

Design Analysis of a New Generation of Suezmax Tankers

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A thoroughly investigated design of a new generation of Suezmax tankers incorporating the builder's consideration in the form of a condensed mathematical model is presented. The design model is provided for practical application and for a fast assessment of the conceptual design. The design model is subjected to different methods of design analysis in order to determine an adequate design and the appropriate procedure applicable in the design office. In addition, the computational, building and operational uncertainties involved in the design and mathematical model are considered. The uncertainty analysis based on tolerances indicates a wider choice of designs within acceptable limits.

INTRODUCTION

The enlarged profile of the Suez Canal, along with intensive development of double-hull structures during the past number of years, has had a great impetus on the design of a new generation of Suezmax tankers.

Basic dilemmas in the design of tankers concern the longitudinal bulkheads, shape of the midship section, cargo loading/unloading equipment, capacity and design of segregated ballast tanks, as well as the arrangement of engine room, and have been substantially influenced by the relevant IMO and US-OPA requirements. The deepening of the Suez Canal had a considerable effect upon maximal ship dimensions [Suez Canal Authority 1986, 1995].

Two reasons which motivated the present work:

- Suezmax size itself suiting physical passage through the Canal.
- Expectation that the Suezmax tanker will show other advantages and become a convenient and preferable size for future oil carriers.

Furthermore, the fact that Split Shipyard has already built a series of eight segregated ballast tankers of 144 000 dwt as well as several double-hull Aframax tankers, all in accordance with TSP Protocol'78, represents a reliable and encouraging basis.

The design concept of the Suezmax tanker is described by a mathematical/numerical model following design principles [Watson & Gilfillan 1977, Taggart 1980]; this concept is subjected to an analysis giving a solid basis for design selection and decision-making, [Žanić, Grubišić & Trincas 1992].

Due to the large number of uncertainties involved in the design model, a certain skepticism may arise among practicing engineers concerning highly sophisticated and accurate numerical procedures.

In practice there exists a wide range of solutions within acceptable limits which cannot be mutually distinguished due to objective, subjective, numerical, operational and other uncertainties or inaccuracies involved in the design model. Some design variables and problem parameters applied in mathematical models, or even all of them, can be uncertain, either with known tolerance limits or with given statistical properties.

The idea underlined in the paper is to investigate the effect of tolerances of variables and parameters, [e.g. Creveling 1996] in post-optimal non linear analysis [e.g. Žiha 1997] of a design of a Suezmax tankers.

DESIGN CONCEPT OF A SUEZMAX TANKER

The basic concept assumes following features:

- The adopted present design assumes double bottom and double sides in way of cargo space in accordance with the respective IMO rules and with the US Oil Pollution Act 1990. The mid-deck tanker concept was considered too, but it was rejected due to lack of experience and some open problems regarding the relevant regulations and requirements.

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NOMENCLATURE

B = Breadth, molded, m

C_B = Block coefficient

CF = cost of fuel, \$/t

CS = cost of steel, \$/t

C_i =distance to i th goal in
 standardized and
 normalized space
 d =draft, m
 d_s =maximal draft, m
 D =depth, m
 DW =deadweight, t
 h_{ts} =influence of built-in high
 tensile steel upon total
 steel, %
 L_{pp} =length between
 perpendiculars, m
 LCF =lifetime fuel cost, \$
 LCT =total lifetime costs, \$
 LT =ship's lifetime, *years*

distance in L_1 metrics
 $L_2 = \sum_i (w_i C_i)^2$
 distance in L_2 metrics
 $L_\infty = \min [\max_i |w_i C_i|]$
 distance in L_∞ metrics
 M_p =power margin
 M_w =weight margin
 N =propeller speed, *rpm*
 NCR =Normal Continuous
 Rating, *kW*
 P_b =engine brake power, *kW*
 $SMCR$ =selected maximum
 continuous rating, *kW*
 $SFOC$ =specific fuel
 consumption, *t/kW h*
 ST =sailing time, *days/year*

TCS =total cost of steel, \$
 t =tolerance in general
 V_{ct} =cargo tanks capacity, m^3
 V_t =speed on sea trials
 at draft d_s , *knots*
 W_i =weight if i -th goal
 W_m =weight of machinery, t
 W_O =outfit weight including
 equipment for cargo, t
 W_S =hull and superstructure
 weight, t

Greek symbols

Δ =displacement, t
 η =service margin
 $\kappa = V_{ct}/L \times B \times D$
 specific volume capacity
 ρ_{sea} =density of sea water,
 appendages included, t/m^3

$$L_1 = \sum_i |w_i C_i|$$

- The tanker is conceived with 12 cargo and 2 slop tanks; the latter may be used for cargo too, when carrying oils of lower density. Such a compartmentation allows three cargo segregations, as usual, and further complies with IMO requirements for segregated ballast tanks protectively located (SBT-PL) as well as with criteria for damaged stability. The double-skin Suezmax tanker could rather easily cope with classification societies' rules, omitting centerline longitudinal bulkhead. Nevertheless, other maritime authorities favor design with centerline longitudinal bulkhead, in view of higher stability standards during loading/unloading operations. Therefore, the adopted concept assumes one centerline longitudinal plane bulkhead with horizontal stiffeners and vertical webs, which is also more efficient with respect to longitudinal strength than the analogous corrugated bulkhead.
- The assumed deadweight equals $DW=150\,000\,t$. The volume of cargo tanks is $V_{ct}=170\,000\,m^3$. The assumed range of navigation of $20\,000\,nm$. Fuel stores, based on average loaded/ballast service speed of $14\,knots$ and sailing time of about 60 days, amounts to $2\,700\,t$ of heavy oil. By adding other stores, i.e. diesel oil, lub oil and fresh water, then crew, provision and extra spares, amounting to about $1\,300\,t$, results a payload $PL=150\,000-4\,000=146\,000\,t$. This gives, against the presupposed cubic capacity, a typical cargo density of about $0.86\,t/m^3$.
- The draft and the beam are defined by Suez Canal limitations. Earlier constraints in draft and

breadth [Suez Canal Authority 1986], had resulted in designs with optimal breadth of $44.5\,m$ for $15.6\,m$ of draft, by which the stipulated deadweight could not be reached. The recent increase of draft to $17.07\,m$ and breadth of $48.16\,m$ [Suez Canal Authority 1995], see Fig. 1(a), influenced design particulars for the better. However, the adopted maximal draft for the design model is $d=d_s=17.10\,m$, assuming that until arrival at the Canal, some stores will be consumed, and the draft at the start of the passage will be about the allowed of $17.07\,m$. The maximal design beam is set to $B=49\,m$, just exceeding the minimal breadth of $48.16\,m$ when the beam-to-draft product $B \times d_s$ is maximal; see Fig. 1(b).

- The block coefficient of 0.828 as the upper bound is assumed empirically, for which a satisfactory hull form can be selected.
- Approximately 60% of high tensile steel is used in the hull construction. It decreases the steel weight of the hull by about 7%.
- The maximal length of the ship is limited to $L_{pp}=265\,m$ in view of length restriction of building berths in Split Shipyard.
- One low speed two-stroke direct coupled diesel engine is assumed. The speed on sea trials at the maximal draft is $V_t=14.7\,knots$. The corresponding speed at slightly lower design draft is approximate $15\,knots$.
- Additional design constraints, the minimal length/beam ratio of $L_{pp}/B=5.6$ and the minimum length-to-depth ratio of $L_{pp}/D=10.5$ are introduced following the empirical assessments in order to avoid potential structural, propulsion and manoeuvrability problems.

- IMO requirements for ballast conditions, concerning the minimum draft and propeller immersion, trim and displacement, are fully met.
- Minimum freeboard requirements are in accordance with ILLC66.

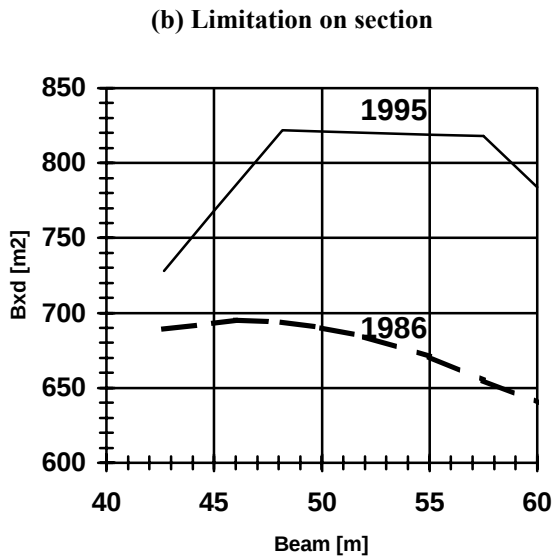
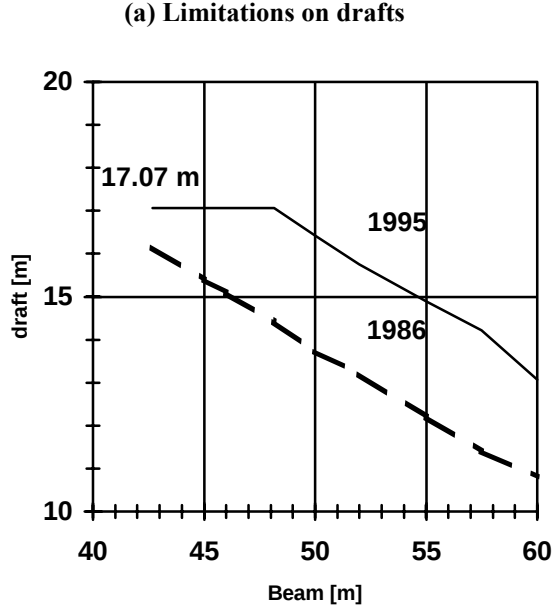


Figure 1 Suez Canal limitations in the years 1986 and 1995

OUTLINE DESCRIPTION OF DESIGN MODEL

The design model is defined by the basic design concept outlined in previous section. A suitable mathematical model is set out for the purpose, based on the widely introduced expressions from the literature, [Watson & Gilfillan 1977, Taggart 1980] as well as those tested and practised by the Split Shipyard. The model depends upon four design variables: L_{pp} , B , d_s and C_B .

The depth of the ship can be obtained from the following relation:

$$D = \frac{V_{ct}}{L_{pp} \cdot B \cdot \kappa} \quad (1)$$

where the value of the specific cubic capacity κ is assumed empirically as 0.620, in order to satisfy the required cargo and water ballast capacity.

The expression for brake power P_b , being equal to the service continuous rating SCR, in kW, has been obtained through regression analysis from as many as 360 ships, and it reads:

$$P_b = 0.0072886 \cdot L_{pp}^{0.04917} \cdot B^{1.03279} \cdot d_s^{0.64437} \cdot C_B^{2.1262} \cdot V_{trial}^{3.2722} \cdot (1 - 0.002966 \cdot L_{pp} / d_s) \quad (2)$$

The regression formula (2) is applicable within the limits $\Delta=171\,000-173\,000\,t$, $L_{pp}=250-260\,m$, $B=45-48\,m$, $d=16.8-17.4\,m$, $C_B=0.80-0.83$, $V_t=14.4-15.0\,knots$ at draft d_s and $N=98\,rpm$ propeller speed and for moderate extrapolations.

Following engineering practice, the selected maximum continuous rating (SMCR) can be obtained by adopting a power margin of $M_p=0.10$, as follows:

$$SMCR = \frac{P_b}{1 - M_p} = \frac{P_b}{0.9} \quad (3)$$

The lighthouse weight (LS) is the sum of the steel hull and superstructure weight (W_s), machinery weight (W_m), outfit weight (W_o) and a margin M_w obtained as follows:

$$LS = W_s + W_m + W_o + M_w \quad (4)$$

where

$$W_s = \left(1 - \frac{h_{ls}}{100}\right) \cdot \left\{ \begin{aligned} &0.0318 \cdot L_{pp}^{1.36} \cdot (B + 0.85 \cdot D + 0.15d_s)^{1.36} \cdot \\ &\left[1 + 0.5 \cdot (C_B - 0.7) + \right. \\ &\left. + 0.5 \cdot (1 - C_B) \cdot (0.8 \cdot D - d_s) / (3 \cdot d_s) \right] \end{aligned} \right\} \quad (5)$$

$$W_m = SMCR \cdot (985 - 0.0034 \cdot SMCR) / 7350 \quad (6)$$

$$W_o = (0.2646 - L_{pp} / 1620) \cdot L_{pp} \cdot B \quad (7)$$

The ship's displacement can be obtained either by expressing the hydrostatic balance of buoyancy and weights, using main particulars, or by using deadweight and ship's weights:

$$\Delta = \rho_{sea,appendices} L_{pp} \cdot B \cdot d_s \cdot C_B = DW + LS \quad (8)$$

The design model upper bounds on design variables following engineering reasoning in the basic concept, are:

$$\begin{aligned} L_{pp_{max}} &\leq 265m, B_{max} \leq 49m \\ d_{s_{max}} &\leq 17.1m \\ C_{B_{max}} &\leq 0.828 \end{aligned} \quad (9)$$

The lower bounds on the design model are those defining the range of validity of the regression formulae, and in general are satisfied for the considered design model.

Additional constraints on principal dimensions are selected to suit ratios:

$$\begin{aligned} L_{pp} / B &\geq 5.6 \\ L_{pp} / D &\geq 10.5 \end{aligned} \quad (10)$$

Finally, the freeboard requirement is checked according to ILLC66.

In addition, a simple utility function out of many possible, particularly interesting from the shipbuilder's point of view, using only basic economic considerations on the total lifetime costs, is defined by the engine brake power P_b and steel weight W_s of the ship structure.

The lifetime fuel costs can be assessed by the following considerations:

$$\begin{aligned} LCF &= LT \cdot ST \cdot 24 \text{ hours/day} \cdot SFOCCF \cdot P_b = \\ &= 16632 \cdot CF \cdot P_b \end{aligned} \quad (11)$$

where

LT=15 years the ship's lifetime

ST=280 days/years days at sea

SFOC=165 10^{-6} t/kW h specific fuel consumption

CF=100 \$/t assumed specific fuel cost.

The total cost of steel is obtained as:

$$TCS = W_s \cdot CS \quad (12)$$

where

CS=1000 \$/t is the assumed specific built-in steel cost.

The total lifetime cost is defined as follows:

$$LCT = LCF + TCS \quad (13)$$

SUEZMAX TANKER DESIGN ANALYSIS

The engine and the steel represents over a half of the total costs of material built into the ship.

Therefore the two considered design objectives are the ship's displacement Δ and the selected maximum continuous rating SMCR. By inspection in a preliminary analysis, the objective functions representing Δ and SMCR as well as the utility functions and constraint functions are found monotonous in the considered range of design variables and design parameters. Therefore, the solutions could be defined by the active constraints on the boundary of the feasible region, and no modal solution is expected within the feasible region.

Twelve possible designs for anticipated boundary values of design variables are calculated and presented in Table 1. Each of the selected designs can be represented in the two-dimensional space denoted as Δ -SMCR space, considering SMCR as a function of Δ , giving a grid of possible designs (not necessarily feasible designs); see Fig. 2(a).

The feasible designs are obtained by satisfying all the requirements, design constraints and bounds, and can also be represented in Δ -SMCR diagram; see Fig. 2(b).

Each of the designs from the Δ -SMCR space can be represented in the two-dimensional subspace spanned by the two most influential design variables length, L_{pp} and breadth B , denoted as L_{pp} - B space; see Fig. 3. Some of the characteristic designs of interest from the lowest contour on Fig. 2(b), denoted as A-J, are given in Table 2.

The relation of design variables L_{pp} , B and C_B (for $d_s=17.1$ m) to displacement Δ , for the designs A-J, are given in diagrams in Fig. 4(a-c).

There are two families of interesting designs with respect to active constraints:

- first family with the active constraint $L/B_{min}=5.6$, designs A-D.
- second family with the active minimal freeboard constraint, designs F-J.

Note that for the design E, both of the constraints, the L/B_{min} and minimal freeboard requirement, are active.

The utility function values of initial cost of steel TCS, of the lifetime costs of fuel LCF, and the total lifetime costs LCT, for interesting (Pareto optimal) designs A-J are given in Table 3; see also Fig. 5.

From Table 3. as well as from Fig. 5. it is obvious that the applied utility function enriches its nominal minimum value in the design J; i.e., the ship with the least propelling power (the longest ship) is advantageous considering its nominal lifetime costs.

Table 1 Designs 1-12 for anticipated bounds of design variables

Designs	Objectives		Variables					Weights			
	SMCR kW	Δ tons	L_{pp} m	B m	d m	C_B -	D m	W_s tons	W_o tons	W_m tons	LS tons
1	14404	172644	255.0	49.92	16.6	0.800	21.54	19446	1364	1834	22644
2	14125	172726	260.0	48.98	16.5	0.800	21.53	19601	1325	1800	22726
3	14316	172199	265.0	48.08	16.5	0.800	21.51	19756	1287	1768	22811
4	14946	172536	255.0	45.20	16.5	0.828	22.31	19320	1317	1899	22536
5	14657	172625	260.0	47.30	16.5	0.828	22.29	19481	1280	1865	22626
6	14380	172715	265.0	46.43	16.5	0.828	22.28	19642	1243	1831	22716
7	14169	172174	255.0	48.04	17.1	0.800	22.38	19053	1313	1808	22174
8	13916	172264	260.0	47.14	17.1	0.800	22.37	19213	1275	1775	22263
9	13652	172355	265.0	46.27	17.1	0.800	22.36	19374	1238	1743	22355
10	14727	172099	255.0	46.39	17.1	0.828	23.18	18959	1268	1873	22100
11	14443	172196	260.0	45.02	17.1	0.828	23.16	19125	1232	1839	22196
12	14170	172293	265.0	44.69	17.1	0.828	23.15	19291	1196	1806	22293

Table 2 Designs A-J with minimal SMCR and Δ , Pareto optimal designs, non-dominated designs

Des-igns	O b j e c t i v e s				V a r i a b l e s					W e i g h t s			
	SMCR	norm	Δ	norm	L_{pp}	B	d	C_B	D	W_s	W_o	W_m	LS
	<i>kW</i>		<i>tons</i>		<i>m</i>	<i>m</i>	<i>m</i>	-	<i>m</i>	<i>tons</i>	<i>tons</i>	<i>tons</i>	<i>tons</i>
(No feasible solution under L=257.5)													
A	14584	1.00	172148	0.00	257.5	45.96	17.1	0.8280	23.17	19042	1250	1856	21482
B	14489	0.88	172163	0.08	258.0	46.07	17.1	0.8245	23.07	19069	1252	1845	22166
C	14316	0.65	172199	0.26	259.0	46.25	17.1	0.8183	22.89	19120	1254	1824	22198
D	14146	0.43	172234	0.46	260.0	46.42	17.1	0.8122	22.71	19172	1257	1803	22232
E	14096	0.36	172247	0.53	260.5	46.48	17.1	0.8110	22.68	19192	1254	1797	22243
F	14050	0.30	172256	0.58	261.0	46.38	17.1	0.8100	22.65	19211	1253	1792	22256
G	13991	0.23	172276	0.68	262.0	46.22	17.1	0.8097	22.64	19245	1246	1784	22275
H	13931	0.15	172295	0.80	263.0	46.07	17.1	0.8094	22.63	19278	1239	1777	22294
I	13875	0.08	172318	0.90	264.0	45.91	17.1	0.8092	22.62	19311	1232	1770	22313
J	13817	0.00	172335	1.00	265.0	45.76	17.1	0.8089	22.61	19345	1225	1763	22333

Note: Normalisation is performed to obtain objective values in 0-1 interval with respect to the extreme values.

Table 3 Utility function values, lifetime costs of interesting designs A-J

Designs	A	B	C	D	E	F	G	H	I	J
TCS Mil\$	19.04	19.07	19.12	19.17	19.19	19.21	19.24	19.28	19.31	19.34
LCF Mil\$	21.83	21.68	21.42	21.17	21.10	21.03	20.94	20.85	20.77	20.68
LCT Mil\$	40.87	19.75	40.54	40.34	40.29	40.24	40.18	40.13	40.08	40.03

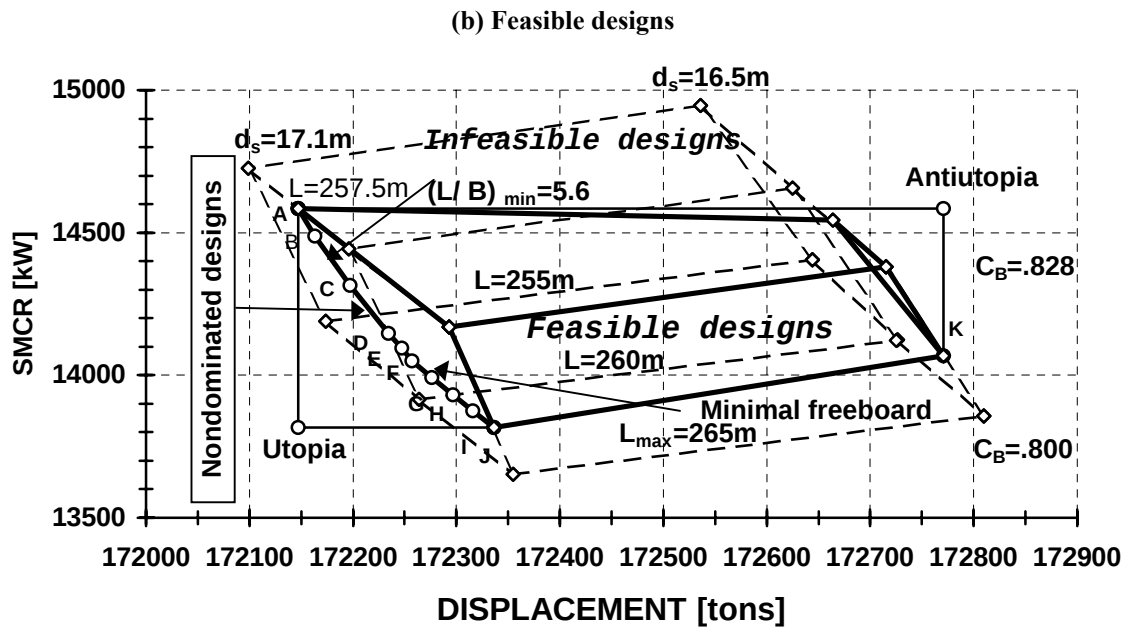
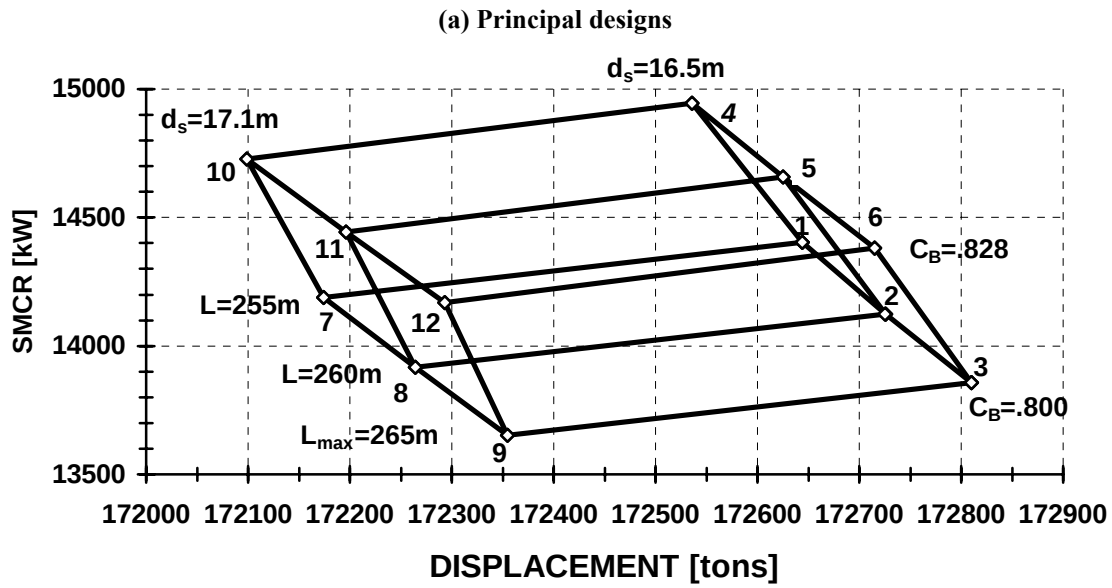


Figure 2 Designs in Δ -SMCR space, attribute space

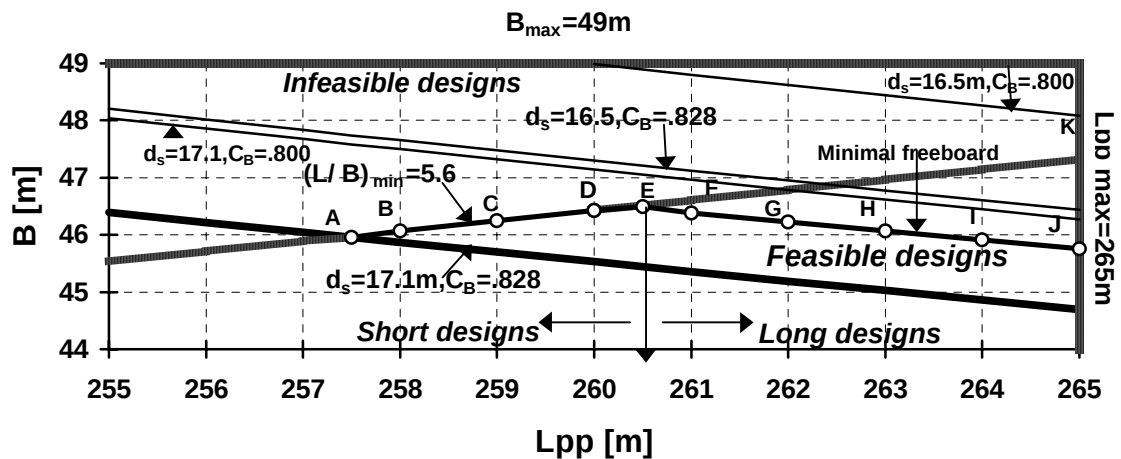


Figure 3 Designs in design subspace L-B

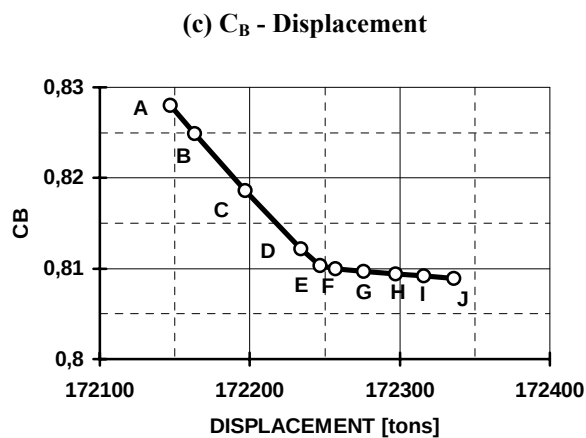
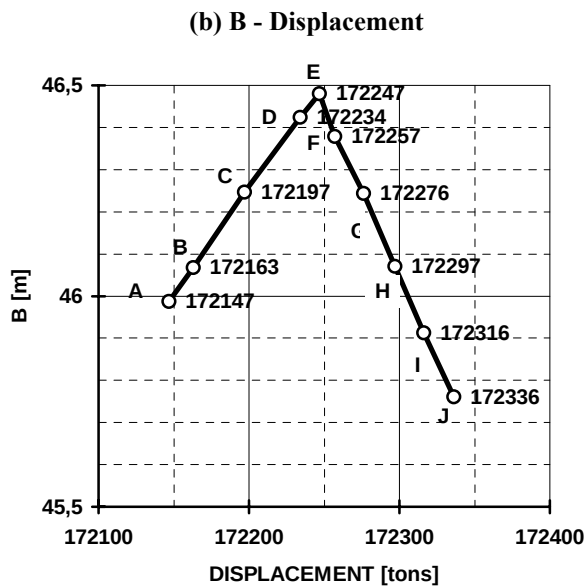
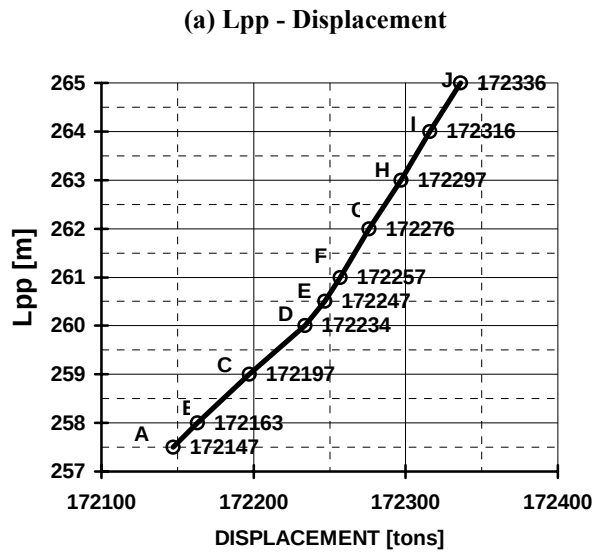


Figure 4 Relation of the design variables L, B, C_B and displacement Δ for designs A-J

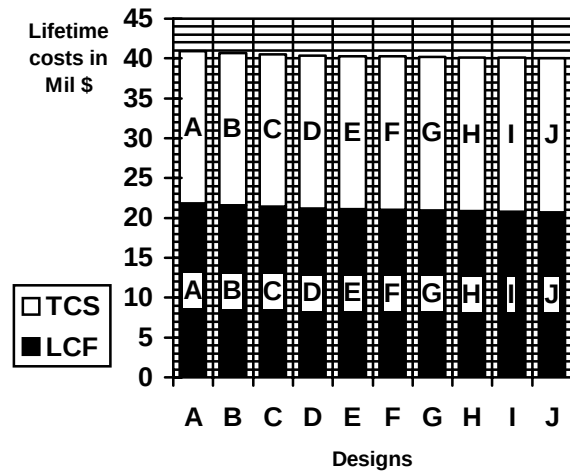


Figure 5 Total lifetime costs of interesting designs A-J

BICRITERIAL DECISION-MAKING APPROACH

The evaluation process can be considered as a mapping from design space to attributed space. The design process is in contrary mapping from the attributed space to the design space, i.e., calculation of most appropriate values of design variables for given aspiration level of attributes [Žanić, Grubišić & Trincas 1992].

Let us consider first the favorable and unfavorable extreme of attribute functions. The first objective is to minimize displacement, $\Delta_{\text{MIN}}=172\,148\text{ t}$, presented by design A. The second objective is to minimize selected maximum continuous rating, $\text{SMCR}_{\text{MIN}}=13\,817\text{ kW}$, presented by the design J, see Fig. 2(b).

The first "anti-objective" is the maximal displacement $\Delta_{\text{MAX}}=172\,771\text{ t}$, presented by design J. The second "anti-objective" is the maximal selected maximum continuous rating presented by design A.

The considered design criteria are conflicting; i.e., for lower displacement a higher power is needed, and vice versa.

There is no optimal solution of the considered design model; i.e., there is no solution for which all the attribute functions enrich their extreme in objectives all at once.

The ideal solution defined by a favorable extreme of attributed functions is infeasible, therefore denoted as "utopia." Utopia is defined by intersection of coordinates of the design points A and I, and in the same context, "anti-utopia" is the most unfavorable combination defined by intersection of coordinates of the design points A and J, see Fig. 2(b). The "utopia" and the "anti-utopia" are infeasible, due to violation of all constraints.

Nondominated or efficient solutions (Pareto optimal solutions) correspond to designs which are better than any other feasible design in at least one objective, and

can be identified by inspection as the lowest contour in Fig. 2(b). The characteristic nondominated designs correspond to interesting designs denoted A-J; see also Table 2.

A bicriterial approach with weighted goals is considered next. The subjective weighting factors W_1 and W_2 relating to Δ and SMCR without any particular physical or commercial meaning, can vary in the normalized range 0-1. The results are given in Table 4.

Due to different physical meanings of the objectives, i.e., incommensurable units, the goal programming is performed in reduced standardized attribute space.

Reduction is provided to determine the subspace bounded by optima of individual objectives.

Normalisation is performed to obtain all objective values in the 0-1 interval.

The goal programming approach is presented next.

The objective function is determined as a distance between the design and a predefined goal (target). Targets are in general unattainable aspirations on design attributes, often based on subjective assessments. Different metrics are available (L_1 , L_2 and L_∞).

The first target is set equal to the ideal (utopia), and therefore is giving the compromising solution by definition, and the other targets are subjectively assessed. The results of the goal programming approach are the compromise solutions given in Table 5.

The bicriterial decision-making approach requires a significant level of subjective assessments and experience with the interpretation of the results of design selection.

Table 4 Design selection by weighted goals approach

No	W_1	W_2	Δ t	norm	SMCR kW	norm	L_{pp} m	B m	d m	C_B	
1	0.50	0.50	172244	0.515	14084	0.348	260.4	46.48	17.1	0.810	
2	1.00	0.00	172147	0.000	14584	1.000	257.5	45.96	17.1	0.828	(Design A)
3	0.00	1.00	172335	1.000	13817	0.000	265.0	45.76	17.1	0.809	(Design J)

Table 5 Design selection by compromising based on L_1 , L_2 and L_∞ - metrics

G O A L S				C O M P R O M I S I N G S O L U T I O N S						V A R I A B L E S			
No	Δ $tons$	norm	SMCR kW	norm	Metrics	Δ $tons$	norm	SMCR kW	norm	L_{pp} m	B m	d m	C_B
1	172148	0.0	13817	0.0	L_1	172243	0.508	14093	0.360	260.3	46.482	17.1	0.828
2	172266	0.6	13817	0.0	L_1	172266	0.631	14023	0.269	261.5	45.292	17.1	0.828
3	172148	0.0	14278	0.6	L_1	172212	0.342	14250	0.565	259.4	46.309	17.1	0.816
1	172148	0.0	13817	0.0	L_2	172243	0.508	14093	0.360	260.3	46.482	17.1	0.821
2	172266	0.6	13817	0.0	L_2	172295	0.786	13933	0.152	263.0	46.070	17.1	0.809
3	172148	0.0	14278	0.6	L_2	172189	0.220	14366	0.716	258.7	46.196	17.1	0.820
1	172148	0.0	13817	0.0	L_∞	172231	0.444	14156	0.441	260.0	46.424	17.1	0.812
2	172266	0.6	13817	0.0	L_∞	172295	0.786	13933	0.152	263.0	46.070	17.1	0.809
3	172148	0.0	14278	0.6	L_∞	172183	0.187	14402	0.763	258.5	46.157	17.1	0.821

EVALUATION OF UNCERTAINTIES FOR SUEZMAX TANKER DESIGN MODEL

The uncertainties for the Suezmax tanker design are considered in terms of tolerances. The assessment of tolerances was found more appropriate from the shipbuilder's point of view. Much information about the uncertainties is available as tolerances rather than as statistical properties. It is also easier to interpret the results of uncertainty

analysis expressed in terms of tolerances which can be hold under control by inspection. Most of the contractual obligations for shipbuilders are given in the form of tolerances. The worst-case approximate tolerance analysis with nonlinear problems [Creveling 1996] or more general post-optimal uncertainty assessment [Žiha 1997] can be applied.

Computational and model uncertainties

The powering uncertainty with respect to selected maximum continuous rating SMCR can be assessed from the regression analysis of engine brake power

P_b , given the standard deviation of 50 kW. The tolerance is taken as threefold standard deviations:

$$t_{P_b}^{upp} = +150kW, t_{P_b}^{low} = -150kW$$

The tolerance of the power margin M_p is assumed following engineering reasoning as:

$$t_{M_p}^{upp} = +0.02, t_{M_p}^{low} = -0.01$$

The tolerance on SMCR can be calculated as:

$$t_{SMCR}^{upp} = \frac{P_b + t_{P_b}^{upp}}{1 - (M_p + t_{M_p}^{upp})} - \frac{P_b}{1 - M_p} kW$$

$$t_{SMCR}^{low} = \frac{P_b + t_{P_b}^{low}}{1 - (M_p + t_{M_p}^{low})} - \frac{P_b}{1 - M_p} kW$$

Considering the whole range of engine brake power P_b , the mean tolerance can be calculated:

$$t_{SMCR}^{upp} = +490kW, t_{SMCR}^{low} = -320kW$$

The tolerances on light ship weight LS and displacement Δ can be obtained empirically by considering tolerances on component weights of the ship.

Following tolerances on steel weight W_s , machinery weight W_m and outfit weight W_o are assumed:

$$t_{W_s}^{upp} = +200t, t_{W_s}^{low} = -100t$$

$$t_{W_m}^{upp} = +50t, t_{W_m}^{low} = -30t$$

$$t_{W_o}^{upp} = +150t, t_{W_o}^{low} = -70t$$

Consequently, the tolerance on the light ship weight LS can be calculated as:

$$t_{LS}^{upp} = +400t, t_{LS}^{low} = -200t$$

Since the required nominal deadweight DW is constant, the displacement tolerance for nominal displacement Δ is the same as for the light ship weight LS:

$$t_{\Delta}^{upp} = +400t, t_{\Delta}^{low} = -200t$$

Operational uncertainties

The ship's lifetime is not limited on the nominal value and usually is longer, but sometimes it can be shortened too, for example as shown:

$$t_{LT}^{upp} = +5years, t_{LT}^{low} = -2years$$

The specific fuel consumption SFOC deviation from the nominal values is usually declared by the manufacturer and for the anticipated main engine is given as 3%.

The lifetime deviation of SFOC can be even greater than the declared values, and is assumed as follows:

$$t_{SFOC}^{upp} = +8 \frac{10^{-6}t}{kWh}, t_{SFOC}^{low} = +2 \frac{10^{-6}t}{kWh}$$

The cost of fuel CF over ship's lifetime is hardly predictable. The following tolerance is assumed:

$$t_{CF}^{upp} = +20 \frac{\$}{t}, t_{CF}^{low} = -10 \frac{\$}{t}$$

The sailing time ST uncertainties are obtained from statistical data for tankers [Soares & Moan 1982], and are presented in terms of following tolerances:

$$t_{ST}^{upp} = +5days, t_{ST}^{low} = -10days$$

The lifetime fuel cost LCF tolerance can be calculated as:

$$t_{LCF}^{upp} = (LT + t_{LT}^{upp})(ST + t_{ST}^{upp})24hours/day \cdot (SFOC + t_{SFOC}^{upp})(CF + t_{CF}^{upp})(P_b + t_{P_b}^{upp}) - LCF, \$$$

$$t_{LCF}^{low} = (LT + t_{LT}^{low})(ST + t_{ST}^{low})24hours/day \cdot (SFOC + t_{SFOC}^{low})(CF + t_{CF}^{low})(P_b + t_{P_b}^{low}) - LCF, \$$$

Building uncertainties

The following tolerance on assumed specific built in steel cost CS is:

$$t_{CS}^{upp} = +100 \frac{\$}{t}, t_{CS}^{low} = -250 \frac{\$}{t}$$

The tolerance of total cost of steel TCS is calculated as:

$$t_{TCS}^{upp} = (W_s + t_{W_s}^{upp})(CS + t_{CS}^{upp}), \$$$

$$t_{TCS}^{low} = (W_s + t_{W_s}^{low})(CS + t_{CS}^{low}), \$$$

Total lifetime costs uncertainties

Finally, the tolerance of the total lifetime cost LCF is calculated as:

$$t_{LCT}^{upp} = t_{LCF}^{upp} + t_{TCS}^{upp}, \$, t_{LCT}^{low} = t_{LCF}^{low} + t_{TCS}^{low}, \$$$

The derivatives of the total lifetime cost function with respect to the design parameters are:

$$\begin{aligned}\frac{\partial LCT}{\partial T} &= ST \cdot 24 \cdot SFOC \cdot CF \cdot P_b \\ \frac{\partial LCT}{\partial ST} &= LT \cdot 24 \cdot SFOC \cdot CF \cdot P_b \\ \frac{\partial LCT}{\partial SFOC} &= LT \cdot ST \cdot 24 \cdot CF \cdot P_b \\ \frac{\partial LCT}{\partial CF} &= LT \cdot ST \cdot 24 \cdot SFOC \cdot P_b \\ \frac{\partial LCT}{\partial P_b} &= LT \cdot ST \cdot 24 \cdot SFOC \cdot CF \\ \frac{\partial LCT}{\partial W_s} &= CS \text{ and } \frac{\partial LCT}{\partial CS} = W_s\end{aligned}$$

For calculated values of P_b and W_s , for example, of design "A", the appropriate values of the derivatives (i.e. rates of change or sensitivity factors) in foregoing equations are 1 455 367, 77 966, 1.32×10^{11} , 218 305, 1 663, 1 000 and 1 9042, respectively. All the derivatives are greater then zero under all circumstances for all designs.

By substituting the appropriate tolerance values, the tolerance of the lifetime costs, for nominal ship's lifetime, as presented in Table 3, is given in Table 6.

Table 6 Tolerance on lifetime costs of interesting designs A-J in Mil \$

Design	A	B	C	D	E	F	G	H	I	J
$t_{TCS} \text{Mil\$}$	+2.12	+2.12	+2.13	+2.14	+2.14	+2.14	+2.14	+2.15	+2.15	+2.15
	-4.84	-4.84	-4.85	-4.86	-4.87	-4.88	-4.89	-4.90	-4.90	-4.91
$t_{LCF} \text{Mil\$}$	+6.44	+6.40	+6.33	+6.26	+6.22	+6.20	+6.18	+6.16	+6.14	+6.12
	-2.87	-2.85	-2.82	-2.79	-2.79	-2.77	-2.76	-2.75	-2.74	-2.73
$t_{LCT} \text{Mil\$}$	+8.57	+8.53	+8.46	+8.40	+8.38	+8.36	+8.34	+8.32	+8.29	+8.27
	-7.70	-7.69	-7.68	-7.67	-7.66	-7.66	-7.66	-7.65	-7.65	-7.64

Discussion on the design uncertainty analysis

Let us consider first the displacement Δ and selected maximum continuous rating SMCR with respect to computational uncertainties of the mathematical model. The overall difference in displacement Δ of designs A and J is $\Delta_J - \Delta_A = 172\,335 - 172\,148 = 187\,t$ and it is less of the calculated displacement tolerance limits of $+400\,t$ or $-200\,t$; see Fig. 7. In addition it is less of the assumed steel weight tolerance of $+200\,t$ and also less of the generally adopted deadweight penalty tolerance of about $400\,t$ to $500\,t$ for ships of the considered size. Moreover, the entire difference in displacement of all the feasible designs is $\Delta_K - \Delta_A = 172\,771 - 172\,148 = 623\,t$, and a great many feasible designs can be tolerated from a displacement point of view. The overall difference in SMCR of designs A and J is $SMCR_A - SMCR_J = 14\,584 - 13\,817 = 767\,kW$. Considering designs A to J, the discrimination of groups according to tolerance limits can be achieved by using the powering tolerance on SMCR of $+490\,kW$ and $-320\,kW$. By using design E as the reference points, two clusters can be identified by inspection; see Fig. 7.

characterized by smaller length, lower displacement, higher propelling power and by the active constraint L/B.

- The second group, denoted as the "long" design comprises designs D-J. The "long" designs are characterized by greater length, higher displacement, lower propelling power and by active freeboard limitation.

In addition, clustering can be performed also by the normalized objective values of Δ and SMCR presented in Table 2., representing the relative importance of individual objective to a specific design. For both the objectives, the half-value 0.5 of the normalized objectives is between designs C and D, indicating the two earlier identified clusters denoted as "short" and "long" designs.

The overall difference in total built-in steel cost, especially interesting from the shipbuilder's point of view, between designs A and J is $TCS_J - TCS_A = 19.34 - 19.04 = 0.30\, \text{Mil\$}$, which is below the calculated building uncertainties of $+2.14$ and $-4.87\, \text{Mil\$}$, see Fig. 6.

- The first group, denoted as the "short" design, comprises designs A-D. The "short" designs are

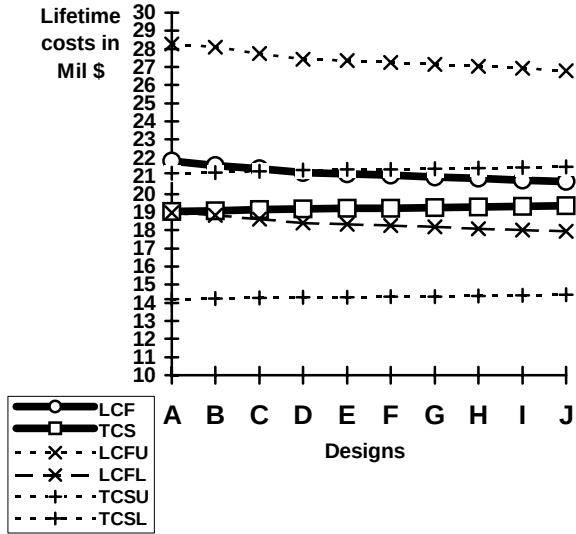


Figure 6 Lifetime costs uncertainties

The overall difference in lifetime fuel cost between designs A and J is
 $LCF_A - LCF_J = 21.83 - 20.68 = 1.15$ Mil\$,
 which is below the calculated uncertainties of $+6.24$ and -2.80 Mil\$, see Table 6 and Fig. 6.

The uncertainty in total lifetime cost of $+8.40$ and -7.40 Mil\$ highly exceeds the overall difference in total lifetime cost, interesting for shipowners, between designs A and J, of
 $LCT_A - LCT_J = 40.87 - 40.03 = 0.84$ Mil\$,
 as well as the maximal difference between the feasible designs with highest and lowest cost of $41.25 - 40.03 = 1.22$ Mil\$.

Considering the building and operational uncertainties of designs A-J, a very high dispersion of lifetime costs under assumed conditions is detected; see Table 6 and Fig. 6. Moreover, the considered feasible designs have wide tolerance limits of operational costs under uncertain conditions.

The amount of the uncertainties of the total steel cost and lifetime fuel cost can change benefits of selected designs with respect to the total lifetime cost. Even much smaller changes in uncertain design parameters, assumed in the paper, can affect ordering of designs with respect to considered objectives in the ship's lifetime.

The uncertainties from the shipowner's point of view can be even greater with regard to the uncertain commercial conditions during the ship's operational lifetime, using, for example ship's merit factor or required freight rate as possible objectives.

Practical verification of the design procedure is difficult, probably impossible for the entire ship's lifetime. At least, the comparison to similar ships designed elsewhere or already operating can be helpful in calibration of data and improvement of the design procedure. Therefore, the principal data of recently announced Suezmax tankers, available in professional publications, are given in Table 7.

The investigation of the uncertainties in a design analysis can indicate a wider range of satisfactory solutions within tolerable limits. Such an approach can give an adequate explanation that in uncertain conditions the strict, mathematically defined optimum cannot often be clearly distinguished from a number of other apparently suboptimal solutions.

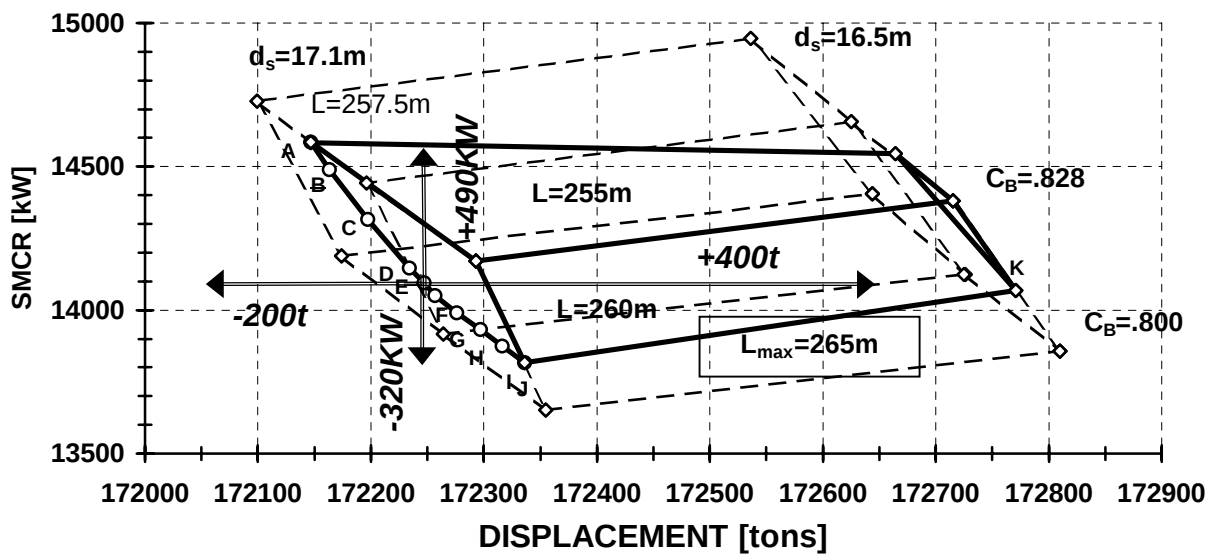


Figure 7 The computational uncertainties on SMCR and Δ , attribute space

Table 7 Recently built Suezmax tankers: principal, operational and building data

L _{oa} m	Principal dimensions				Operational data						Building data	
	L _{pp} m	B m	d m	D m	DWT t	Speed knots	Range NM	MCR kW	rpm	NCR kW	rpm	
274.3	263.3	44.5	16.93	24.7	142674	14.6	20000	14480	83	13030	80	IHI-Japan
269.0	258.0	46.0	17.50	24.4	153000	15.0	20000	20900	83	18810	80	Halla Eng
278.0	265.0	43.0	17.00	24.0	144000	14.0		14700				NKK
276.0	264.0	45.1	17.10	23.8	150000	14.0		22380	94			Fincantieri
274.0	264.0	46.0	16.60	23.6	148000	15.0	22700	21050	91	18945		Samsung
274.0	264.0	47.8	16.00	22.8	148500	15.0	22700	20940	88	18850		Samsung

CONCLUSIONS

The presented compact mathematical model comprises the relevant design requirements on Suezmax tankers based on comprehensive design consideration. The experience of the outlined mathematical model with four design variables and with two design objectives encourages the idea that even simple models can be used at the beginning of the design process. This can be achieved by implementation of numerically reliable and practically tested design procedures based on experiences in the shipyard and on verified engineering methods and data. The presented task can be considered as method-independent; i.e., any reliable numerical/optimization method is applicable to solve this problem. Graphical, analytical, and tabular presentations can help decisions.

The selected Suezmax tanker design attributes have commercial and physical meanings and their cardinal weights or aspired goals must not be subjectively assessed. The identification of nondominated designs was found as a useful guideline in the design procedure. The unicriterial decision support using utility function based on technical and economical considerations of tanker design, production and operation, free of the designer's subjective assessments, was found more appropriate of the bicriterial approach.

The uncertainty analysis can explain why so many different ships of the same type have been successfully operating ocean-wide, in spite of their different principal characteristics, as well as how an experienced designer could guess a satisfactory design within tolerable limits.

Note that the breadth of interesting designs of 45.76 m to 46.42 m is significantly below the permissible breadth for Suez of 48.16 m (due to minimal freeboard requirement); i.e., the breadth-to-draft product $B \times d_s$ is less than maximum allowed 814 m². This means that even larger tankers, with deadweight greater than the selected 150 000 tdw, could pass the Canal if some of the constraints could be lifted.

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