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STOCHASTIC LIFE CYCLE SHIP DESIGN OPTIMIZATION

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Abstract. In the presented research study, a parametric model of a bulk carrier design is utilized in order to explore the technical and economic ship design features (design attributes) in the frame of a stochastic optimization procedure. The life cycle assessment of a newbuilding's investment that includes ship's acquisition and operation cost for ship's life cycle is affected by a variety of cost and other parameters have an inherent uncertainty. The ship design attributes are herein represented by six main ship parameters that define the basic characteristics of a vessel: length, breadth, depth, draft, block coefficient and speed. Among the ship characteristics that are related to high uncertainty are ship's energy consumption in terms of fuel consumption, fuel mix and fuel prices. In the present paper, an attempt is made to investigate how the uncertainty of estimations of the fuel consumption, fuel mix and prices, which are made at an early stage of ship design, can affect the outcome of the ship design optimization procedure with respect to ship's life cycle cost. Therefore, a stochastic optimization procedure is being applied, which is utilizing well established optimization algorithms and techniques in a robust and efficient manner. Sample results of this stochastic optimization are compared with solutions of a deterministic optimization and eventually lead to a rational basis for the decision making regarding the life cycle assessment of ship investments.

1 INTRODUCTION

During the preliminary design phase of the design process of a vessel, the technical and economic performance of each alternative design must be evaluated based on the trading pattern and operating environment, the range of feasible technical designs, the estimations of building and operating costs [1]. Of course, in order to ensure the viability of an investment that includes the purchase and usage of a vessel for a certain period of time, the entire life cycle of the vessel should be taken into consideration and the optimum design will be the result of a holistic optimization procedure that includes design methodologies that deal with all the complexities of the vessel as whole [2, 3]. In addition, there are numerous restrictions/regulations that add many constraints, with which the design procedure must comply (stability regulations, strength regulations, safety regulations etc.). The complexity of the ship design procedure can only be handled by introducing optimization methodologies which allow the designer to define the design problem along with its constraints and come up with various optimum solutions based on his desired goals [4]. This deterministic approach, leads to certain optimal solutions that minimize (or maximize) some objective functions. Of course, when dealing with the preliminary design of a vessel, various aspects of the life cycle of the vessel must be taken into consideration and a comprehensive investment analysis is required that includes many economical and technical parameters with significant uncertainties. Therefore, the main problem of the designer is how to assess these uncertainties and include them in a stochastic design methodology [5, 6, 7]. This is demonstrated in the present study, with an example that incorporates the fuel price uncertainty into the preliminary design optimization process of a bulk carrier vessel.

2 PRELIMINARY SHIP DESIGN OPTIMIZATION

2.1 The model

In order to estimate all the necessary technical and economical elements of an investment that includes the acquisition and usage/operation of a bulk carrier vessel for a certain period of time, a parametric bulk carrier model known from the literature has been utilized [8]. This model, which is presented in Appendix A, calculates all the basic elements of the investment by using six basic characteristics of the ship: length, breadth, depth, draft, speed and block coefficient. The model, although simplified, captures the basic relationships between the above mentioned characteristics and all the technical and economic parameters of the investment, thus enabling the designer to compare different solutions in respect to those parameters.

2.2 Case study definition

In the present case study, it is assumed that the ship owner wants to order a bulk carrier vessel of 100,000 ton DWT, which will be operating between the ports of Rotterdam and New Orleans (distance between ports: $R \approx 4800$ nm, Figure 1). The required design speed of the vessel is 15 knots (this refers to the speed of the vessel, when the engine operates at its Maximum Continuous Rating - MCR). The owner will pay the ship price with a 70% loan for ten years at 8% interest and 30% down payment. The life-cycle period of the investment and ship's economic life is 20 years.

Figure 1: New Orleans – Rotterdam route

3 METHODOLOGY

3.1 Investment evaluation

In order to evaluate the total investment, an evaluation criterion is required that will allow the designer to compare the different designs and to select the optimum. The selected criterion for this study is the Required Freight Rate (RFR). The cash flows of the overall investment are summarized in figure 2.

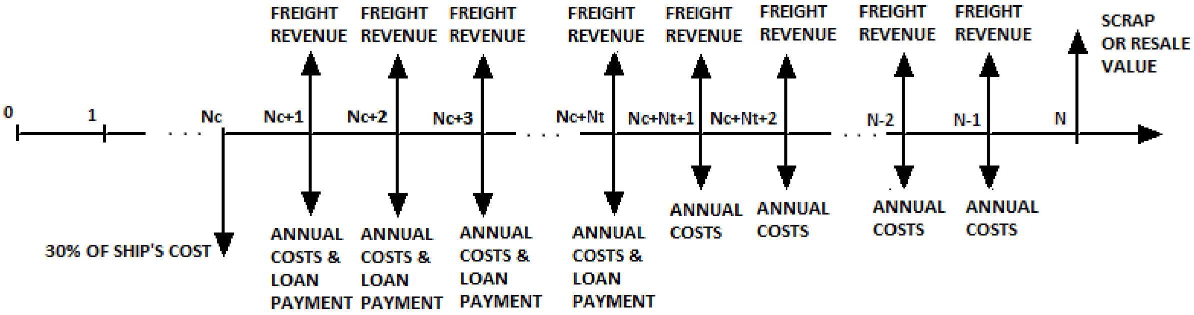

Figure 2: Investment cash-flows

The RFR is calculated by the following formula [9]:

$$RFR = \sum_{1}^{N}\left[\frac{PW(Operating\ cost) + PW(Ship\ acquisition\ cost)}{Cargo\ tonnage}\right] \tag{1}$$

Where N is the investment period and PW is the 'Present Worth' of the operating and ship acquisition costs. Basically, the RFR is the freight that will result in an investment with zero Net Present Value NPV or a pre-defined minimum profit. In the present model, the RFR is calculated numerically by using the so-called *bisection method* [10]. For the examined investment, the NPV is calculated by the following formula.

$$NPV = -30\%\ OF\ SHIP'SCOST \cdot \frac{1}{(1+i)^{Nc}} + \cdots \tag{2}$$

$$(FREIGHT\ REVENUE - ANNUAL\ COSTS - LOAN\ PAYMENT) \cdot PWF(Nt, r) \frac{1}{(1+i)^{Nc}} + \cdots$$

$$(FREIGHT\ REVENUE - ANNUAL\ COSTS) \cdot PWF(N', r) \cdot \frac{1}{(1+i)^{Nc+Nt}} + \cdots$$

$$(SCRAP\ OR\ RESALE\ VALUE) \cdot \frac{1}{(1+i)^{N}}$$

Where:

$$r = \frac{1+i}{1+f} - 1 \tag{3}$$

$$PWF(N, r) = \frac{(1+r)^N - 1}{r \cdot (1+r)^N} \tag{4}$$

$$N' = N - Nt - Nc \tag{5}$$

i : interest rate
f : inflation rate
Nc : construction time
Nt : total number of annual loan payments
N : investment period

3.2 Introducing uncertainty to the optimization process

In order to introduce mathematical uncertainty in the parameters in the problem, it is assumed that the uncertain parameters follow a certain probability distribution [11]. The probability distribution is calculated based on the more likely values for an investment's or cost element. The steps for estimating the probability are summarized below:

- Estimate the most optimistic and pessimistic values of the uncertain variable (range).
- Divide the range.
- Estimate probability of 'best estimate' for each interval midpoint (see the example of the calculation of fuel price probability distribution at the results of this study)

Once the probability distributions have been established, the objective function of the optimization problem is the mean value of the RFR which is the integration of the probability distribution and the RFR on the whole range of the uncertain variable [12].

$$\mu_f(x) = \int RFR(x) \cdot p(x)\, dx = \sum_{k=0}^{n} RFR_k(x) \cdot p_k(x) \tag{6}$$

Where RFR(x) is the Required Freight Rate, p(x) is the probability distribution value at x, x is the fuel price, n is the number of the midpoints of the divided fuel price range.

Of course, this methodology can be extended to any number of uncertain parameters.

$$\mu_f(x) = \int\int \dots \int f(x_1, x_2, \dots, x_i) \cdot p(x_1, x_2, x_3)\, dx_1\, dx_2 \dots dx_i \tag{7}$$

3.3 Optimization algorithm

The optimization is herein performed in the MATLAB environment [13]. The examined problem is a nonlinear constrained optimization problem, therefore the Sequential Quadratic Programming (SQP) algorithm is used, which is an accurate and reliable method for this kind of problems [14]. It should be noted that this method is used in both the conducted deterministic and the stochastic optimization methodologies. The term ‘stochastic’ refers to the employed probabilistic assessment methodology (in which it is considered that certain variables do not have a single value, but follow a probability distribution within a certain range) and not to the optimization algorithm.

4 RESULTS

4.1 Deterministic Optimization at the design speed

A deterministic optimization is performed first at the design speed (14.5 knots), for the anticipated mean value of fuel for the next years (500 $/ton). Therefore, the optimization variables are the five basic parameters of the vessel (e.g. length, breadth, depth, draft and C_B). The objective function is the Required Freight Rate (RFR) and the optimization results are presented in table 1.

Table 1: Deterministic optimum design

Length	L =	232.8 m
Breadth	B =	38.8 m
Depth	D =	21.8 m
Draught	T =	16.0 m
Block Coefficient	C_B =	0.790

The RFR for the above design is 22.68 $/ton. This is the result of an optimization procedure which assumes that the vessel’s mean speed is 14.5 knots during the whole life-cycle, without taking into consideration any fuel price uncertainty.

4.2 Stochastic Optimization

4.2.1 Fuel price probability distribution

The accurate prediction of the fuel price for the whole investment period is practically impossible, noting that in recent time the uncertainty refers, also, to fuel type (HFO, MGO, LNG etc) and/or fuel mix. Still, the ship owner needs this information (even a rough estimation) in order to evaluate his investment. Therefore, instead of following a ‘single-value’ approach like we did in the deterministic optimization, we assume that the mean fuel price for the investment period will lie somewhere between two extreme values (optimistic/pessimistic scenario) with certain probability that is based on some analysis that the ship owner has performed. In figure 3, the bunker prices at Rotterdam and New Orleans ports for a 12 month period are presented.

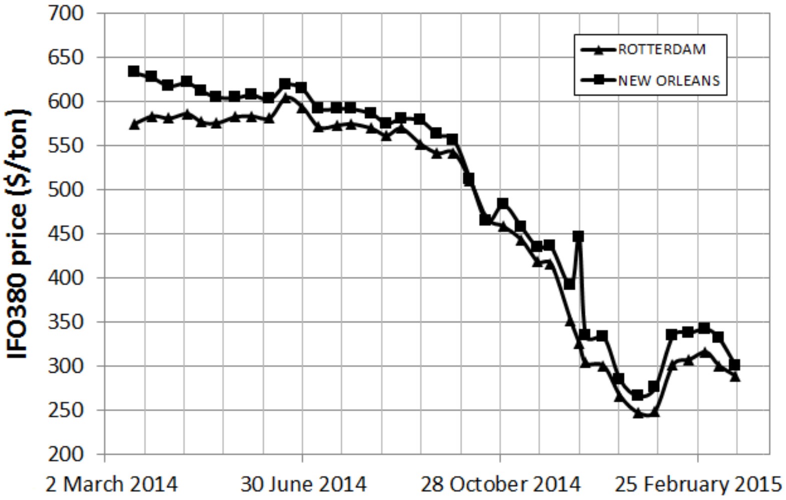

Figure 3: Rotterdam and New Orleans Bunker Price [15]

For example, we assume that the mean fuel price for the next years will be 250$, in the most optimistic scenario, and 650$ in the most pessimistic one. In addition, the ship owner is thinking conservatively and assumes the fuel price's mean value to be closer to the pessimistic scenario. Thus, the determination of the probability distribution is based on the ‘best estimates’ of the ship owner, considering some uncertainty range.

For example, dividing the range of the fuel price by four, the probabilities of the ‘best estimates’ are defined for each midpoint of the intervals. In our case, the chance of the mean fuel price to be 300$ is assumed to be 5%, for 400$ is 15%, for 500$ is 50% and for 600 is 30% (noting that the intervals and the percentages are herein taken arbitrarily in order to demonstrate the methodology). The final probability distribution is calculated in table 2 and presented in figure 4.

Table 2: Fuel price probability estimation

interval	midpoint	probability distribution
250 - 350 $	300 $	0.05
350 - 450 $	400 $	0.15
450 - 550 $	500 $	0.50
550 - 650 $	600 $	0.30
	SUM	**1.00**

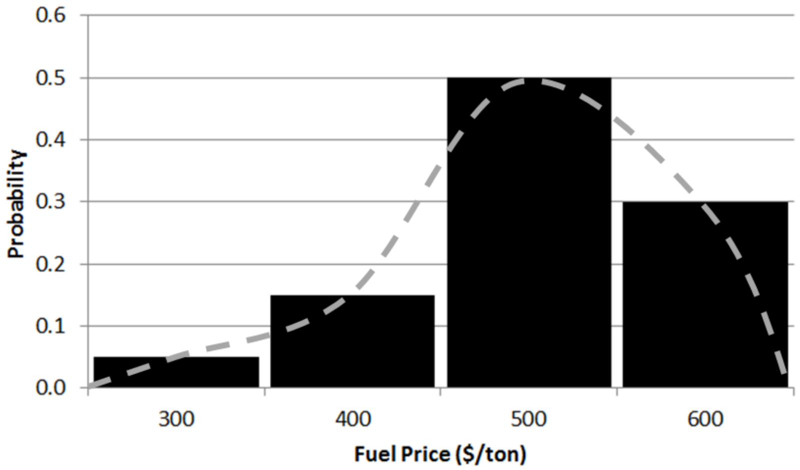

Figure 4: Fuel price probability distribution

4.2.2 Stochastic Optimization Results

The result of the conducted stochastic optimization provides the optimum vessel for an optimum speed profile based on the assumed fuel price probability distribution. The optimization results include the optimization of the five basic characteristics of the vessel (table 3) and the speed profile of the vessel (figure 5). It should be noted that the *design* speed of the vessel (speed when the engine operates at 100% MCR) remains the same. The optimization parameter is the *service* speed of the vessel, which is affected by the fuel price uncertainty. It should be noted that the change of the Specific Fuel Oil Consumption SFOC [2] , when operating at reduced engine rating, was taken into consideration.

Table 3: Stochastic optimum design

Length	L =	223.6 m
Breadth	B =	37.3 m
Depth	D =	21.8 m
Draught	T =	16.0 m
Block Coefficient	C_B =	0.850

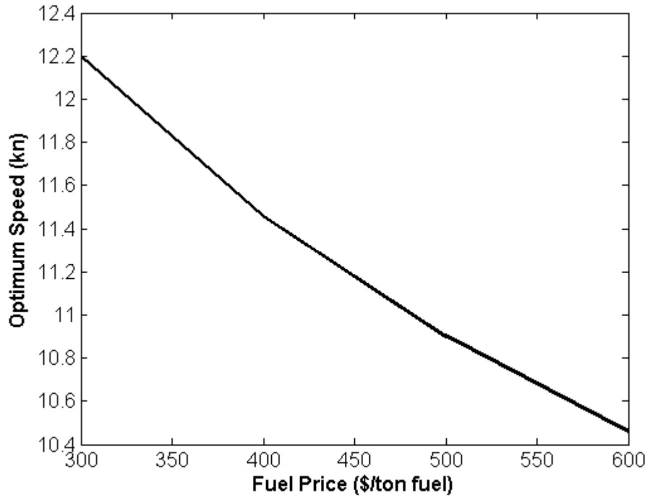

Figure 5: Optimum speed profile

It should be noted that the herein conducted optimization neglects some parameters that also affect the optimum speed profile (e.g. weather conditions, added resistance/powering in waves), but it is still valid in principle, namely higher fuel prices will inevitably lead to service speed reduction in order to lower the operational cost of the vessel and reduce its RFR.

4.3 Comparison of deterministic and stochastic methodology

The results of the deterministic and the stochastic optimization methodology are comparatively presented in table 4.

Table 4: Comparison of Stochastic and Deterministic optimization results

	Deterministic Optimization Methodology	Stochastic Optimization Methodology
Length	L = 232.8 m	L = 223.6 m
Breadth	B = 38.8 m	B = 37.3 m
Depth	D = 21.8 m	D = 21.8 m
Draught	T = 16.0 m	T = 16.0 m
Block Coefficient	C_B = 0.790	C_B = 0.850

Both optimization methodologies lead to realistic designs, meaning that the design parameters of each vessel lie within the statistical ranges of dimensions of existing vessels [2]. In order to have a fair comparison between the two designs, the deterministic design may also be also optimized with respect to the service speed. From figures 6 & 7, however, it is evident that even if the deterministic design is optimized for a varying design speed, it will not be as profitable as the stochastic design, which was optimized for an optimum service speed.

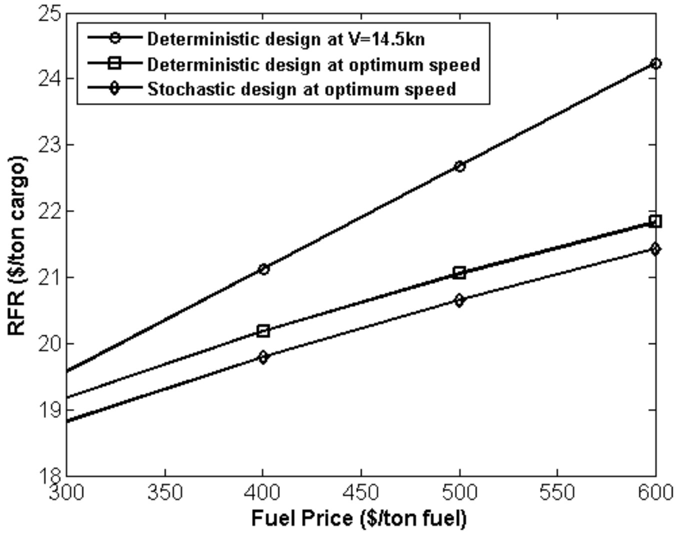

Figure 6: RFR vs fuel price

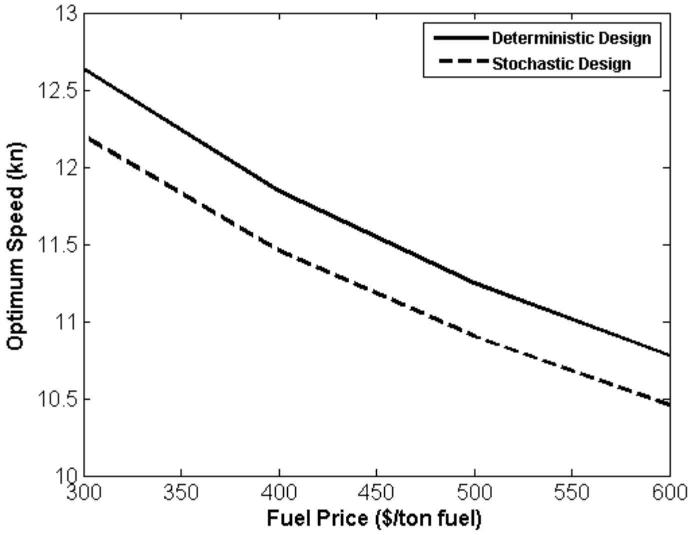

Figure 7: Optimum speed profiles

Thus, the stochastic optmization leads to more competitive designs (lower RFR) and better accounts for the uncertainties of various life-cycle cost parameters, among which the fuel price is of prime interest. The presented methodolgy can be easily extended to account also for the uncertainty of other technical of economic parameters.

5 CONCLUSIONS

The presented study proves that any assumption made at the conceptual/preliminary design phase of a ship regarding the uncertainty of economic and other parameters affects significantly the overall outcome of the investment. Therefore, a stochastic optimization methodology, where all the uncertainties of the most important parameters are taken into consideration, is recommended and is expected to minimize significantly the risk of the investment.

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APPENDIX A – PARAMETRIC BULK CARRIER MODEL

The parametric bulk carrier model of Sen & Yang (1988) is briefly presented below.

L: Length (m)
B: Beam (m)
D: Depth (m)
T: Draft m(m)
C_B: Block coefficient
V_S: Service speed (knots)
V_D: Design (or maximum) speed (knots)

Capital costs = $0.2 \cdot$ship cost
Ship cost = $1.3 \cdot (2000 \cdot Ws^{0.85} + 3500 \cdot Wo + 2400 \cdot P^{0.8})$
Steel weight: $W_s = 0.034 \cdot L^{1.7} \cdot B^{0.7} \cdot D^{0.4} \cdot C_B{}^{0.5}$
Outfit weight $W_o = L^{0.8} \cdot B^{0.6} \cdot D^{0.3} \cdot C_B{}^{0.1}$
Machinery weight $W_m = 0.17 \cdot P_{max}{}^{0.9}$
Displacement = $1.025 \cdot L \cdot B \cdot T \cdot C_B$
Power: P = displacement$^{2/3} \cdot V_S{}^3 / (a + b \cdot Fn)$
Froude number: $Fn = V/(g \cdot L)^{0.5}$, g: gravity acceleration
$a = 4977.06 \cdot C_B{}^2 - 8105.61 \cdot C_B + 4456.51$
$b = -10847.2 \cdot C_B{}^2 + 12817 \cdot CB - 6960.32$
Running costs = $40000 \cdot DWT^{0.3}$
Deadweight: DWT = displacement − light ship weight
Light ship weight = $W_s + W_o + W_m$
Voyage costs = (fuel cost + port cost) ·RTPA
Fuel cost = 1.05·daily consumption·sea days·fuel price
Daily consumption = $0.17 \cdot P \cdot 24/1000 + 0.2$
Sea days = round trip miles/24·Vs
Round trip miles= $2 \cdot 4800 = 9600$ nm
Fuel price = 300 £/t
Port cost = $6.3 \cdot DWT^{0.8}$
Round trips per year: RTPA = 350/(sea days + port days)
Port days = 2·(cargo deadweight/handling rate + 0.5)
Cargo deadweight = DWT − fuel carried − miscellaneous DWT
Fuel carried = daily consumption·(sea days + 5)
Miscellaneous DWT = $2 \cdot DWT^{0.5}$
Handling rate = 8000 t/day
Vertical centre of buoyancy: $KB = 0.53 \cdot T$
Metacentric radius: $BM_T = (0.085 C_B - 0.002) \cdot B^2 / (T \cdot C_B)$
Vertical centre of gravity: $KG = 1.0 + 0.52 \cdot D$

<u>Constraints:</u>
$L/B \geq 6$
$L/D \leq 15$
$L/T \leq 19$
$T \leq 0.45 \cdot DWT^{0.31}$
$T \leq 0.7D + 0.7$
DWT = 100,000
$0.79 \leq C_B \leq 0.85$
$F_n max \leq 0.32$
$GM_T = KB + BM_T - KG \geq 0.07B$
$Vk \leq Vk,max$

The RFR calculation was added to the above model. Herein, the RFR is calculated by using the bisection method in order to calculate the freight that results in a zero-profit investment (e.g. zero NPV).

$$NPV = -30\%\ OF\ SHIP'SCOST \cdot \frac{1}{(1+i)^{Nc}} + \cdots$$

$$(FREIGHT\ REVENUE - ANNUAL\ COSTS - LOAN\ PAYMENT) \cdot PWF(Nt, r) \frac{1}{(1+i)^{Nc}} + \cdots$$

$$(FREIGHT\ REVENUE - ANNUAL\ COSTS) \cdot PWF(N', r) \cdot \frac{1}{(1+i)^{Nc+Nt}} + \cdots$$

$$(SCRAP\ VALUE) \cdot \frac{1}{(1+i)^{N}}$$

Where:

$r = \frac{1+i}{1+f} - 1$

$PWF(N, r) = \frac{(1+r)^{N}-1}{r \cdot (1+r)^{N}}$

$N' = N - Nt - Nc$

i : Interest rate
f : Inflation
Nc : Construction time
Nt : Total number of annual loan payments
N : Investment period