OPERATION-BASED OPTIMIZATION OF SHIP DESIGN FOR DRY BULK VESSELS

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ABSTRACT

One of the most important decisions for the dry bulk ship-owners building a new vessel or buying a ship is to determine how big a vessel should be. Ship owners surely intend to obtain an optimal ship size, either minimizing transport costs per ton or maximizing profits per day.

However, most of the past studies devoted their attention to the size growth of container vessels, while questions like what are the determinants behind the size growth of dry bulk carriers, what are important restrictions and risks for large vessels, and how to determine the optimal ship size on a particular trade, have not been investigated systematically in the past. Therefore, our paper attempts to build an interactive logistics scheme including three basic systems, namely the design model, the shipping system and the shore logistic system, based on the technical-economic analysis for determining optimum ship's main dimensions at the basic design stage for ship owners when they build a new ship and for determining optimal solutions to logistic system for steel makers to import iron ore in the dry bulk shipping market.

The tools used in the paper vary from a conceptual vessel design model calculating the optimal ship dimensions given the deadweight within a logistical reality till Monte Carlo simulation of port-sea systems in order to sketch the impact of the shore based facilities, including the ore-storage melting-furnace system on ship size. The whole optimization process is completed within the Crystal Ball software by embedding Microsoft Solver to deal with the design solution. The proposed methodology provides a tool to analyze problems in ship design, ship operation and logistics system and show the required flexibility in the decision-making for different parties.

Key words: *The optimum ship size, Dry bulk vessels, Monte Carlo Simulation, Logistic system*

INTRODUCTION

The optimization of ship design is always one of the most important research subjects in maritime industry. Within ship design, three main stakeholders are involved, namely, the ship-owner, the shipbuilder and the first (time)-charterer. For the ship-owner, he defines the main specifications in close cooperation with the time charterer and pays for the ship. The detailed design of the hull, machinery and construction are left for the shipbuilder and subcontractor. Because ship owners always keep in mind the economical advantage of a ship, they usually make their decisions with ship design based on economic grounds. In other words, the optimal solution of ship design for ship owners is the one that can either minimize operating costs or maximize the potential earnings during ship operational life.

The subject of optimal ship design for ship owners has been investigated by many researchers. A considerable number of maritime economists focus on the determination of optimal ship size or speed. Examples are Jansson and Shneerson (1982, 1987), Garrod and Miklirs (1985), Talley and Pope (1988), Lim (1994), Cullinane and Khanna (1999, 2000), Sys et al (2008) among others. These studies give an insight into the optimization of ship size or ship speed, from which it can be concluded that one cannot make general statements about optimal ship size and speed. In other words, the optimization process is actually related with the ship service requirements. However, the optimization approaches in these studies include only ship size or speed, no other major design influencing parameters are examined.

Therefore, this paper proposes an integrated scheme of technical, logistical and economic analysis for ship owners to optimize the ship design, particularly in determining the main technical specifications, including main dimensions, deadweight, design and economical speed, and the power requirement at the conceptual design stage. As literature indicates the optimization of ship design has to be based on specific service requirements and cannot be analyzed without reference to the ship operations, our paper focuses on the design of ore carriers in the dry bulk market, utilized to serve the transportation of iron ore imported from Brazil to China. Specifically, we assume a new company is set up by a steel mill, and a shipping company, to be jointly in charge of the iron ore transportation with new ships to be designed and built. In this case, questions like: what is the carrying capacity of a ship, what is the maximum speed of a ship, how many ships are required, etc. should be the concerns of both the steel mill and the ship-owner.

On the whole, there are three main systems in the whole optimization process: the ship design model; the shipping system and the shore logistics system. The technical and economical variables in ship design, the economic variables based on ship's practical operation in the shipping system and other variables in the shore logistics system, are all interconnected. Any changes to major technical variables can result in changes to others and vice versa. The economic objectives can be achieved subject to some constraints through optimization iterations among three parts. The optimization results are obtained by Monte Carlo simulation within the Spreadsheet[1] based Crystal Ball software by embedding Solver to deal with the design solution.

The main differences of our research with previous studies rest with three aspects. Firstly, apart from required ship size and speed, other main technical specifications of the ship are determined during the optimization process. Secondly, the shore logistics plan is incorporated into the whole optimization process, and Monte Carlo simulation is needed to vary extra sea time and port time in the shipping system, as well as monthly iron ore demand of the steel mill in the shore logistics plan, which significantly influences the ship design as well. The incorporation of a

[1] The spreadsheet program Excel

logistics scheme into the whole process increases the complexity of the design option. Thirdly, ship design schemes can be tailored to meet various economic objectives considered by different parties. The proposed methodology not only provides a tool to analyze the trade-off between various transport costs or trade-off between costs and earnings, but it also provides an insight in the interdependency of shore facilities, logistical aspects and ship design, and will show the required flexibility in the decision-making for dry bulk ship-owners and steel mills.

THE OPTIMIZATION MODEL DESCRIPTIONS

The optimization model in this paper attempts to design a series of ships with different deadweight, having the optimum main technical specifications and to obtain the optimum logistic plan for each of these designs.

The ships are used to serve transportation of a certain amount of iron ore. The logistic cost per unit is utilized as the objective of the optimization problem. In this paper, the minimum logistic cost per ton must be obtained to guarantee that the optimum ship design and logistic plan are achieved. In other words the collection of optimal designs with varying deadweight and shore logistical plans belonging to each specific design enables the user to choose the optimal deadweight based on the cost per ton.

Descriptions of the three systems

There are three main systems in the whole optimization process: the design model; the shipping system and the shore logistics system. The technical variables in the ship design system, such as the deadweight, the design speed, the depth, etc., the economic variables based on ship's practical operation in the shipping system, such as the shipping cost, the logistics cost, etc., and other variables in the shore logistics system, are all interconnected. Any changes to major technical variables can result in changes to others and vice versa. The economic objectives can be achieved subject to some constraints through optimization iterations between three parts.

Specifically, the design model covers the ship data, machinery data, power data and some economic data, as illustrated in table 1. The specific design model is only focused on the determination of the main technical parameters of the ship, main dimensions, economical speeds and the required power, while given a deadweight. The design parameters need to fall within specified ranges. A minimum and a maximum value are set on the constrained parameters and the determination of the minimum and the maximum values depends on the characteristics of these parameters. In table 1, Loa means the length overall of the vessel, Lwl the length on the waterline of the vessel, D depth of the vessel, B breadth of the vessel, T draft, Cb block coefficient and V speed of the vessel.

Table 1- Components of the Design model

Input	Constrained parameters	Output
♦ Design deadweight	♦ Lwl/D	♦ Loa, Lwl, B, D, T, Cb
♦ T max	♦ Lwl/B	♦ Economical speed laden and ballast.
♦ Fuel use in gram/kWh	♦ B/T	♦ Fuel consumption per day laden and ballast.
♦ Rpm propeller and diesel engine	♦ T	♦ Installed power
♦ Design speed	♦ Cb	♦ Lightship
♦ Economic data	♦ Displacement	♦ Costs per ton-mile
	♦ V	

The shipping system covers the voyage data, ship data, port data and their economic data, as illustrated in table 2. All of these data are necessary in calculating voyage cost, ship running cost and capital cost which incur during the ship's normal operation. Ship data are imported from the design model. For instance, the fuel consumption per day is calculated based on the specific fuel consumption and the required power at the economical speed, which originate from the design model. Additionally, the new-building price is estimated based on building cost plus a certain percentage of market dependent profits. In this paper, the profit level is estimated based on the average level of the period from 2000 to 2009, covering both the strong market conditions and the weak market conditions. The building cost comes from the design model as well. Any changes to the ship data will result in changes to the shipping costs.

Table 2- Components of the Shipping System

Voyage Data	Voyage Distance	laden and ballast	mile
	Cargo quantity		ton
	Sea Time	laden days, ballast days plus sea margin	d
	Port time	Loading and discharging time plus port margin	d
	Canal Time	canal days if any	d
Ship Data	Annual operation days		day
	Deadweight		ton
	Operating Speed	Laden speed and Ballast speed	knot
	Consumption at sea	IFO at sea(l) and at sea(b)	ton
		Diesel oil at sea	ton
	Consumption at port	IFO and MDO consumption	ton
	Crew number		
Port data	Cargo Handling rate	Loading and discharging rate	
	Harbour Cost per unit		$/ton
Other data	Bunker price	prices for IFO and MDO	$/t
	Interest rate		
	Loan period		
	Depreciation year		
Number of Shipments per vessel per year			
Annual voyage cost per vessel			$
Annual operating cost per vessel			$
Annual capital cost per vessel			$
Annual total shipping costs			$
Shipping Costs per unit			$/ton

The shore logistic system covers the demand data, inventory data, order data and other economic data, utilized to calculate the inventory costs, as shown in table 3. Total inventory costs typically include holding, ordering, shortage, and purchasing costs. In a continuous review system, managers continuously monitor the inventory position. Whenever the inventory position falls at or below a level R, called the reorder point, the manager orders Q units, called the order quantity. When you receive the order after the lead-time, the inventory level jumps from zero to Q, and the cycle repeats.

Order quantity in the shore logistic system is equal to one shipment of a vessel, determined by cargo stowage factor and ship deadweight in the design model. Lead time here refers to the total round voyage time, determined by the sailing time at sea and the service time at loading and discharging terminals, which come from the shipping system. In this paper, the round trip time, not the laden voyage time, is denoted as lead time, because it's the total time spent for one shipment. In this way, three systems are all connected to each other.

Table 3-Components of the logistics system

Demand data	annual steel production capacity	ton
	maximal iron ore demand per year	ton
	weekly iron ore demand	ton
Order data	order quantity	ton
	reorder point	ton
	unit order cost	$
Inventory data	Initial inventory	ton
	weekly holding quantity	ton
	weekly lost sales	ton
	unit storage cost	$/ton
Lead time	actual round voyage time	days
Beginning inventory and position each week		ton
Ending inventory and position each week		ton
Order cost		$
Hold cost		$
Short cost		$
Total cost		$

The optimization structure

This paper employs the Crystal Ball software by embedding Microsoft Excel Solver to deal with the optimization problem. The Microsoft Excel Solver is intended to acquire ship optimum design values, by changing a set of design parameters, subject to certain constraints, to minimize the objective function in the design model based on the economic calculations. The Solver uses the Generalized Reduced Gradient (GRG) method, as implemented in an enhanced version of GRG2 code in Lasdon and Waren [1978]. The GRG2 code has been proven in use over many years as one of the most robust and reliable approaches to solving difficult nonlinear problems. Solver not only finds a feasible solution to a problem, but also locates the local optimal solution, given a set of cells (representing decision variables) that it can change, a set of constraints that must be satisfied, and one cell (denoting the objective function) that must be optimized for the minimum, maximum, or on-the-target.

As mentioned above, the optimization process incorporates the shore logistic system in this paper. Typically, the objective in the shore logistic system is to minimize total inventory costs. In shore logistic system, demand is usually uncertain, and the lead time can also vary. To avoid shortages, managers often maintain a safety stock. In such situations, it is not clear what order quantities and reorder points will minimize the expected total inventory cost. Simulation, therefore, can be used to address this question and Crystal Ball is used to perform a Monte Carlo Simulation on the spreadsheet.

Before simulation, probability distributions are created to describe the uncertainty of specific input variables, referred to in Crystal Ball as "assumptions." Apart from “assumptions”, “decision variables”, values to be set by the user, and “forecast” containing formulas and equations that we want to analyze after a simulation, should also be defined before simulation. When you run a simulation, Crystal Ball generates a random number for each assumption and places that new value in the cell. Excel then recalculates the model.

In the simulation model, iron ore demand, shipping time at sea and service time at terminals are assumptions. Deadweight of the vessel in the design model and reorder level in the shore logistic system are specified as “decision variables”. The logistics cost per ton is defined as “forecast”, which must be minimized.

We assume the iron ore demand fluctuates about a mean of expected demand, which follows a Gaussian distribution. In view of some unexpected sea state and wind conditions, we describe the shipping time at sea by a Gamma distribution function with density

$$g(t) = e^{-t/\theta} \frac{t^{k-1}}{\theta^k \Gamma(k)} \qquad (1)$$

Where t is the random variable; θ a shape parameter and k the scale parameter. Both k and θ are positive values and k in this paper is a positive integer.

At terminals, there are always some unexpected conditions, which create the possibility of delay in berthing vessels and the breakdown or failure that affects ordinary operations. In the case of delays due to port congestions or decelerations of operations, port time at loading and discharging terminals must be varied. Hence, service time at terminals can be represented by a Gamma distribution, as used in Assumma, V. et al (2006).

$$T_p = T_{pd} + T_{ps} \qquad (2)$$

where T_p is the total service time at terminals; T_{pd} is the deterministic loading or discharging time under ordinary conditions; T_{ps} is the stochastic time calculated under unexpected conditions, represented by a Gamma distribution function.

For each optimization, a new value is selected within the defined range of decision variables. Because Microsoft Excel Solver is embedded into the design model by creating an Excel macro to invoke it before every simulation trial, the Solver is at first invoked to run and produce the optimum values in the design model, some of which will be exported into the shipping system and shore logistic system. Afterwards, a Crystal Ball simulation (e.g., 1000 trials, The number of trials is chosen based on the standard error of the mean of the forecast values) starts to run. The mean value of the forecast will be saved after simulation and be checked to see if the requirement is met and so is considered feasible. If the requirement is not met, the solution is considered infeasible. The Crystal Ball runs another simulation on a new set of decision variables and repeats this process, constantly searching for the minimum logistics cost per ton until it either works through every possible solution or reaches the end of the set running time.

Specifically, the optimization process starts with new initial values of deadweight and reorder level. Based on one deadweight, there are innumerable options for the design parameters. The optimum option is obtained through Solver by achieving the minimal shipping costs per ton-mile. After Solver, the optimum design parameters are exported such as deadweight, the economical speeds laden and ballast, power installed, fuel consumption per day at laden and ballast, lightweight, T, B, D, Loa, Lwl, etc, and these outputs are utilized in the Monte Carlo simulation to make economic estimations. After each simulation, we can get the logistics cost per ton and obtain one set of outputs, including the main design parameters, number of vessels, reorder level and initial inventory. The optimal solution achieving the minimum logistics cost per ton can be identified after all steps of simulation within the specified time

Figure 1 shows the general structure of this optimization problem and the simulation process is illustrated in figure 2. The optimization process is commenced by setting the initial value of the decision variables. Using relevant basic parameters located in the Input, all basic calculations are executed during each system. The results are then exported to the output by satisfying all constraints accordingly. After the maximum and minimum values of each constraint verify the result, the objective function is verified whether the new value of the objective function is less than that of the previous one. This process is repeated until obtaining the global minimum value.

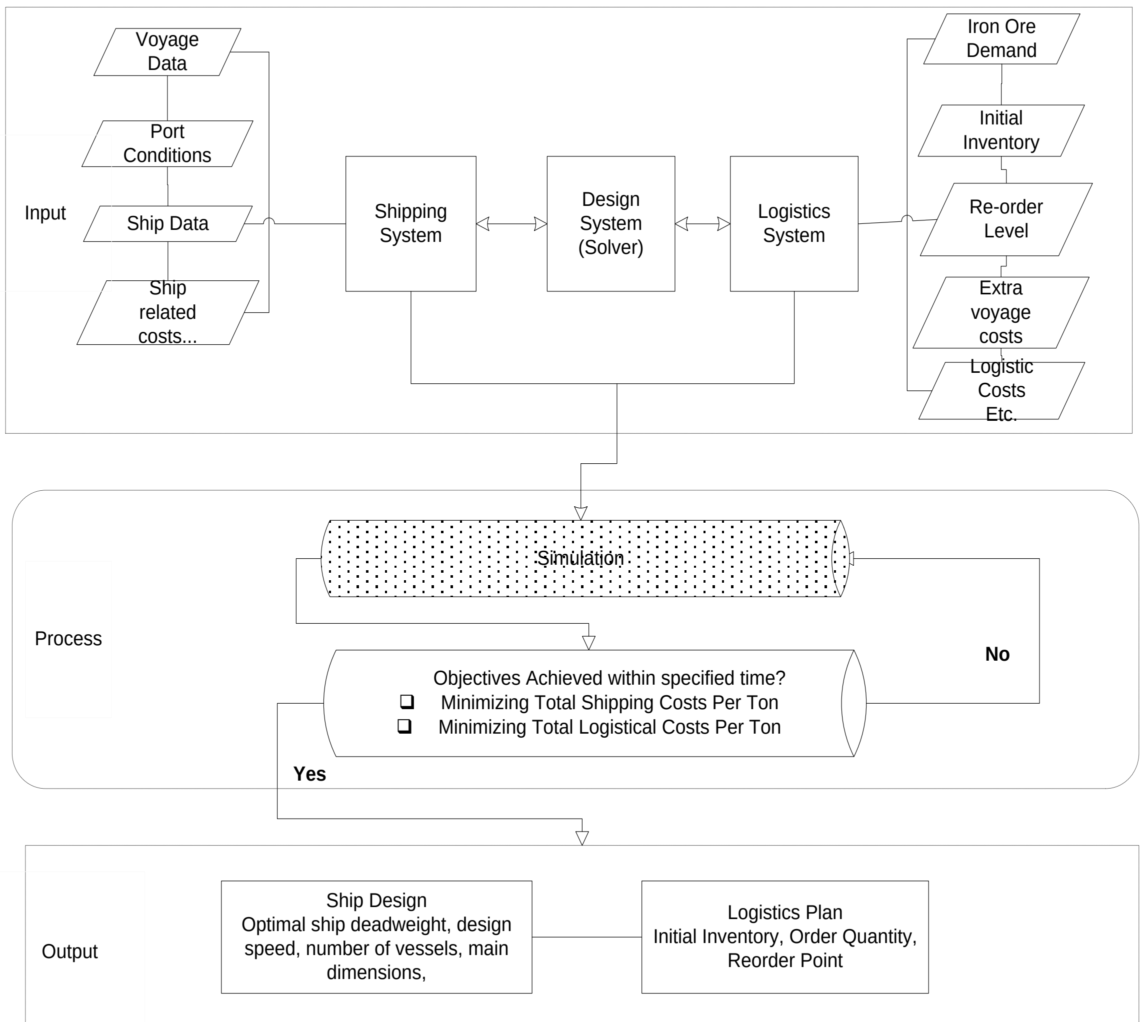

Figure 1-The optimization structure

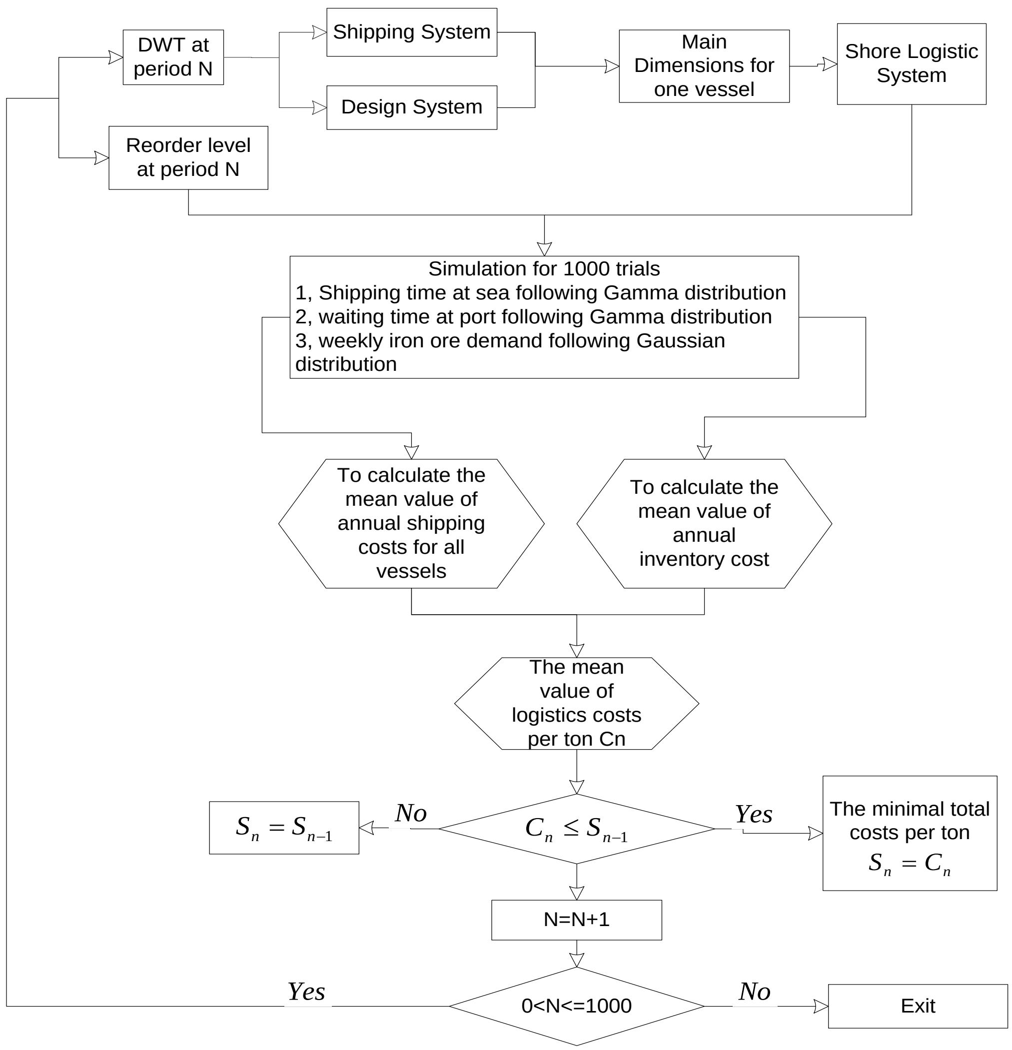

Figure 2- The simulation process

EMPIRICAL ANALYSIS

The years since 2004 have witnessed the large expansion of seaborne trade of iron ore, a consequence of the huge demand of iron ore by China. In order to guarantee the steady supply of iron ore, large steel mills tend to sign long-term contracts with ship-owners or set up a new company with large ship owners to transport imported iron ore every year. Due to large amounts of iron ore needed to be shipped annually, the current fleet of ship-owners cannot meet the demand of transportation, they tend to build new ships.

Under this background, the analysis is made to design dry bulk fleet with optimum ship design, and to achieve the optimum logistics plan, which can achieve the economic objective for both ship owners and steel mills. The ships are used to serve transportation of a certain amount of iron ore during the voyage from Tubarao, Brazil to Beilun, China. The economic objective here is to minimize total logistic cost per ton, determined by several variables, namely the shipping cost, the inventory cost of cargo and the annual tons of cargo carried.

Economic estimations in each system

Each of the three basic systems, including the design, shipping and logistics system, covers input, constraints, equations and output. All the basic calculations in each system are made by equations, such as various costs concerning ship operation and logistics plan, fuel consumption, the required revenues, etc.

In the design model, the determination of ship resistance and power prediction is carried out using the power prediction method created by Holtrop and Mennen(1979). Three power calculations are made in the design model. One is for the installed power based on a maximum service speed of 14.5 knots, the average design speed of all bulk carriers regardless their size, which is used to determine the initial investment consistently. The decision of fixing the design speed at 14.5 knots is supported by various tests within Solver. Specifically, in this paper, vessels are designed and built to transport iron ore on specified consecutive round voyages during a fixed long period, the service speed, therefore, seems to be little influenced by the market charter rate level, but by the bunker price level. We assume the bunker price of IFO and MDO as the mean value of each during the past decade from 2000 to 2009. Since the bunker prices are fixed, the optimum operation speed can be achieved for a specified design speed. We test different options of design speed at 13, 13.5, 14, 14.5 and 15 knots for the vessels ranging from 8,000 to 50,000 dwt and the results indicate the optimum speed remains at the range of 13 to 14 knots. Under the condition of the design speed larger than the optimum operation speed, we lock the design speed in this paper at 14.5 knots. This choice is bolstered by the fact that the average design speed remains at 14.5 for existing dry bulk vessels built from 1975 to 2010. The other two are the ballast and laden power calculations. Both are parameters to be optimized which results in the economically optimal ballast speed and laden speed. A real freeboard calculation is added and the entrance angle has been made a function of the Cb and other dimensions. The detailed power calculations can be found in appendix.

The estimation of building costs is made using the approach in Aalbers(2000). The building cost of a ship comprises costs of nine systems in a ship, including general and engineering system, hull and conservation, ships equipment, accommodation, electrical system, propulsion and power generation, systems for propulsion and power generation, bilge and ballast system and cargo system. These calculations employ material costs, man hours, labour costs and many constants taken from many related sources. Every optimization of the main design parameters is achieved by Solver. The target of which in this paper is to minimize the shipping costs per ton-mile. This economic target is determined by the capital cost, operation cost, voyage cost and shipping distance, while the latter two are dependent on the figures of the shipping system.

In the shipping system, the voyage data part is one of the vital ones in the optimization model. Voyage figures such as the total annual operation days, the trip distance, margin time at sea and port, loading factors, port loading and discharging rates, harbour unit cost and so on are all collected from Chinica Shipbrokers Co., Ltd. The estimated daily fuel consumptions, ballast and laden, are close to practical data. To determine the number of voyages per year, a non-integer number of operated ships might be generated. While both the number of voyages and the number of operated vessels in this paper should be integer and they are determined by the simulation process. As mentioned above, the shipping time at sea and service time at terminals are assumed to follow a gamma distribution. The scale is set to be 0.8, shape 2 and location 0 in gamma distribution functions of shipping time both at laden speed and at ballast speed. It means the average time margin at sea is 1 days (3% of the shipping time), and unexpected time at sea ranges from 0 to 3.0 days with certain probability for one laden voyage. In the gamma function of service time at both terminals, the parameters are 1 for scale, 3 for shape and 0 for location, which means the unexpected time ranges from 0 to 9 days with certain probability for both terminals. All the figures are obtained by interview with ship-owners.

When it comes to the calculation of the capital cost, it is related with new-building price, loan repayment scheme and the depreciation plan. In this paper, the new-building price is estimated based on building cost plus a certain percentage of profit. In our case, we assume that equity takes up 60 per cent, while loan 40 per cent with 6 per cent interest rate for redemption within 10 years. The choice of the optimal deadweight is not influenced by the different combinations of financing the new-building vessels. The results can be available from authors. The operating cost comprises the repair and maintenance, stores and lubricants, insurance, crew cost and management cost. The estimation of Aalbers(2000) is used to work out the total operating cost, among which, the repairs and maintenance take up approximately 0.5% of the ship value, stores and lubricants 0.4%, insurance 1%, crew expenses 0.5% (20 crew) and management cost 6% of the total fixed cost(the capital cost plus the operating cost). The estimated operating cost is close to the cost constructed from Drewry dry bulk forecaster (2007).

In the shore logistic system, iron ore demand follows a normal distribution. The maximal iron ore demand per year can be estimated based on the annual maximum steel production capacity. We assume 1 metric ton of steel needs 1.67 metric tons of iron ore. The mean value is estimated as 90% of the maximal demand, which means the furnaces are 90% utilized. The standard deviation is 3% of the mean value. Secondly, order quantity (Q) refers to one shipment quantity, and the order cost here is the interests incurred during the transport time. The initial inventory should meet the demand for iron ore during the total round voyage time. Lead time here denotes the actual round voyage time for each shipment. Thirdly, holding cost means interests and storage cost during the storage period at the yard. Lost sales cost should be profit lost of steel makers arising from lost production

At the beginning of each week, if any outstanding orders have arrived, the manager adds the order quantity to the current inventory level. Then, determine the weekly demand and check if sufficient inventory is on hand to meet this demand. If not, then the number of lost sales is the demand minus the current inventory. Subtract the current inventory level from the inventory position, set current inventory to zero, and compute the lost sales cost. If sufficient inventory is available, satisfy all demand from stock and reduce both the inventory level and inventory position by the amount of demand.

The next step is to check if the inventory position is at or below the reorder point. If so, place an order for Q units and compute the order cost. The inventory position is increased by Q, but the inventory level remains the same. Schedule a receipt of Q units to arrive after the lead-time. Finally, compute the holding cost based on the inventory level at the end of the week (after demand is satisfied) and the total cost. The total cost covers the holding cost, order cost and short cost if any.

Further description of the simulation

For the ship-owner, it is required to design a number of series dry bulk ships, which have optimum main dimension and optimum specified power but vary looking to the deadweight. For the steel mill, the optimum logistics plan should be made, which includes initial inventory, order quantity, reorder point and lead time. In the optimization process, deadweight and reorder point are set as decision variables, which are varied within the specified range. The value of deadweight ranges from 80,000 dwt to 500,000 dwt, while the reorder point ranges from 1 ton to 4000,000 tons, the latter is large enough. Forecast variable is the logistics cost per ton, which is utilized as the objective of the optimization problem. In other words, the minimum logistic cost per ton must be obtained to guarantee that the optimum design and logistics plan are achieved. The minimum and maximum values of the constrained parameters in the design model have been determined in advance. The limitations of the design variables in the design model can be seen in table 4.

The draft limitation, the maximum allowable draft, is automated and a function of the design deadweight by using a trend. This creates a much greater range for the designs. The maximum draft is 23 meter for both loading and discharging terminals in this paper, the draft limitation has a great impact on the ship design.

Table 4-Limitations of design variables

	Loa	Lwl	B	Cb	V
Minimum	100	100	0	0,7	8
Maximum	500	500	10	0,9	20
	L/D	L/B	T/D	T	Dwt
Minimum	10	5,5	0	0	80000
Maximum	14	7,5	1,0	23,0	500000

The whole optimization process is repeated for 1000 times. 1000 iterations are more enough to get the optimal solution, which will not be changed after 900 iterations in empirical test. For each iteration, the simulation is run for 1000 trials. The reason why we set 1000 trials for each iteration is that the standard error of the mean for the forecast variable, e.g. logistics cost per ton is smaller than 10%. Adaptive and neural network technologies are applied into the Crystal Ball to reduce time in searching for better results. Before each step of simulation, local optimum values for design variables are got by solving the design model with one initial value of deadweight, whilst keeping constant the maximum and minimum value of the constraints. Afterwards, for one value of reorder point, the logistics cost per ton can be worked out through logistics and shipping transport systems. If the logistics cost per ton this time is lower than the previous cost, the cost and outputs will be saved, otherwise, previous ones are still the best values. After 1000 times, we can get the minimal logistics cost per ton, together with other outputs.

Optimization results

We can get different optimal combinations of ship design and logistics plan for a different annual iron ore transport demand. The iron ore demand is dependent on the steel production of a steel plant. Four different steel production capacities have been selected: 1 million, 3 million, 5 million and 7 million tons per year, the iron ore required every year is 1.66 million, 4.98 million, 8.30 million and 11.62 million tons, respectively. The summary of the optimization results for 4 models, each with a different iron ore throughput, is illustrated in table 5 in the appendix. It is observed that the optimization results are very sensitive for the different models. The determination of the minimum and maximum values of the constraints and the outputs, which determine the feasible area of the optimization, is the privilege of the designer. To get an impression by the accuracy of the design model the existing vessel Peen Ore built in 1997 has been added in table 5.

Several conclusions can be drawn from the results. Firstly, there is a tendency towards bigger vessels and higher reorder point/level when transport demand becomes larger, which can be shown in figure 3. The shore logistic system is incorporated into the optimization process, the optimal ship size, therefore, is not the largest possible and is dependent on iron ore demand and logistics plan. Along with different combinations of ship main dimensions for four different iron ore transport demand, the associated unit costs are also obtained. When ship size increases, we can also find decreasing shipping cost per ton-mile and logistics cost per ton as shown in figure 4.

Secondly, the results suggest economical speeds, at which the ship is preferably operated to reduce fuel costs when there is sufficient cargo demand. Economical speeds are around 12 knots at laden and 13 knots at ballast when IFO price is $300/ton and MDO price $480/ton. The ship always consumes slightly less fuel oil in ballast condition. The economical speeds are produced and do not deviate much if new calculations in the design model are made with the same input data. However, changes to the bunker prices and the design speed have a substantial impact on the economical speeds. For instance, in the optimization model of 1.66 million tones iron ore demand annually, when the bunker prices soar to $450 and $600 per ton for IFO and MDO, the economical speed at laden is reduced from 12.23 knots to 10.80 knots.

Thirdly, the constraints on port draught determine vessel's main dimension. The current existing ships are all draft limited. No draft limit means a much larger depth and draft at the cost of width, minimising wet area and lightship. In our optimization model, the draught is limited up to a maximum of 23 meters. The ship design parameters can be seen in table 6. When the maximum draught limitation is changed to 20 meters, results obtained from the same optimization process reveal that there is a distinct tendency towards larger block coefficients in combination with wider vessels, and both the shipping costs per ton-mile and the logistics costs per ton are increased, which can be illustrated in figure 5. The detailed results for 20 meters maximum draught can be seen in table 6 in appendix. Again, the sensitivity of the design mainly depends on that of the input parameter values and the width of the constraint as well as the preciseness of the adopted equations.

Finally, the inventory cost is largely dependent on the order quantity and reorder level. There is a trade-off between both. A larger reorder point will create a higher inventory level on average, resulting in a lower total shortage cost but a higher total holding cost. A larger order quantity will incur lower total ordering costs resulting from ordering less frequently. The optimal order quantity and reorder level after simulation in table 5 can result in the relatively lowest possible inventory cost, even when there is still variability in the weekly iron ore demand.

This optimization methodology has the required flexibility in the decision-making for both ship owners and steel mills. Additional tasks can easily be added within the optimization model. By adding constraints to some variables, such as initial inventory and draft, or by changing some variables, such as annual transport demand of iron ore and the specific voyage, we can get different results. This kind of optimization process can also be utilized to either to minimize or to maximize the objective function. Further sensitivity analysis can also be made to investigate the influence of input variables on outputs and economic objectives.

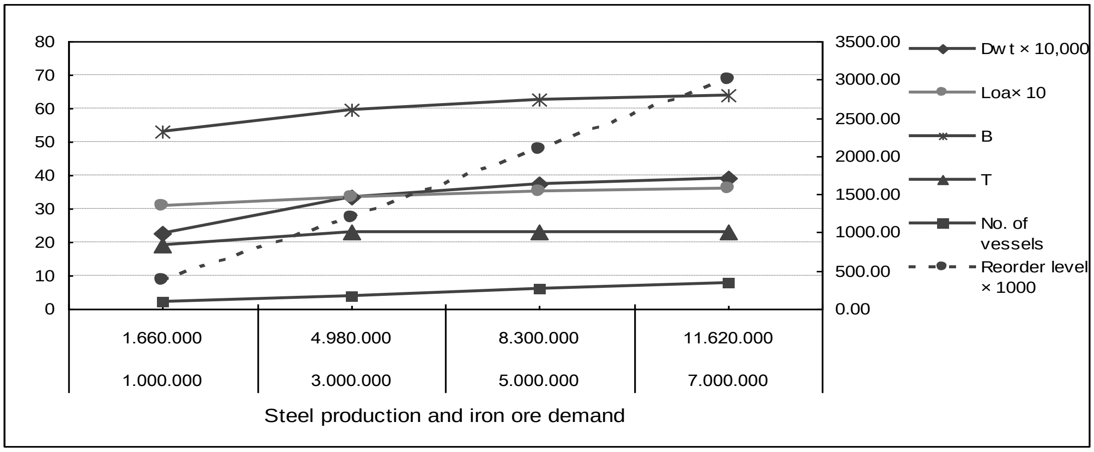

Figure 3- The optimum ship size, main dimensions and the number of vessels for various iron ore demand

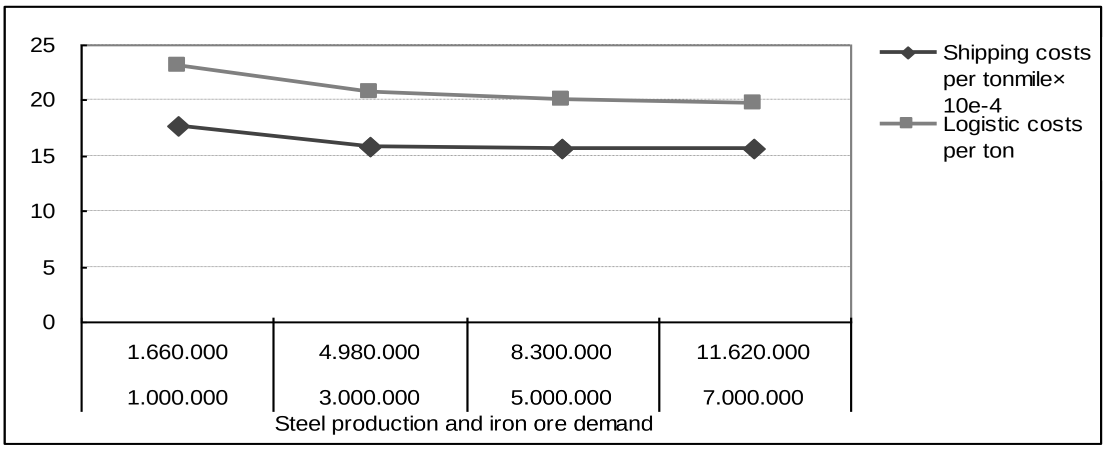

Figure 4- The optimum shipping costs per ton-mile and logistics costs per ton for various iron ore demand

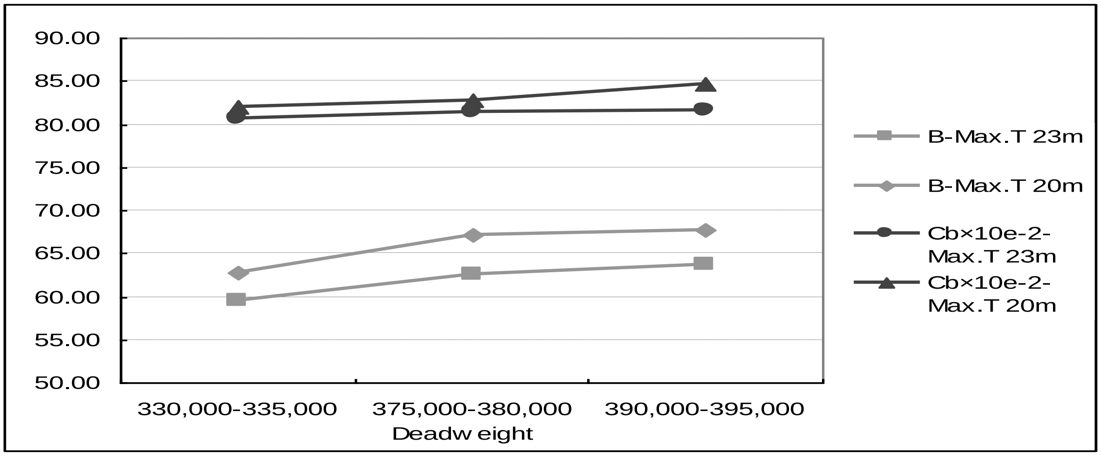

Figure 5-The different breadth and block coefficient of various ship deadweight for draft limitations at 20 meters and 23 meters respectively.

CONCLUSIONS

In the present paper, the optimization model has been constructed and used to determine the dry bulk fleet with the optimum ship main dimensions and its power requirement at the conceptual design stage, together with the optimum logistics plan. The economic objective is defined as the one that minimizes the logistics cost per ton, which needs to consider common interests of both the ship owner and the steel mill. It means not only the optimum ship design should be generated to lower the shipping costs for the ship owner, but also that the optimum logistics plan should be obtained to lower the inventory costs for the steel plant.

The case study is executed for iron ore transportation during the voyage from Tubarao, Brazil to Beilun, China. Three basic systems, namely the basic design model, the shipping system and the shore logistic system, have been set up to carry out the analysis. The whole optimization process is completed through Monte Carlo Simulation within the spreadsheet based Crystal Ball software by embedding the Microsoft Solver to deal with the design solution.

The optimum ship main dimensions, speed, power requirement, number of vessels, and logistics plan are all obtained through the optimization model. For various iron ore transport demand, different optimization models are produced and distinct results are obtained. The proposed methodology not only provides a tool to analyze the trade-off between total transport costs and inventory costs, but it also provides an insight in the interdependency of shore facilities, logistical aspects and ship design, and can offer the required flexibility in the decision-making for both dry bulk ship-owners and steel mills.

References

Aalbers, A. (2000). Evaluation of ship design alternatives, In proceedings of he 34th Wegemt School, June, Delft, the Netherlands, pp. 1-16.

Assumma, V. and Vitetta, A. (2006). Micro simulation models in a RO-RO high speed services intermodal container terminal: ordinary and perturbed conditions. European Transport Conference, Strasbourg, France, September, 2006.

Cullinane, K and Khanna, M.(1999) Economies of scale in large container ships, Journal of Transport Economics and Policy 33 (2), 185–208.

Cullinane, K. and Khanna, M.(2000) Economies of scale in large containerships: Optimal size and geographical implications, Journal of Transport Geography, 8, 181–195.

Drewry dry bulk forecaster (2007), Drewry Consultancy, http://www.drewry.co.uk/publications

Garrod, P. and Miklirs, W. (1985). The optimal ship size: a comment. Journal of Transport Economics and Policy 19(1), 83.

Holtrop, J. and Mennen, G.G.J. (1979). Het voorspellen van het voortstuwingsvermogen in het voorontwerpstadium op grond van statistische gegevens. Schip en Werf, 12, 100-103.

Jansson, J. O. and Shneerson, D. (1982), The Optimal Ship Size, Journal of Transport Economics and Policy, 16(3), 217-238.

Jansson, J. O. and Shneerson, D. (1987), A Model of Scheduled Liner Freight Services: Balancing Inventory Cost against Ship Owner's Costs, The Logistics and Transportation Review, 21(3), 195-215.

Lasdon, L.S., Waren A.D., Jain A. and Ratner, M. (1978). Design and testing of a generalized reduced gradient code for nonlinear programming. ACM Transactions on Mathematical Software. 4: 34-49

Lim, S. D. (1994), Economies of Container Ship Size: A New Evaluation, Maritime Policy and Management, 21(2), 149-160.

Sys, C., Blauwens, G., Omey, E., Van De Voorde, E. and Witlox, F. (2008). In search of the link between ship size and operations. Maritime Policy and Management, 31(4), 435-463.

Talley, W. K. and Pope, J. (1988). Inventory costs and optimal ship size. The Logistics and Transportation Review, 24, 107–120.

Appendix

1. The optimization results

Table 5. Simulation Results of different transportation demand with maximum draft limited at 23 meters

Steel production	1.000.000	3.000.000	Peen Ore(1997)	5.000.000	7.000.000	t/yr
Max. Iron Ore demand	1.660.000	4.980.000		8.300.000	11.620.000	t/yr
Dwt	225000	335000	332398	375000	390000	ton
Loa	309.56	335.13	332.0	352.91	359.41	m
Lwl	302.01	326.96	326.0	344.30	350.65	m
B	52.83	59.45	58	62.60	63.75	m
D	25.66	30.61	30.2	30.55	30.53	m
T	19.19	23.00	23	23.00	23.00	m
Cb	0.802	0.807	0.804	0.815	0.817	
v laden econ.	12.23	12.19		12.19	12.20	kn
V ballast econ.	13.31	13.15		13.09	13.08	kn
v design	14.50	14.50	14.7	14.50	14.50	kn
Wsm	27909	36745	37538	40986	42607	ton
Pb installed	19009	24026	25849	26188	26975	kW
S	22964.9	28899.3		31525.0	32501.1	m2
Costs per ton-mile	0.00178	0.00159		0.00157	0.00157	$/t-mile
Number of vessels	2.0	4.0		6.0	8.0	
Reorder level	375.00	1207.00		2100.00	3000.00	ton
Initial inventory	367.38	1155.31		1962.86	2767.33	ton
Logistic costs per ton	23.13	20.81		20.06	19.65	$/ton

Table 6. Simulation Results of different transportation demand with maximum draft limited at 20 meters

Steel production	1.000.000	3.000.000	5.000.000	7.000.000	t/yr
Max. Iron Ore demand	1.660.000	4.980.000	8.300.000	11.620.000	t/yr
Dwt	225.000	330.000	380.000	395.000	ton
Loa	309.5	356.3	380.7	382.2	m
Lwl	302.0	347.6	371.5	372.8	m
B	52.8	62.8	67.1	67.7	m
D	25.66	26.5	26.5	26.6	m
T	19.19	20	20	20	m
Cb	0.802	0.820	0.828	0.847	
v laden econ.	12.23	12.18	12.19	11.99	kn
V ballast econ.	13.31	13.06	13.02	12.81	kn
v design	14.50	14.50	14.50	14.50	kn
Wsm	27909	39460	45529	46384	ton
Pb installed	19009	25122	28054	30168	kW
S	22964	30254	33862	34758	m2
Costs per ton-mile	0.00177	0.00166	0.00164	0.00164	$/t-mile
Number of vessels	2	4	6	8	
Reorder level	385	1210	2200	3010	ton
Initial inventory	363	1156	1972	2812	ton
Logistic costs per ton	23.13	21.78	20.70	20.66	$/ton

2. The lightweight estimation method

This weight estimation method is as follows:

The Lloyds equipment number E :

E =L * (B+T) + 0,85 * L * (D-T)

Structural steel W_{si} = K* $E^{1.36}$ at a standard block coefficient of 0,7 at T = 0,8*D and with K ship type dependent, for bulk carriers around 0.031 ± 0.002. Eventually Ws corrected for the real block coefficient. The accommodation was neglected.

Ws = Wsi*(1+0.05*(Cb-0,7))

Outfit weight as a function of L_{pp} and (Lpp*B). This approach is excluding cranes.

Wo = wo * (Lpp * B) = (0.31975 – 0.00058 * Lpp) * (Lpp * B)

Machinery weight.

The dry machinery weight is a function of the torque and as such a function of the ratio MCR/rpm, with MCR as the maximum continuous rating in kW and rpm the number of revolutions per minute. While the area of investigation is on the bigger size of vessels the rpm has been set on 90, indicating two stroke engines.

Wd = 12*$(MCR/rpm)^{0.84}$

Weight of the remainder.

The remaining weight of the engine room equipment is determined by the function Wr = K * $MCR^{0.7}$ with K = 0.69 for bulk carriers.

With eventually

Wsm = Ws + Wo + Wd + Wr

The weight of a vessel according a statistical approach with the main dimensions of the vessel as parameters enables us to set a benchmark for each vessel in the database and calculate the percentage more or less weight.

3. The power estimation method

The estimated parameters are:

Cm set on 0,995

Cp prismatic coefficient calculated by means of Cb (known) and Cm

Cwp estimation based on the block coefficient Cb, formula according Henschke

Ie Half Entrance angle of the vessel. It's defined as a function of Cp and Lcb.

Lcb Has been set on 4% forward half ship, believed to be the right position for these type of vessels and speeds.

The input from the database used for these calculations:

L Length on the waterline of the vessel approached by the average of the Length overall and the Length between perpendiculars.

B Breadth of the vessel

T Draft

Displacement

Cb Block coefficient

V Speed of the vessel

The overall propulsion efficiency was calculated for one vessel and set on 0,65.