	7	7	7	
Cost of HFO per Year	US$	263,741.1	563,798.7	845,912.0	1,184,276.8	1,353,459.2	
Cost of DO per Year	US$	5,168.7	15,048.6	30,268.1	59,325.4	77,486.3	
Cost of LO per Year for ME	US$	74,375.0	96,743.2	127,127.7	177,978.8	203,404.3	
Cost of LO per Year for GE + Other Equipments	US$	74,970.0	97,517.1	128,144.7	179,402.6	205,031.5	
Annual Port Cost	US$	118,157.6	354,472.9	590,788.2	827,103.5	945,261.2	
Annual Insurance Cost	US$	32,800.0	98,400.0	164,000.0	229,600.0	262,400.0	
Annual Overhead Cost	US$	22,439.8	66,872.4	136,272.8	267,094.7	348,858.4	
Annual Crew Cost	US$	224,398.4	514,106.9	797,252.8	1,116,153.9	1,275,604.5	
Annual Expected Replacement Cost	US$	76,216.8	99,138.9	130,275.8	182,386.1	208,441.3	
Annual M/R Cost	US$	247,368.4	321,764.2	422,821.9	591,950.6	676,515.0	
Annual Dry Docking Expenses	US$	477,478.6	807,868.7	1,395,019.6	2,734,238.3	3,571,250.0	
Annual Administration Cost	US$	30,116.6	89,749.8	182,892.5	358,469.3	468,204.7	
Annual Operating Cost	US$	1,647,231.1	3,125,481.5	4,950,776.1	7,907,980.1	9,595,916.5	
Total Loan	US$	14,476,990.2	25,508,106.8	30,375,585.1	30,375,585.4	30,375,585.4	
Owner Equity	US$	4,825,663.4	8,502,702.3	10,125,195.0	10,125,195.1	10,125,195.1	
Annual Total Cost	US$	3,347,693.0	6,121,654.1	8,518,680.9	11,475,885.0	13,163,821.3	
	Min Value	CONSTRAINTS					Max Value
Relbility Function	0.800	0.95	0.95	0.95	0.95	0.95	0.950
Average Cargo Weight per ship	500.000	10,841.5	25,457.2	32,639.5	32,639.5	32,639.5	30,000.000
Total pumping capacity	1.000	1,184.9	1,500.0	1,500.0	1,500.0	1,500.0	400.000
Pump Capacity	1.000	296.2	375.0	375.0	375.0	375.0	100.000
Specific Fuel Oil Consumption for full load ME	0.300	0.418	0.397	0.389	0.389	0.389	0.500
Specific Fuel Oil Consumption for full load GE	0.300	0.443	0.440	0.439	0.439	0.439	0.500
Burril Number	0.200	0.498	0.499	0.500	0.500	0.500	0.500
Local Cavitation Number	0.200	0.20	0.20	0.20	0.20	0.20	1.000
% Rated BHP Requirement	50.000	89.33	89.41	89.45	89.45	89.45	100.000
Required Freight Rate	10.000	49.78	34.37	30.05	28.73	28.58	80.000
L/B Ratio	6.000	6.000	6.000	6.000	6.000	6.000	7.000
Max allowable ship length at port	50.000	116.9	155.4	169.2	169.2	169.2	200.000
Length of Water Line	50.000	111.1	147.6	160.7	160.7	160.7	200.000
Length Between Perpendicular	50.000	105.5	140.3	152.7	152.7	152.7	200.000
	Min Value	g(x)	g(x)	g(x)	g(x)	g(x)	Max Value
Number of ships	1.000	1.0	1.0	2.0	2.0	3.0	3.000
Draught	7.000	7.6	10.2	11.0	11.0	11.0	11.000
B/T Ratio	2.000	2.3	2.3	2.3	2.3	2.3	3.150
Block Coefficient	0.800	0.9	0.9	0.9	0.9	0.9	0.960
Service Speed	10.000	12.0	12.0	12.0	12.0	12.0	13.000
Propeller Rpm	70.000	169.6	127.3	117.9	117.9	117.9	200.000
Diameter Propeller	4.590	5.0	6.6	7.1	7.2	7.2	7.150
Propeller Pitch	120.000	0.75	0.75	0.75	0.75	0.75	1.200
Time Required for Preventive Replacement	60.000	60.0	60.0	60.0	60.0	60.0	100.000
Port Time Per Trip (loading)	10.000	10.0	18.5	23.8	23.8	23.8	100.000
Number of Unloading Pump/host	2.000	4.0	4.0	4.0	4.0	4.0	4.000
Economic Cost of Transport		44.17	28.76	24.44	23.12	22.97	