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Cloud Computing and Generative Ship Designs for New Age of Shipbuilding

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Abstract:
Empirical estimations are basis for preliminary design of ships. The errors in these estimations may be marginal or significant depending upon vessel configuration and operation. The present paper talks of a method where the ship design begins with requirements' input. This in turn simulates generative designs, identifying the design space by fitting the design against required criteria and assumptions, then generates CAD model using NURBS surface, and performs iterative optimization and decision making based on multi-variable parameters. Since these are actual CAD models, it helps in better estimation of actual parameters in ship design which improves empirical estimations. This process reduces significant errors and becomes critical in preliminary ship design. With rising cloud computing focus, these calculations are able to be performed faster and more efficiently, helping naval architects to identify design space faster; this paper serves as a baseline for exploring more parallel algorithms using cloud computing on the given philosophy.
Given case is a container ship utilizing global optimization algorithms with freight rate as objective. Focus is on generating full ship design, including compartmentalization, utilizing generative designs and no designer involvement.

Keywords: *Cloud computing, generative designs, optimization models, future technologies*

1. Introduction

Major ship characteristics can be identified during the basic ship design stage. Detailed designing aside, basic designs are consequential to cost and performance since the process includes ship dimension selection, decision on hull form, and estimating power requirements, including arrangement of hull, machinery, and major structure. During the design phase, very limited information is available to the designer to carry out important decisions which have significant impact on vessel performance. [1] In such cases, the design becomes more dependent on designer's experience and engineering judgement, and furthered by relevant data from past designs.

The present paper adopts the optimization methodology to facilitate the fast exploration of a series of design alternatives, in search of 'optimum' solution subject to specific owner's requirements. [2] The checks and modifications are controlled by the constraints which are usually defined by limitations on dimensional ratios, tonnage measurements and stability and freeboard requirements. The iterative process resolves the simple elements and relevant calculations, after which the elements can be combined into the total ship design.

2. Generalized Formulation of the Optimization Problem

Optimization is targeted towards the objective function or criterion of optimization. The problem can be subjected to boundary conditions or constraints to restrict the solution space. These constraints themselves can be formulated as equations or inequalities. The optimization problem is formally stated as follows: [3]

F(X) → Objective Function
Subject to
$K_i(X) \leq 0$ i = 1,.., NCON Inequality Constraints
$X_j^L \leq X_j \leq X_j^U$ j = 1,.. NDV Side Constraints
X: Vector of design variables
NCON: Number of constraints
NDV: Number of design variables
Xj^L: Lower bound on design variable
Xj^U: Upper bound on design variable

To solve an optimization problem, it is usually started with an initial design point $\mathbf{X}^0$. The next design point is determined by:

$$\mathbf{X}^{(j+1)} = \mathbf{X}^{(j)} + \alpha\mathbf{S}^{(j)}$$

Where j is the iteration number, α is the step length and **S** is the searching direction.
All the relationships considered in the optimization model must be known and expressed as functions.

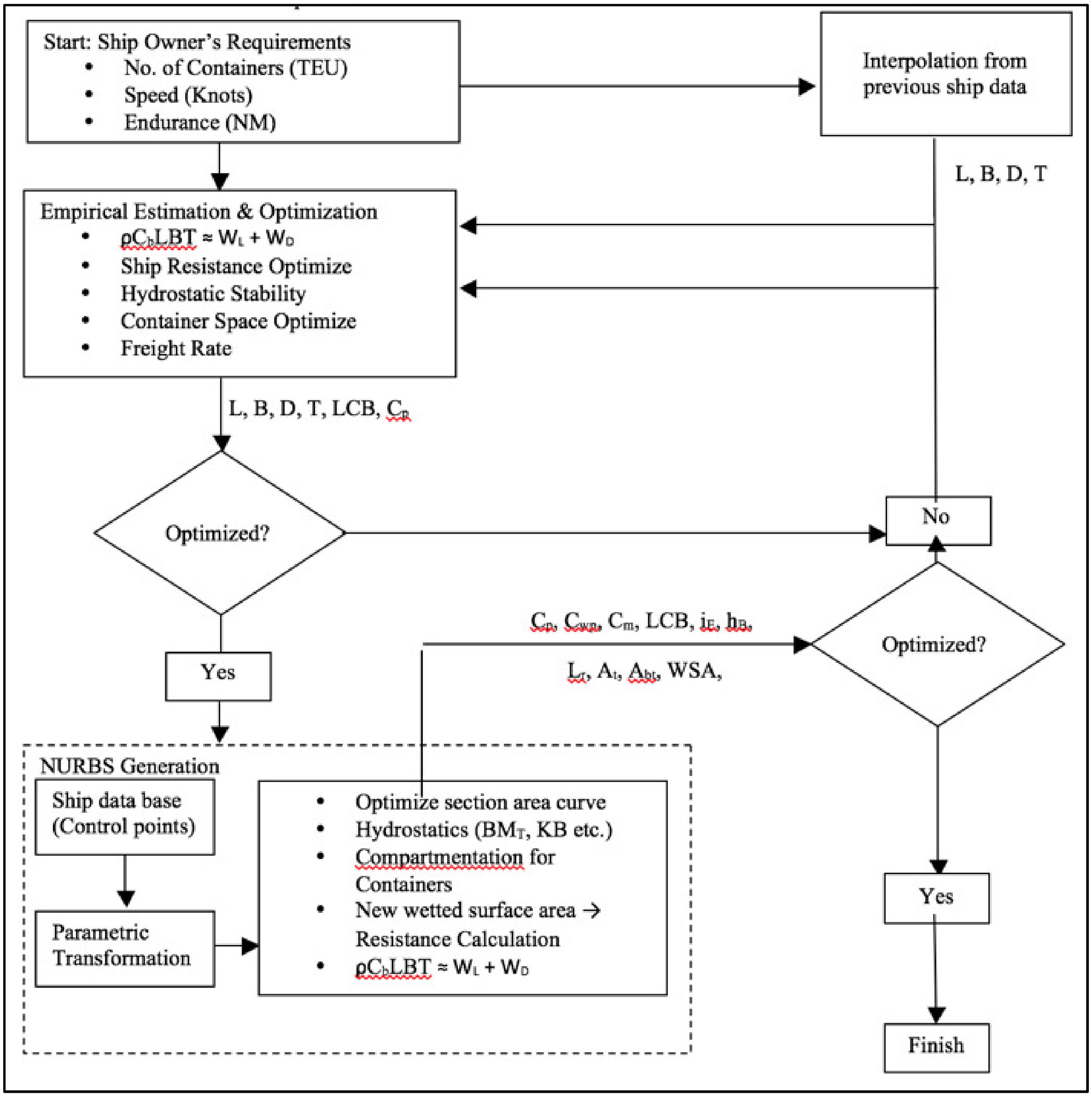

Figure 1: Basic Process Workflow

2.1. Optimization Algorithms

A variety of optimization algorithms exist which can be used for solving our containership design problem. The design variables are L, B, D, T and the objective function is the freight rate. [3]

For minimum, they're all based on the principle that:
x^* is defined as the point for which there exists some $\delta>0$ so that for all x such that

$$||x - x^*|| < \delta;$$

the expression $f(x^*) \leq f(x)$holds; that is, on some region around x^* all the function values are greater than or equal to the value at that point.

We are using three different algorithms for our global optimization problem, namely

- Global Search
- Pattern Search
- Genetic Algorithm

2.1.1. Global Search

The Global Search method uses a deterministic gradient-based scatter-search algorithm to generate multiple-starting points. It filters non-promising start-points based upon objective and constraint function values. [6] It then runs a constrained non-linear optimization solver (sequential quadratic programming) to search for global-minimum from the remaining points. The freight-rate is a smooth convex objective function [3], and thus we can use this method to find the global minimum. The results are in validation with the MultiStart approach with a very large number of generated start-points confirming the global minimum. [7]

2.1.2. Pattern Search

Pattern search method is a deterministic non-gradient based optimization algorithm. Hence it can be used on functions that are not continuous or differentiable. [4] This becomes important specially in case of container ship design where parameters contributing to the objective function, such as container numbers, are step-wise functions and non-differentiable. Final convergence depends on choice of start-point.

2.1.3. Genetic Algorithm

Genetic algorithm is a stochastic non-gradient based optimization algorithm. A population of randomly generated individual parameters called a generation is created; with each generation, fitness value of each individual in population is evaluated. The fitness value is usually the value of objective function in the optimization problem being solved. Commonly, algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached. [5] Genetic Algorithm, however, converges with choice of generation.

3. Ship Performance Evaluation

The objective of ship performance module is to calculate the technical and economic performance of the ship.
Holtrop and Mennen's method is used for resistance estimation. Container number is calculated on basis of ship database.

3.1. Resistance Calculation

Holtrop and Mennen's [8] method is used to predict the resistance of the ship. The total resistance can be given as:

$$R_{Total} = R_v + R_w + R_{app} + R_{tr} + R_b + R_a;$$

Holtrop's formulation is based on statistical analysis of resistance data. All the components of resistance are calculated from parameters calculated on basis of owner's requirements. Effective Power (EHP) and Shaft Horse Power (SHP) are also determined using empirical formulas. 10% service allowance is given for EHP prediction and propulsive efficiency is assumed to be 0.66 for SHP calculation.

3.2. Container Calculation

The total number of containers can be separated as number of containers below the deck (TEU_b) and number of containers above the deck (TEU_d). The tier number for containers above deck (TN_d) has also been defined. [3]

$$TEU = TEU_b + TEU_d$$

$$TEU_b = S_b L_b B_b D_b$$

$$TEU_d = S_d L_d B_d TN_d$$

$$S_b = (0.8479C_b - 0.0918)$$

$$S_d = 0.7534$$

where TEU is the total number of containers carried by the ship and is an integer value, S_b, S_d are corresponding stowage factors taken from ship database, and L_b, B_b, D_b are number of containers along the length, breadth and deck depth respectively.

3.3. Weight Estimation

Weight estimations are done empirically using the Watson-Gillifan method. The total weight of the ship is divided into components as follows:

$$W_{Total} = W_L + W_D$$

$$W_L = W_s + W_m + W_o + W_{app}$$

$$W_D = W_{con} + W_{fuel} + W_{misc}$$

Steel weight is the weight of hull structure including the main structure and deckhouse. Machinery weight is determined by the shaft horse power of the main engine. Fuel weight is determined by the shaft horse power of the engine, the service range, the speed of the ship and the specific fuel consumption with an additional ten-percent allowance.

3.4. Round Trip Time

Empirical calculations are made to calculate the loading-unloading time in days. Also, port-waiting time and sea-time was calculated to estimate number of trips that can be made by the ship in a year. The time spent at sea depends on service range and speed. The annual operational time (Ot) of ship is taken to be 350 days and port waiting time (Pwt) is taken to be 2 days. The loading-unloading time (Lut) is a function of number of cranes and loading/unloading speed of each crane. [3]

One round trip time is given as,

$$\text{Drt} = \text{Lut} + \text{Pwt} + \text{St}$$

Number of round trips in a year can be thus given by,

$$\text{NT} = \frac{Ot}{Drt}$$

3.5. Cost Estimation

3.5.1. Building Cost

Building cost is calculated empirically using the man-hours required based on the weights, size and other general parameters of related components and use of the man-hours to calculate the labour costs. [3]

3.5.2. Operating Cost

Annual fuel cost, port expenses, crew wages, stores and supplies, insurance, maintenance and repair cost are constituents of the operating cost. The interest rate has been assumed to be 15% and operational ship life is taken to be 25 years. [10]

3.5.3. Required Freight Rate

The main concern for the owner is whether the ship will make profit or not. The total costs for the ship can be broken into building cost and operating cost. These further determine what freight-rate will have to be charged by the owner to make profits. In our paper, we obtain the freight-rate to break-even – i.e. profit and rate of return are nil; the freight rate is the objective function. The optimization process on freight-rate leads to design of a container ship with more savings potential and market competitiveness.

The objective function – normalized freight-rate per container per day is given by

$$\mathbf{F(X)} = \frac{\text{RFR}}{\text{RFR}_0}$$

where, RFR – required freight rate per container per day is given by

$$\text{RFR} = \frac{Annual\ Average\ Cost}{NT \times Capacity \times St}$$

and RFR_0 is the freight rate per container per day at the initial design point.

4. Optimization Module

The optimization module uses the normalized freight rate as the objective function which can be pursued with any of the three optimization algorithms as presented before.

The owner can input the three parameters – speed, container number, and service range. Conditions on average weight of each container, dimensional parameter and ratio restrictions can be put to obtain distinct solution space. The optimization module also allows for stability regulation checks (such as minimum freeboard) to restrict solution space.

5. Surface Generation Module

The surface generation module makes use of NURBS surfaces.

A NURBS surface of degree (p, q) is defined as: [9]

$$S^w(u, v) = \sum_{i=0}^{n} \sum_{j=0}^{m} N^{i,p}(u) N^{j,q}(v) P^{(i,j),w}$$

where $P^{(i,j),w}$, $i = 0,\ldots,n$; $j = 0,\ldots m$, form the so-called control net defined by a set of weighted control point $P^{(i,j),w} = (w_{i,j}x_{i,j}, w_{i,j}y_{i,j}, w_{i,j}z_{i,j}, w_{i,j})$ and $N^{i,p}(u)$, $i = 0,\ldots,n$, and $N^{j,q}(v)$, $j = 0,\ldots,n$, are B-spline basis functions defined over the knot vectors

$$U = \{u_0,\ldots.,u_r\},\ u_i \le u_{i+1},\ i = 0,\ldots,r\text{-}1$$

$$V = \{v_0,\ldots.,v_r\},\ v_i \le v_{i+1},\ j = 0,\ldots,s\text{-}1$$

NURBS are very popular both in the academic and commercial geometric modelling world offering advantages of affine transformation (rotation, scaling, and translation). It is easier to change their shape through the manipulation of control points, weights and knots.

6. Performance Evaluation and Compartmentation

The developed GUI can be used for different hydrostatics calculation and curves for section area, volume and coefficients. Furthermore, automatic compartmentalization under IRS rules for any shape of the hull can be done for container compartments, bulkheads, and engine spaces.

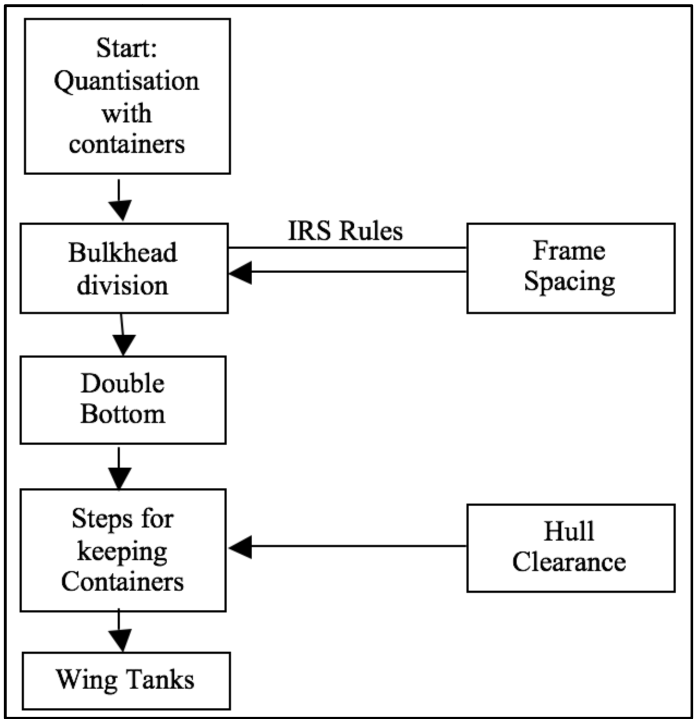

Figure 2: Method for Compartmentalization

7. Cloud Computing and Design Exploration

For a brief introduction on applicability of cloud computing, on all the defined algorithms, two scenarios can be produced – creating generative designs sequentially with each server having its own boundary conditions (Figure 3) or each server doing parallel calculations concurrently (Figure 4).

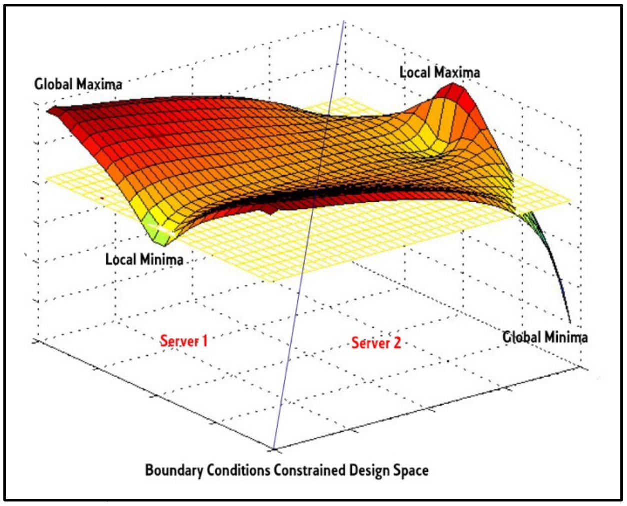

Figure 3: Servers with uniquely defined boundaries and finally merging the two results of objective function

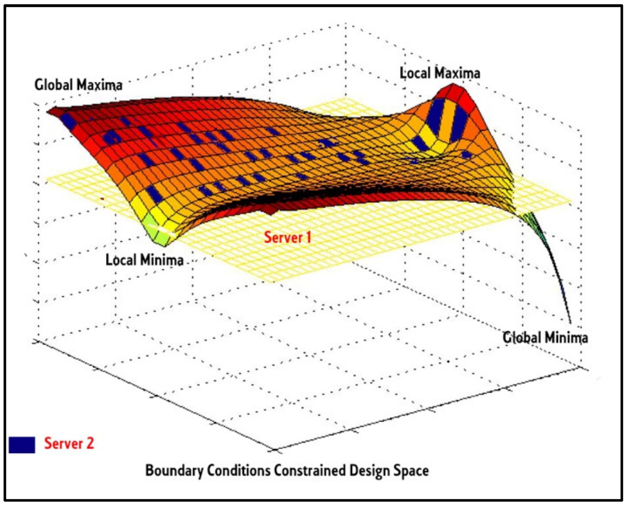

Figure 4: Servers performing node calculations independently and parallel, combining the two results

Owner's Requirements	
Speed	20 Knots
Container Number	1850
Endurance	15000 NM
Average Container Weight	10.1 Tons

Table 1: Test Case Owner's Requirements

Optimization Dimensional Bounds				
	L	***B***	***D***	***T***
Lower Bound	138	22	12	8
Upper Bound	208	34	20	14
Starting Point	173	28	16	11

Table 2: Test Case Optimization Dimensional Bounds

Optimization Constraints		
Ratio	***Lower Bound***	***Upper Bound***
L/B	6.0	7.0
L/D	9.5	13.5
L/T	14.5	25
B/T	2.25	3.75
B/D	1.6	2.2

Table 3: Test Case Optimization Constraints

Optimization Tolerances		
	Mean	***Tolerance***
Displacement		100 Tons
Container Number	1850	20
GMt	0.45 m	0.15 m
Freeboard > Freeboard_{min}		

Table 4: Test Case Optimization Tolerances

Design Point					
	L	***B***	***D***	***T***	***F(X)***
Initial Point	185.6	30.9	16.6	10.5	1
GlobalSearch	190.6	31.7	14.4	9.0	0.9891
Pattern Search	191.4	31.7	14.4	9.0	0.9904
Genetic Algorithm	191.2	31.7	14.4	9.0	0.9901

Table 5: Test Case Optimization Problem Results

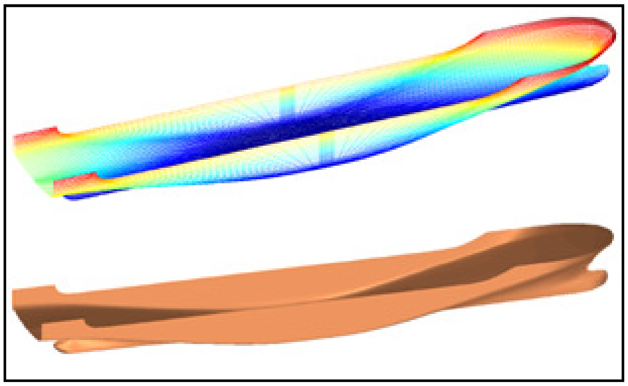

Figure 5: Test Case under Global Search – Hull NURBS Surface

L	190.6 m
B	31.7 m
D	14.4 m
T	9.0 m
C_b	0.590
C_p	0.603
C_m	0.978
C_{wp}	0.817
LCB	0.87 m aft of midship
L_r	88.9 m
i_E	18.2°
A_t	0
A_{bt}	19.3 m^2
h_B	3.9 m
WSA	7190 m^2

Table 6: Test Case under Global Search – Hull Hydrostatics

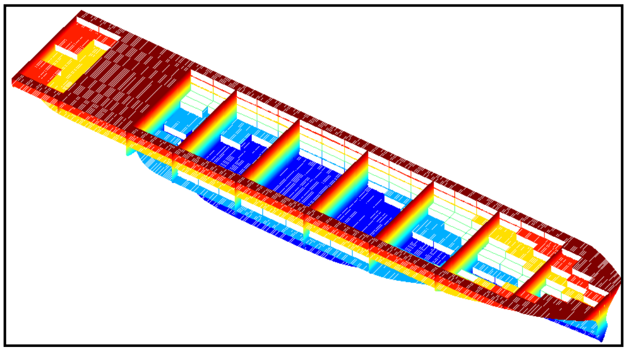

Figure 6: Test Case under Global Search – Hull Internal Structure

8. Conclusion

An integrated methodology for basic preliminary design evaluation, optimization and visualization has been presented utilizing upcoming technologies such as cloud computing. A cohesive unit approach has been adopted to obtain a single objective function from different performance and economic variables varying from operation costs and building costs. The errors in empirical estimations, if not eliminated fully, have been reduced; the design obtained from this approach will subsequently have greater potential for profitability than current procedures.

9. Acknowledgements

We're greatly indebted to our mentors at Cybermarine and ST Marine for their constant guidance and insight into cloud computing and their generous help regarding our detailed analysis.

10. Nomenclature

ρ	Density of water (kg m^{-3})
L	Length on the waterline (m)
L_{oa}	Overall length of ship (1.05×L) (m)
B	Breadth on the waterline (m)
D	Depth at mid-ship (m)
T	Draft of hull (m)
LCB	Longitudinal Centre of Buoyancy (m)
C_b	Block coefficient
C_p	Prismatic coefficient
C_m	Midship coefficient
C_{wp}	Waterplane coefficient
TEU_b	Container number below deck
TEU_d	Container number above deck
TN_d	Tier number for containers above deck
S_b	Stowage factor - containers above deck
S_d	Stowage factor - containers below deck
W_s	Hull steel weight (tonnes)
W_m	Machinery weight (tonnes)
W_o	Outfit weight (tonnes)
W_{app}	Appendage weight (tonnes)
W_L	Ship lightweight (tonnes)
W_D	Ship deadweight (tonnes)
Lut	Load-unload time per return trip (days)
St	Time spent at sea per round trip (days)
Pwt	Port waiting time per round trip (days)
S_b	Stowage factor (containers above deck)
R_{Total}	Total resistance of the ship (kN)
R_v	Viscous resistance of the ship (kN)
R_w	Wave resistance of the ship (kN)
R_{app}	Appendage resistance of the ship (kN)
R_{tr}	Immersed transom resistance (kN)
R_b	Bulbous bow resistance (kN)
R_a	Ship model co-relation resistance (kN)
i_E	Half-angle of entrance (degree)
L_r	Length of run (m)
h_B	Height of centre of bulbous bow (m)
A_t	Immersed transom area - no speed (m^2)
A_{bt}	Transverse area of bulb bow (m^2)
WSA	Wetted surface area of hull (m^2)

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