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RESEARCH PAPER

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A study on the preliminary ship design method using deterministic approach and probabilistic approach including hull form

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Abstract This paper describes a preliminary ship design method using deterministic approach and probabilistic approach in the process of hull form design. In the deterministic approach, an interdisciplinary ship design method integrates principal dimension decisions and hull form variations in the preliminary ship design stage. Integrated ship design, as presented in this paper, has the distinctive feature that these parameters are evaluated simultaneously. Conversely, in sequential design, which is based on the traditional preliminary ship design process, hull form designs and principal dimension decisions are determined separately and sequentially. The current study adopts the first method to enhance the design quality in the early design stage. Furthermore, a probabilistic approach is applied to ship design to resolve uncertainties in design information more efficiently than a deterministic approach would.

Keywords Preliminary ship design · Principal dimension decision · Hull form variation · Deterministic approach · Probabilistic approach

1 Introduction

Ship design essentially applies iteration to satisfy the relevant requirements, such as stability, power, weight, and strength. In the preliminary ship design stage, most shipyard designs (Fig. 1) commence with hull form variations (for example, the existing section's characteristic transformation and variation of CP and LCB) after determining the principal dimensions based on parent (basis) ship information. This traditional preliminary design process provides insufficient and sequential design information (Fig. 2a) because hull form variations can be determined only after principal dimension decisions are made. Based on these features, conventional design may not optimally balance ship design solutions. Multidisciplinary design optimization (MDO) is considered among the solutions to the above-mentioned problems. Recently, sequential design-based MDO has been applied to preliminary ship design (Lee et al. 2001), but in that study, designs required individual optimization, and techniques were highly dependent on empirical formulation. Moreover, this approach required additional design iterations. In particular, design evaluation costs continued to increase due to the characteristic properties of sequential design with feedback. Therefore, MDO must be included in the integrated design strategy to obtain high necessity on the industry field. This study aims to concurrently (Fig. 2b) integrate principal dimension decisions and hull form variations, concurrently, to enhance the effectiveness of preliminary ship design. In addition, computational aspects must be considered in the optimization iteration when principal dimension decisions and hull form variations are integrated and hydrostatic coefficients are applied. In the initial stage, meanwhile, ship design is conducted by restricting design information and uncertain design estimation. To effectively consider all the uncertainties of the design information, the preliminary ship designs based on probabilistic and deterministic approaches must be compared.

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2 Preliminary ship design for deterministic approach

2.1 Traditional preliminary ship design

Traditional preliminary ship design, as shown in Fig. 3, was conducted (using a typical iterative process) to determine fundamental parameters, such as length, breadth (beam), depth, draft, power, or alternative sets of characteristics, all of which met the speed, cargo capacity, and deadweight requirements. Variation of the hull form was conducted after making the principal dimension decisions. Thus, this conventional ship

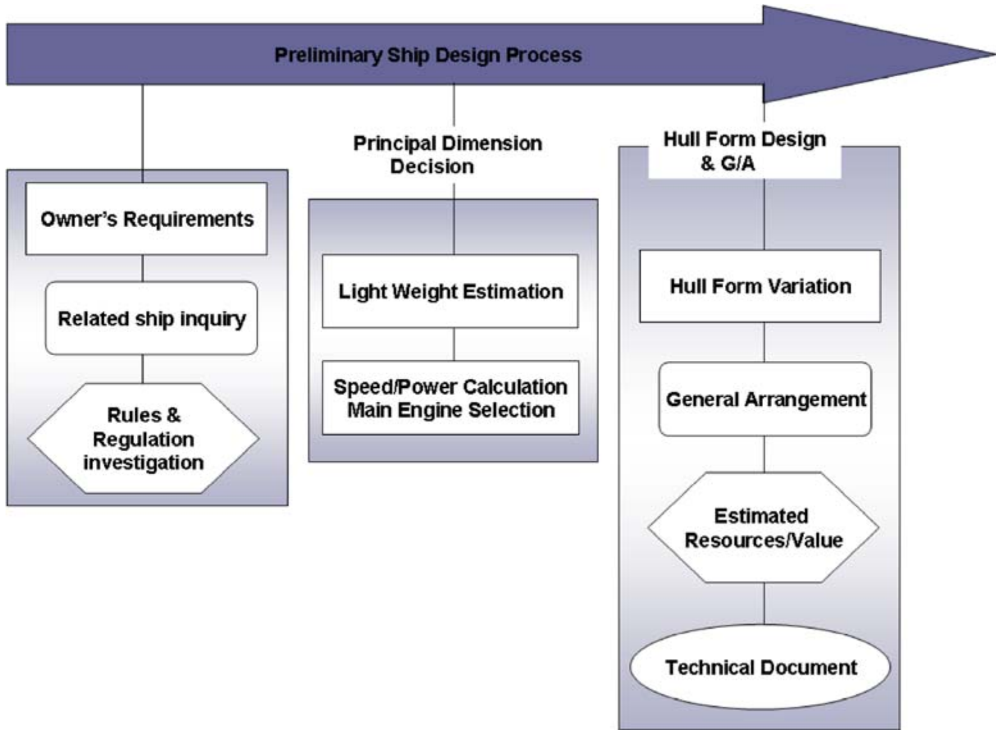


Fig. 1 Preliminary ship design process

design, which is based on making design decisions sequentially, involves numerous iterative processes, all of which must work toward satisfying all requirements. Especially, when feedback is used, this design must carry out additional iterations, ultimately increasing estimated design costs.

2.2 Sequential preliminary ship design optimization

Sequential preliminary ship design optimization (Fig. 4) is a methodology used in the traditional ship design process and supplements existing optimization schemes. Traditional preliminary ship design, as illustrated in Fig. 3, requires many iterations, so sequential preliminary ship design optimization is used to enhance computational efficiency.

2.3 Integration of interdisciplinary ship design including hull form

In integrated interdisciplinary ship design (Fig. 5), principal dimensions and hull form variations are evaluated concurrently. These parameters were thus intimately associated because hydrostatic coefficients could be directly computed and simultaneously susceptible to the analysis of the iterative optimization process through hull blending module and hydrostatic module. This method, based on concurrent design

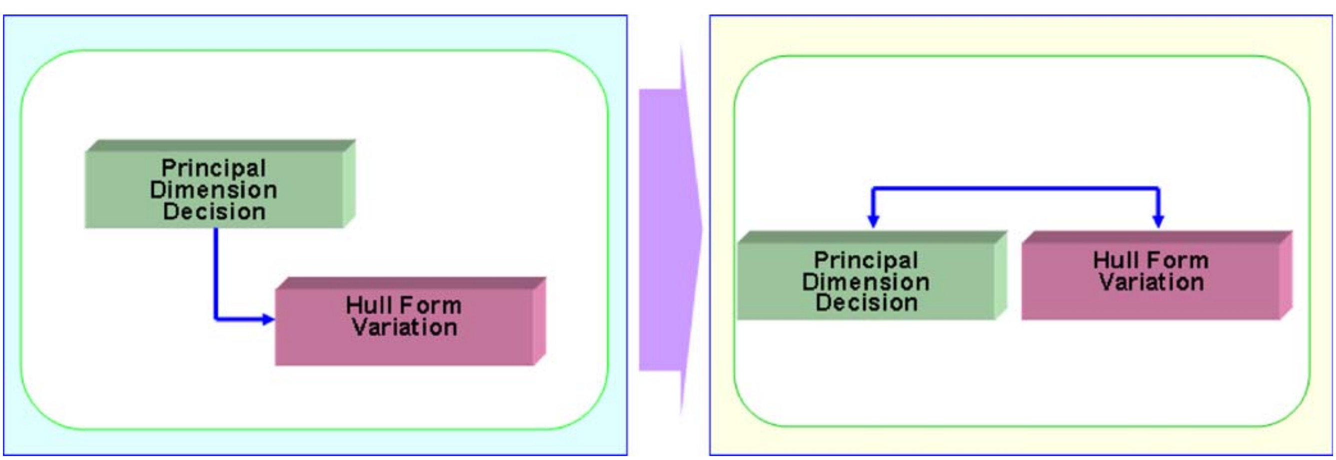
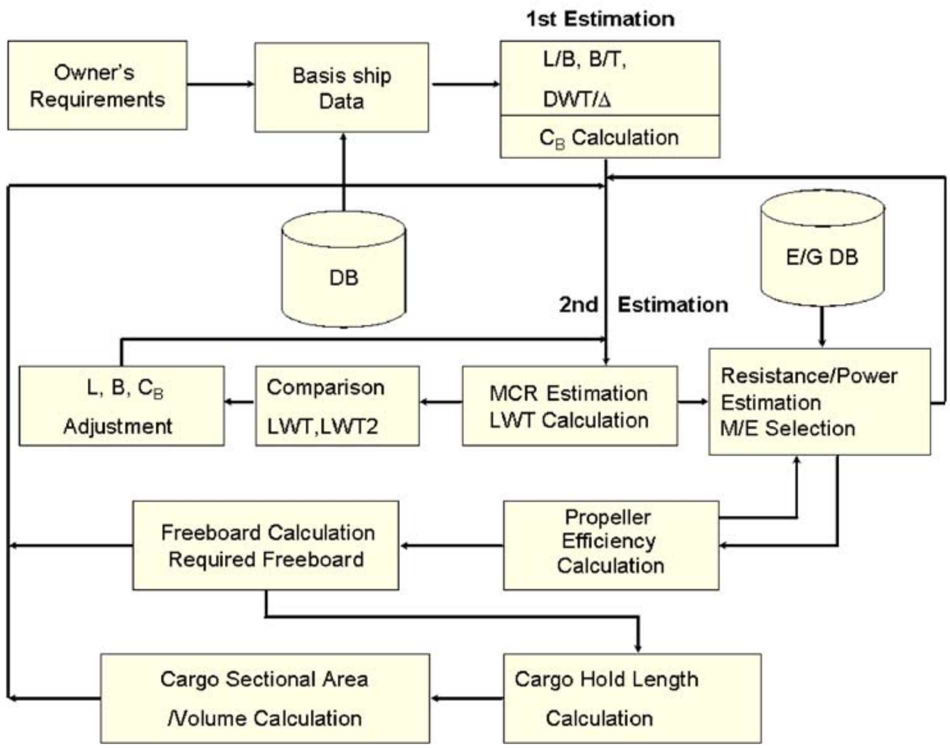


Fig. 2 Preliminary ship design information

Fig. 3 Traditional preliminary ship design



information, is thus considered to be a well-established design method and, in particular, is preferable to the sequential design method.

2.4 Hull from blending technique

Hull form is the design variable used for determining hydrostatic coefficients. The blending coefficient, C_i, was therefore used in hull geometry for controlling the hull shape. The hull blending process (Fig. 6) is assumed to result in the blended hull, in which the basis hull is mixed. This blending technique, (1), was done at Virginia Tech (Neu et al. 2000a,b).

$$\text{Resultant (or blended) ship hull} = \Sigma C_i \times \text{Basis Hull}_i$$
$$\text{such that,} \quad \Sigma C_\mathrm{i} = 1$$
$$\text{and,} \quad 0 \le C_i \le 1, \; i = 1, 2 \ldots, N \tag{1}$$

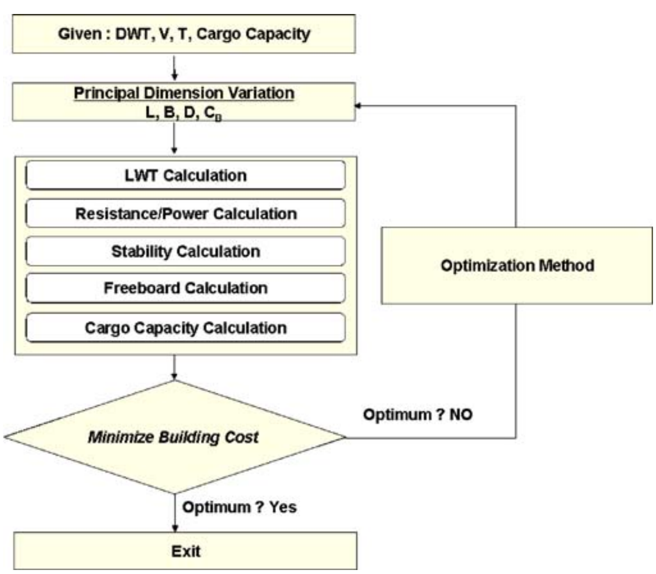


Fig. 4 Sequential preliminary ship design optimization

3 Collaborative optimization (CO)

There have been considerable advances in MDO which is an efficient optimization method for designing large-scale and coupled multidisciplinary systems. Collaborative optimization (CO) (Braun 1996) was recently developed in the MDO research field and was actively researched. The CO formulation (Fig. 7) consists of a two-level hierarchical scheme and a system optimizer that optimizes using the least-squared error method of the subsystem design variables (x_i), satisfying subsystem constraints variables (g_j) and system-level design variables (z) computed from the subspace analysis (y_i). The system-level design variables, z, were assumed to be fixed in the subspace problem. Thus, the disciplinary design variables x_{si}, which are used only by the ith subspace analysis, were distinguished from the interdisciplinary design variables x_i, which are used by more than one subspace analysis. The interdisciplinary compatibility constraints (or

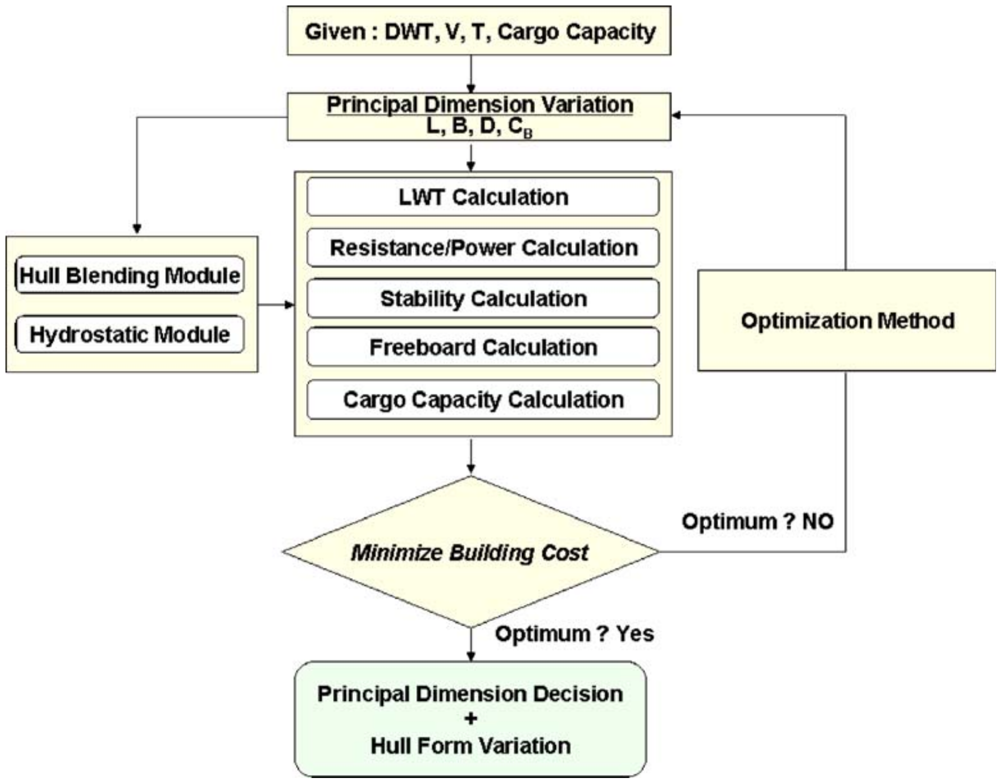


Fig. 5 Integration of interdisciplinary ship design including hull form

discrepancy function, d_i) were formulated as strict equality constraints ($d_i = 0.0$) or inequality constraints ($d_i \leq 0.0001$), where d_i is defined as follows (Kodiyalam 1998):

$$d_i = \left|X_i - Z_i^s\right|^2 + \left|Y_i - Z_i^c\right|^2 \quad (2)$$

where $Z = \{Zs, Zc\}$, Zs represents the system-level design variable, and Zc represents the system-level coupling variable.

4 Preliminary ship design example by deterministic approach

To compare the methods using sequential design information and concurrent design information, five methods were explored as depicted in Table 1. The basis ship used was 278K/300K DWT VLCC, and the design ship was 330K DWT VLCC. This all-in-one method (method 2 and method 3) is formulated as follows.

Given: DWT (deadweight), CV (cargo volume), T (design draft), V (ship speed)
Find (design variables): L, B, D, C_B, D_P, P_i, and A_E/A_O in method 2, and L, B, D, C_i, D_P, P_i, and A_E/A_O in method 3

L (length), B (breadth), D (depth), C_B (block coefficient), C_i (blending coefficient), D_P (propeller diameter), P_i (propeller pitch), A_E/A_O (propeller blade area ratio)
Minimize building cost
Subject to

g_1: $L \cdot B \cdot T \cdot C_B \cdot \rho(1+\alpha) = \text{LWT+DWT}$; buoyancy–weight equilibrium

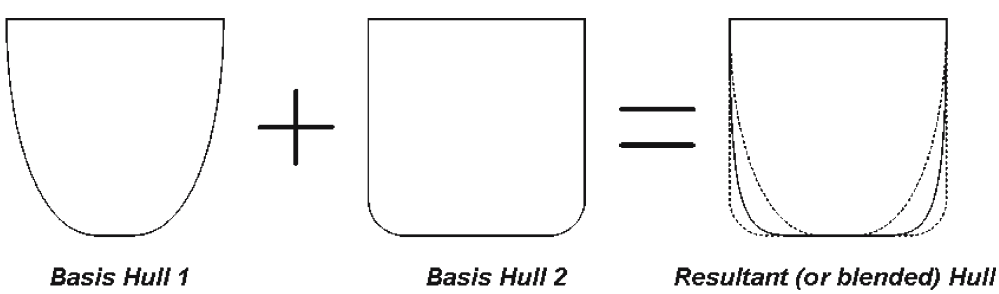
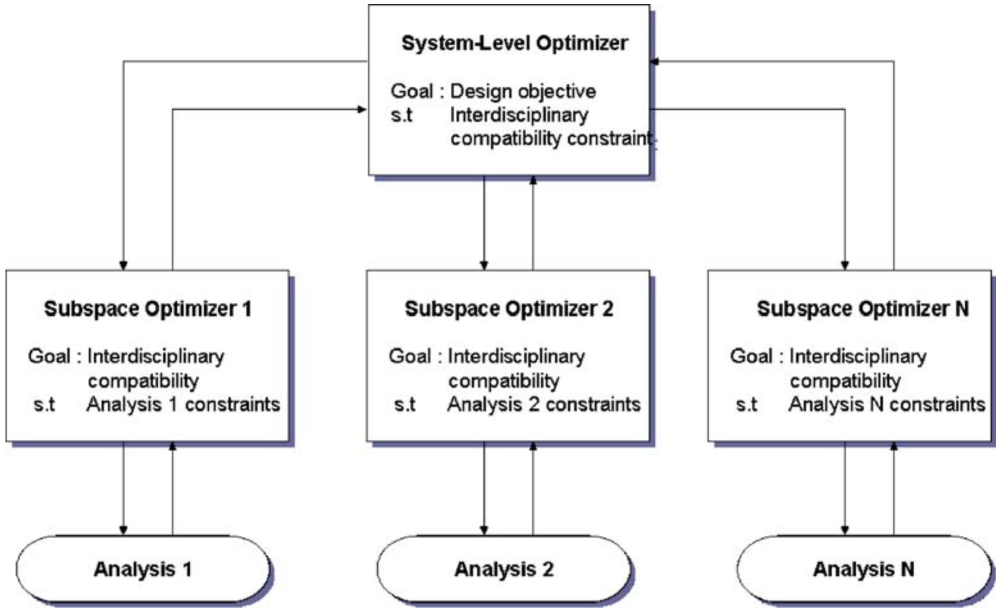


Fig. 6 Description of hull form blending technique

Fig. 7 Collaborative optimization architecture



g_2: $D \geq T + freeboard$; minimum required freeboard condition

g_3: $CV \geq CV_{req}$; required cargo volume constraints

g_4: $0.04B \leq GM \leq 4\pi^2(0.4B)^2/(g\mathrm{Tr}^2)$; initial stability condition

g_5: $C_B/(L/B) \leq 0.15$; obesity coefficient conditions for maneuvering

g_6: $C_B \leq 0.70 + 0.125\ \tan^{-1}[(23 - 100\mathrm{Fn})/4]$; recommended block coefficient by Watson and Gilfillan

Table 1 Use of design method for preliminary ship design example

	Method description	Design information flow	MDO method
Method 1	Separated from principal dimension and hull form variation, based on empirical formulation	Conventional	–
Method 2	Separated from principal dimension and hull form variation, based on empirical formulation	Sequential	All-in-One
Method 3	**Integrated with principal dimension and hull form variation**	**Concurrent**	All-in-one
Method 4	Separated from principal dimension and hull form variation, based on empirical formulation	Sequential	CO
Method 5	**Integrated with principal dimension and hull form variation**	**Concurrent**	CO

g_7: $P\big/(2\pi n) = \rho \cdot n^2 \cdot D_P^5 \cdot K_Q$; propeller must absorb a torque transmitted from the main engine

g_8: $R_T/(1-t) = \rho \cdot n^2 \cdot D_P^4 \cdot K_T$; propeller must deliver a thrust required by the ship in certain speed

g_9: $A_E/A_o \geq \left[K + \frac{(1.3+0.3Z)\cdot T_P}{(D_P^2\cdot(p_o+\rho g h - p_v))}\right]$; propeller must deliver a thrust required by the ship in certain speed

where

α	: Appendage factor
LWT	: Lightweight
GM	: Metacentric height
Tr	: Rolling period
Fn	: Froude number
P	= Power delivered to the propeller by the main engine
T_P	= Propeller thrust = $R_T/(1-t)$
R_T	= Total resistance
t	= Thrust deduction coefficient
n	= Speed of rotation (in revolutions per minute)
K_Q	= Torque coefficient
K_T	= Thrust coefficient
Z	= Number of blades
$P_o + \rho g h$	= Static pressure at propeller shaft center line
P_v	= Vapor pressure
K	= Constant varying from 0 to 0.20

Therefore, this all-in-one scheme of minimizing building cost has eight design variables (L, B, D, C_B, V, D_P, P_i, A_E/A_O or L, B, D, C_i, V, D_P, P_i, A_E/A_O), three equality constraints (g_1, g_7, g_8), and six inequality constraints (g_2, g_3, g_4, g_5, g_6, g_9).

Of the five methods as shown in Table 1, method 1 is the conventional ship design (Fig. 3), method 2 uses the sequential ship design optimization (Fig. 4), method 3 (Figs. 5 and 8) uses the integration of interdisciplinary ship design including hull form, method 4 (Fig. 9) uses CO using sequential design

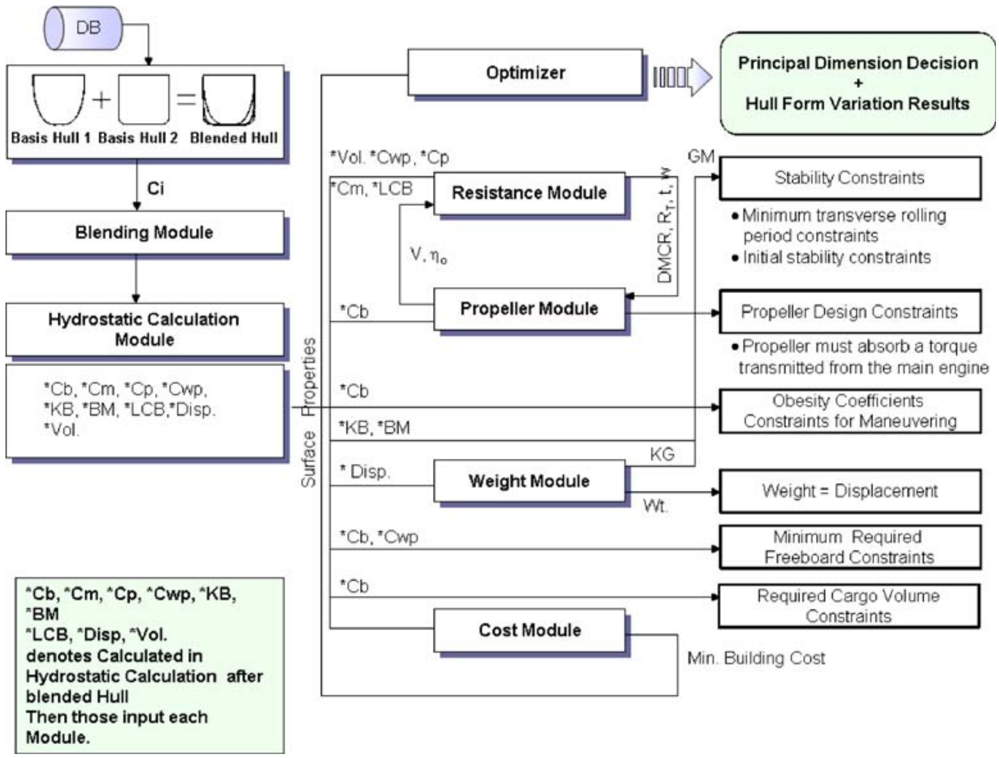


Fig. 8 Example of method 3 of preliminary ship design

information, and method 5 (Fig. 10) uses CO for integration of interdisciplinary ship design including hull form.

Method 4 constitutes a three-subsystem (disciplinary) level, "deadweight requirements", "speed/power requirements", and "cargo volume requirements", to satisfy the interdisciplinary compatibility constraints (d_1, d_2, d_3) at the system level. Method 4 also minimizes the system-level objective function, building cost. Method 5 has a similar formulation to method 4, but an apparent feature of method 5 is the hull form blending coefficient, C_i. That is, method 4 in CO is used to calculate block coefficient, C_B, and method 5 is used to calculate hull form blending coefficient, C_i.

5 An example of preliminary ship design using a probabilistic approach

When deciding principal dimensions during preliminary ship design, ship design is conducted by restricting design information and uncertain estimation. Thus, a probabilistic ap-

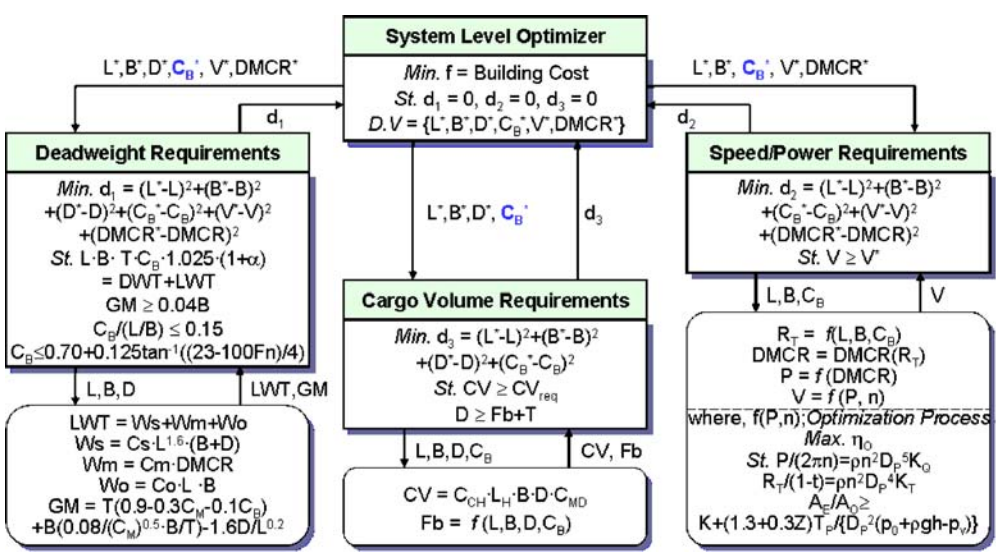
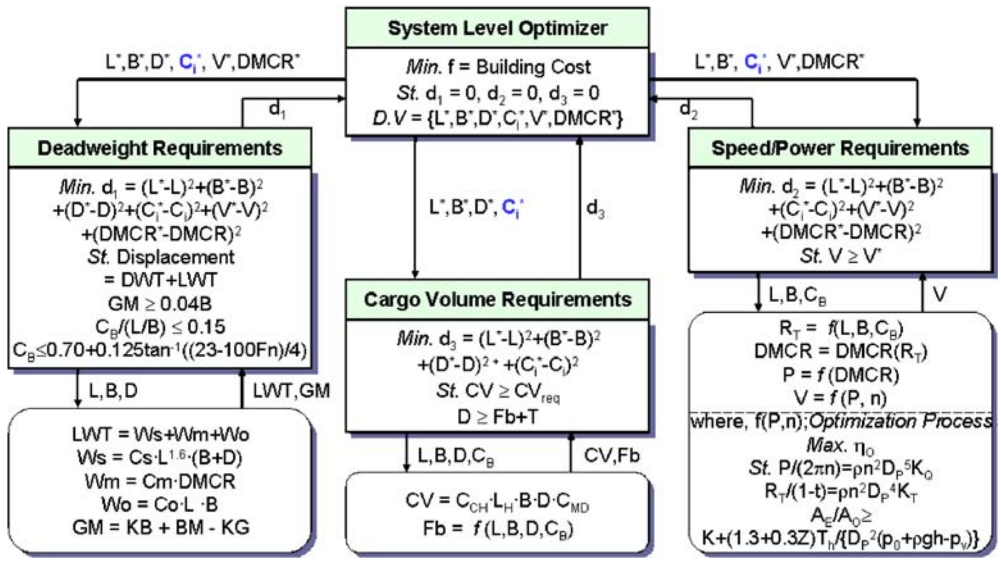


Fig. 9 Example of method 4 of preliminary ship design

Fig. 10 Example of method 5 of preliminary ship design



proach is considered to be a more effective design scheme than the deterministic approach for handling uncertainties or variations of design variables. Knowledge of the total resistance, R_T, is an essential prerequisite for predicting the power when deciding principal dimensions. Probabilistic distributions in proportion to service velocity are known from the experimental data of a model test (Yang 2000) (Figs. 11 and 12) and also can be obtained from a widely known, statistical power prediction method by (Holtrop and Mennen 1982; Holtrop 1984), which is based on a regression analysis. Because of these features, total resistance is treated as a random variable. In this paper, during the principal dimension decision stage, a probabilistic approach, which was efficiently used for the variation of design variables, and a deterministic approach were used to solve a sample ship design (method 2 and method 3) as discussed in the previous section (Figs. 13 and 14). In the probabilistic approach, the limit state equation (LSE), a useful formula by Keller, which is used to avoid cavitation, can be written as (3), where the uncertainty of random variable was assumed to be $\pm 5\%$, the target reliability index (Lee et al. 2002), β, was assumed to be 3.0, and total resistance, R_T, was assumed to be a normally distributed random variable.

$$g(z) = A_E \big/ A_O - \left[K + \frac{(1.3+0.3Z) \cdot T_P}{\left(D_P^2 \cdot (p_o + \rho g h - p_v)\right)} \right] \geq 0 \tag{3}$$

where

A_E/A_O = Propeller blade area ratio (expanded area ratio)
A_O = Propeller disk area $= \pi D_P{}^2/4$
A_E = Expanded blade area derived from the expanded blade outline
D_P = Propeller diameter (m)

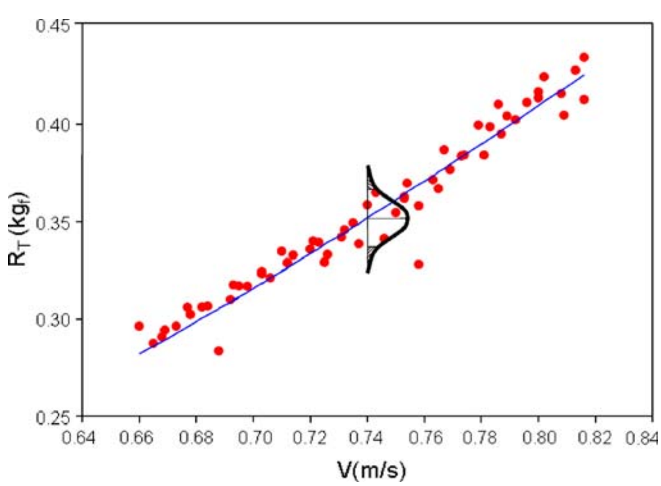


Fig. 11 Measured resistance data of the 300K class VLCC from the 3.0 m (1/100) model

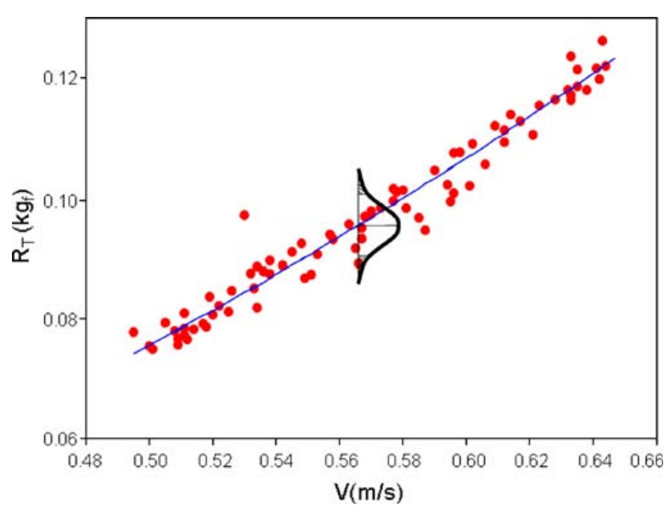


Fig. 12 Measured resistance data of the 300K class VLCC from the 2.0 m (1/160) model

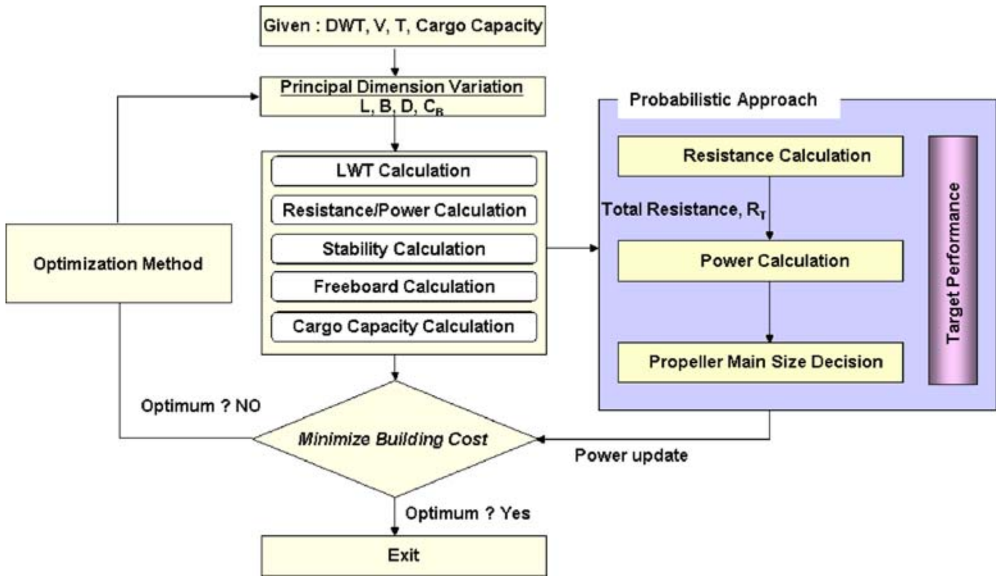


Fig. 13 Probabilistic approach for method 2

T_P = Propeller thrust (kN)=$R_T/(1-t)$
Z = Number of blades
$P_o+\rho gh$ = Static pressure at propeller shaft center line (kN/m^2)
P_v = Vapor pressure
t = Thrust deduction coefficient
K = Constant varying from 0 to 0.20

$$g(z) = \frac{A_E/A_0 \cdot \left(D_P^0 \cdot (p_0 + \rho gh - p_v)\right)}{\left(D_p^2 \cdot (p_0 + \rho gh - p_v)\right)} - \left[\frac{K \cdot \left(D_p^2 \cdot (p_0 + \rho gh - p_v)\right)}{\left(D_P^0 \cdot (p_0 + \rho gh - p_v)\right)} + \frac{(1.3 + 0.3Z) \cdot T_P}{\left(D_P^2 \cdot (p_0 + \rho gh - p_v)\right)}\right] \geq 0 \quad (4)$$

$$g(z) = A_E/A_0 \cdot \left(D_P^2 \cdot (p_0 + \rho gh - p_v)\right) - \left[K \cdot \left(D_P^2 \cdot (p_0 + \rho gh - p_v)\right) + (1.3 + 0.3Z) \cdot T_P\right] \leq 0 \quad (5)$$

$$g(z) = \underline{A_E/A_0 \cdot \left(D_P^2 \cdot (p_0 + \rho gh - p_v)\right)} - \left[\underline{K' + (1.3 + 0.3Z) \cdot T_P}\right] \leq 0 \quad (6)$$

(By contrast with Fig. 15) Resistance term Load term

$$P\big/(2\pi n) = \rho \cdot n^2 \cdot D_P^5 \cdot K_Q \quad (7)$$

$$R_T\big/(1-t) = \rho \cdot n^2 \cdot D_P^4 \cdot K_T \quad (8)$$

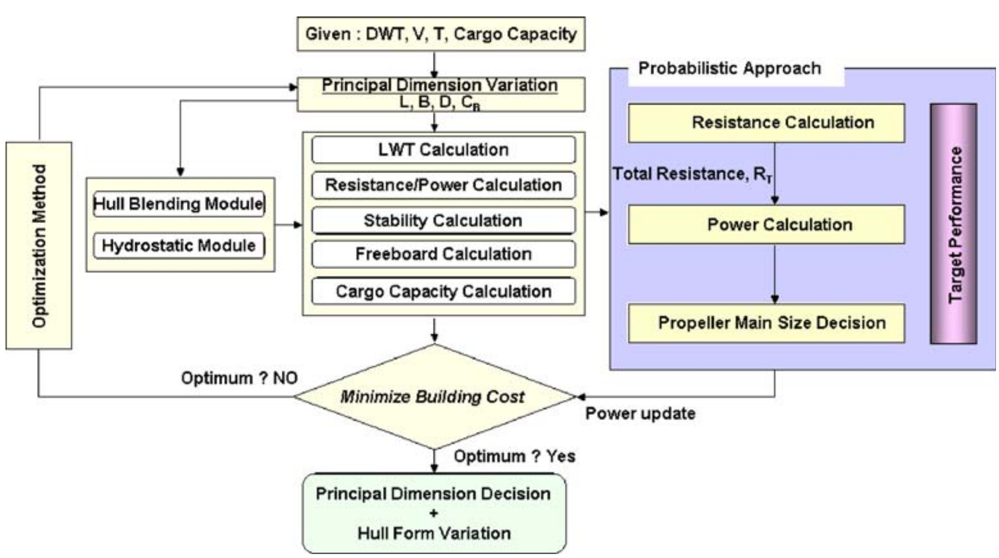


Fig. 14 Probabilistic approach for method 3

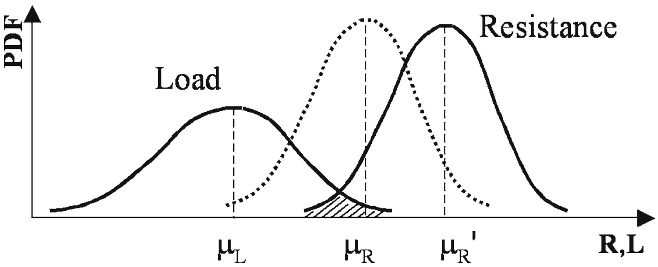


Fig. 15 Change of probability of failure due to change of mean

where

P $=\text{DHP}\cdot\eta_R$
K_Q = Torque coefficient
K_T = Thrust coefficient
DHP = Delivered Power = EHP/η_D
EHP = Effective horse power = $R_T\cdot V$
η_R = Relative rotational efficiency
η_D = Propulsive efficiency
n = Speed of rotation (revolution per minute)

Figure15 shows a sample case of structural reliability analysis considering two terms (the load on the structure, Load, and the resistance of the structure, Resistance). Both Load and Resistance are random in nature; their randomness is characterized by their means, μ_L and μ_R, respectively, as shown in Fig. 15. Let us consider a structure with $\mu_R \to \mu'_R$. The probability of structural failure would decrease (equivalently, the probability density function overlapping the shaded area of the load and resistance graphs diminishes). Similarly, the LSE of the propeller blade area, (3), represents similar behavior as structural reliability as (3)→(4)→(5)→(6). In (6), the total resistance, R_T, is a random variable, and the propeller diameter, D_P, and thrust, T_P, are functions of R_T; in particular, $T_P = R_T/(1-t)$, and propeller diameter varies according to (7) and (8). Finally, in (6), the resistance (*viewpoint of structural reliability*) is the change in the probability of failure due to change of the mean (from the viewpoint of structural reliability).

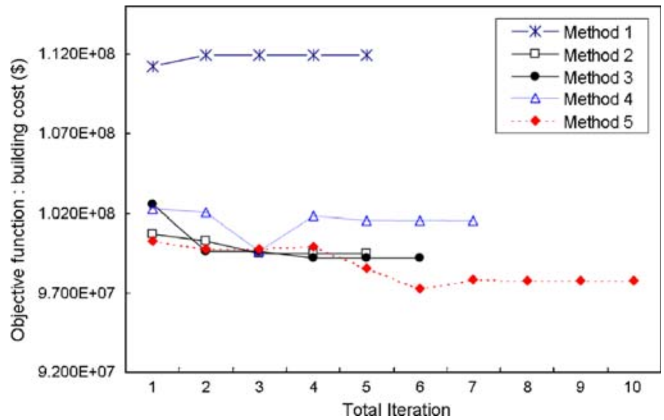


Fig. 16 Convergence history of objective function (building cost) for ship design example

6 Comparison of the deterministic and probabilistic approaches

This paper proposes the integration of interdisciplinary ship design including hull form into the preliminary stage of ship design to overcome difficulties associated with the conventional (sequential) ship design (Table 2). Based on the results of the ship design example (Fig. 16), the relative objective values of the designs produced by various methods are "Objective$_{(\text{method 5})}$ < Objective$_{(\text{method 3})}$ < Objective$_{(\text{method 2})}$ < Objective$_{(\text{method 4})}$ < Objective$_{(\text{method 1})}$". The method 5 design had a 1.48∼14.5% lower objective value than the other methods (Fig. 17) because, as hull forms were adopted as a

Table 2 Comparisons of application example results

		Units	Method 1	All-in-one		CO	
				Method 2	Method 3	Method 4	Method 5
Objective (building cost)		\$	1.19313×10^8	9.94635×10^7	9.91975×10^7	1.01547×10^8	9.77525×10^7
	L	m	325.8	310.0	310.0	312.4	311.4
	B	m	60.4	60.6	57.3	59.5	55.1
	D	m	31.6	29.6	29.4	30.2	26.9
	C_I	–	–	–	0.99	–	0.0
	C_B	–	0.8087	0.8499	0.8112	0.8325	0.8147
	V	knots	15.6	15.6	15.6	15.6	15.6
Optimum	DMCR	PS	40,006.10	35,433.97	35,159.70	35,434.04	35,732.17
	D_P	m	9.83	9.61	10.39	9.39	9.47
	P_I	m	7.07	6.82	7.17	6.49	6.54
	A_E/A_O	–	0.44	0.44	0.56	0.43	0.43
	CV	m^3	378,700.0	420,702.4	396,745.7	379,852.2	380,108.9
	DWT	ton	330,000	330,000	330,000	330,000	330,000
	LWT	ton	39,957.7	36,969.3	35,441.9	40,744.0	33,012.5
System iteration		–	Fifth estimation	5	7	7	10
Function call		–	–	70	141	2,130	7,180

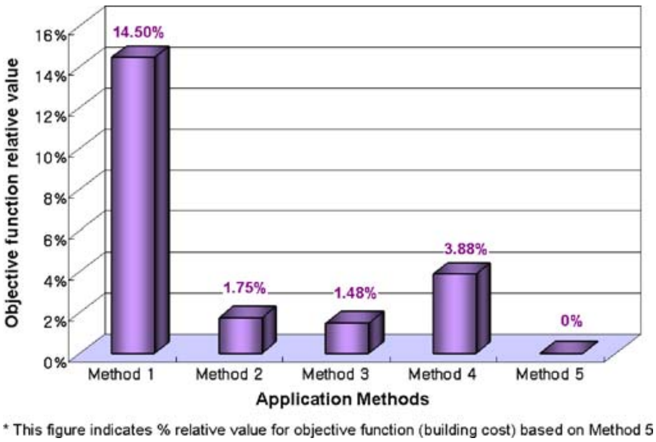


Fig. 17 Comparisons of building costs based on method 5

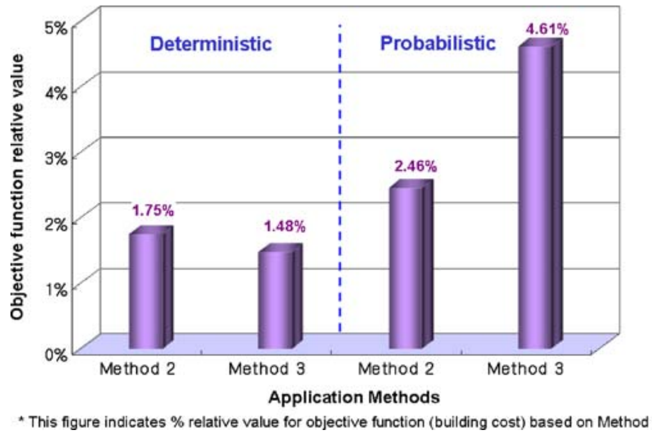


Fig. 18 Comparisons of deterministic and probabilistic results based on method 5

design variable, the extended design space gave better objective solutions than the conventional design approach did.

Furthermore, in the preliminary ship design stage, probabilistic approach was compared to the deterministic approach (Table 3) to manipulate uncertainties, which are expressed by the total resistance, R_T.

Table 3 indicates that variations of total resistance would influence the output value of DMCR, LWT, and building cost; in that order, the thrust of ship, T_S, was then increased with the thrust of propeller, T_P, and the propeller blade area used in a LSE was increased. Based on those results, the propeller principal dimensions (diameter D_P, and pitch P_i) also increased. Therefore, the probabilistic approach using variation of the random variable R_T gave a lower probability of cavitation as depicted in Table 3, $0.5 \rightarrow 0.00135$; that is, in the case of the deterministic approach, the probability of cavitation was 0.5, whereas in the case under probabilistic approach, it was 0.00135.

In conclusion, to integrate principal dimension and hull form decisions concurrently, the proposed method is considered to be superior to the conventional method (Fig. 18). In addition, to deal efficiently with uncertainties in the early design problem, the probabilistic approach is considered to be more appropriate for use in the early design stage than the deterministic one.

7 Conclusions

In traditional preliminary design, hydrostatic coefficients depend on empirical formulations according to sequential design information because hull form variations are determined only after the principal dimensions have been determined. Therefore, this research proposed the integration of interdisciplinary ship design including hull form, which can give more accurate hydrostatic coefficients from hull form infor-

Table 3 Comparisons of deterministic/probabilistic approach using application example

		Units	Deterministic (all-in-one)		Probabilistic (all-in-one)	
			Method 2	Method 3	Method 2	Method 3
Objective (building cost)		$	9.94635×10^7	9.91975×10^7	1.00160×10^8	1.02261×10^8
	L	m	310.0	310.0	310.0	310.0
	B	m	60.6	57.3	60.6	57.3
	D	m	29.6	29.4	29.6	29.4
	C_I	–	–	0.99	–	0.99
	C_B	–	0.8499	0.8112	0.8499	0.8112
	V	knots	15.6	15.6	15.6	15.6
Optimum	DMCR	PS	35,433.97	35,159.70	36,379.97	40,138.75
	D_P	m	9.61	10.39	9.78	10.53
	P_I	m	6.82	7.17	6.96	7.62
	A_E/A_O	–	0.436	0.560	0.444	0.600
	CV	m^3	420,702.4	396,745.7	420,702.4	396,745.7
	DWT	ton	330,000	330,000	330,000	330,000
	LWT	ton	36,969.3	35,441.9	37,031.3	35,843.4
Probability of cavitation, P_c			0.5 ($\beta=0$)	0.5 ($\beta=0$)	0.00135 ($\beta=3$)	0.00135 ($\beta=3$)

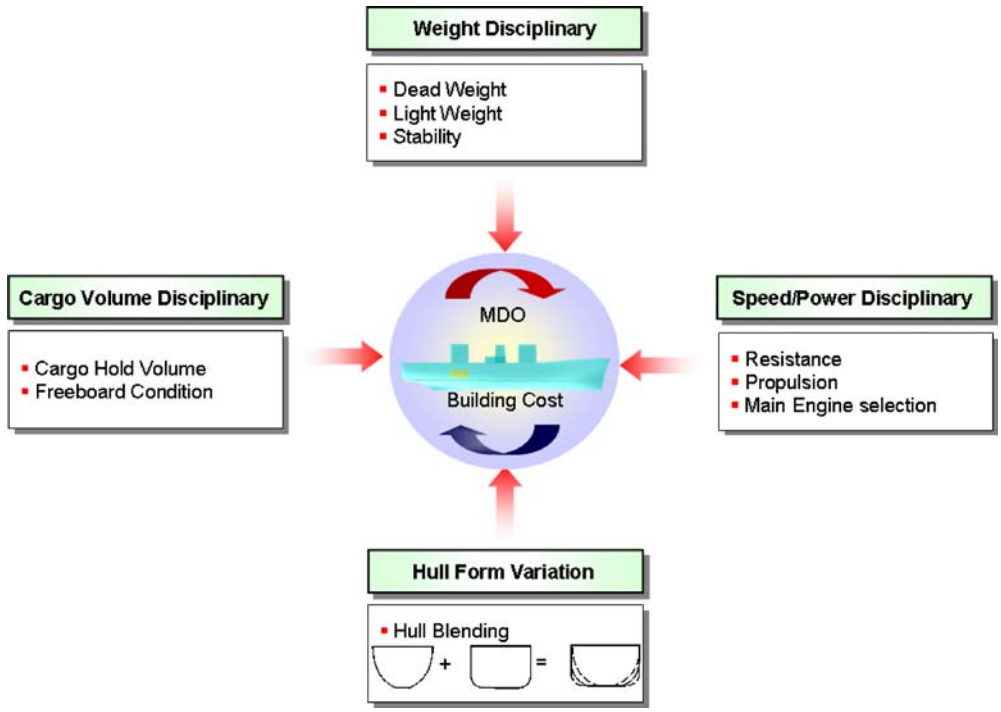


Fig. 19 Proposed method of preliminary design using MDO

mation. These hydrostatic coefficients can then be applied directly to the optimization constraints. To consider concurrently the principal dimension decisions and hull form variations (Fig. 19), a hull form blending technique was introduced. Therefore, the hydrostatic coefficients of the hull can be determined from values such as the midship coefficient (C_m), waterplane coefficient (C_{wp}), and so on. These hydrostatic coefficients can then be used in constraints of optimization formulation (Fig. 8).

As an example, 330K DWT VLCC (Table 1) was used to validate the proposed design process and to compare the traditional and proposed design methods (Table 2, Figs. 16 and 17). In the preliminary design, a probabilistic approach was used to consider design information and uncertain design estimation. Random variables in the probabilistic approach adopt the total resistance, R_T, of the propeller design, and the effects of the probabilistic approach and the deterministic approach on the final results were compared.

Consequently, the probabilistic approach predicted a higher building cost but with a lower probability of cavitation than the deterministic approach did (Table 3 and Fig. 18).

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