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Report

Economic Justification of Design Features for a Universal Dry Cargo Vessel

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Abstract: The economic efficiency of ships is an important indicator of transport vessels, and estimating the economic efficiency of ships is an important task in making investment decisions during the early stages of shipbuilding. This article, based on semi-theoretical and semi-empirical formula methods using the prototype ship of the RST12C project as a basis, estimates and analyzes the main economic indicators of mixed-navigation oil/chemical tankers according to different cargo capacities and speed combinations, for reference by relevant departments.

Keywords: economic efficiency, investment shipbuilding, transport.

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Introduction

For shipping companies, the economic efficiency of a vessel's operation is tightly intertwined with the company's survival. Prior to embarking on the construction of a ship, it is imperative to conduct a thorough and detailed evaluation of its economic viability and make an informed forecast. This analysis represents a critical task for decision-makers [1,2]. It garners significant attention not only from the companies themselves but also from banks, consortia, and other investors [3-5]. The importance of this task cannot be overstated, whether it concerns constructing a new vessel based on an existing design or the potential for the widespread adoption of a novel ship type [6]. Consequently, engineers involved in naval architecture and marine engineering must not solely focus on optimizing the technical performance of the ships. They also have to make rational judgments regarding the economic aspects of their designs [7-10].

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Currently, there is a scarcity of comprehensive literature on calculating ship economic efficiency. As the market economy evolves, bringing profound shifts to ship operational economics, and as financial systems strive to align with global standards, it becomes crucial to undertake a meticulous analysis of ship economic efficiency predictions under this new paradigm [10-12]. Based on the calculation results, a variable will be selected under which the designed ship will achieve the maximum economic benefit, using RST12C (Figure 1) as the prototype ship [13].

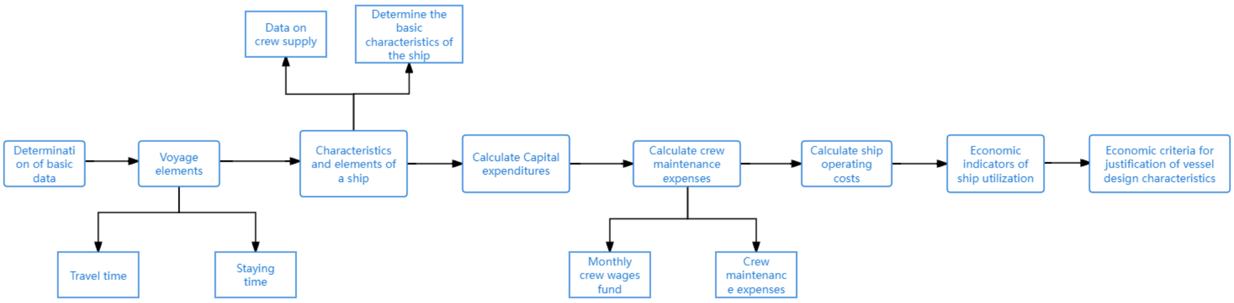

Figure. 1. Mind map for this article

Figure. 2. Project RST12C

1. Initial data

The calculation will be performed on the basis of the initial data given in the table 1.

Table 1. Initial data

Name	Notation	Value
Length of the line	L	1100 m
Speed utilization coefficient	K_v	0,95
Load capacity utilization factor in direct transition	K_1	1
Load capacity utilization factor in reverse transition	K_2	0
Duration of the annual navigation period	T_d	340 days
Time for formalities, arrival, and departure	T_t	1 day
Cargo handling rate at the port of departure	M_1	7000 t/day

Cargo handling rate at the port of arrival	M_2	8000 t/day
Coefficient of transition from the cost of a series-produced ship to the average series construction cost (1.05-1.45) - decreases with the increase in the series	p	1,3
Annual cargo turnover	Q	1200000 t/year
Inflation rate	i	1,08
Crew number	n	13
Price of 1 ton of diesel fuel	C_{df}	935 $/t
Freight rate (cost of transporting 1 ton of cargo)	f_{cm}	47,63 $/t
Regulatory capital expenditure coefficient	E	0,12

2. Voyage elements

Table 2. Voyage elements

Name	**Equation**	**Load capacity options P_{lc}, t**								
		4500			6000			7500		
		Speed options V_s. Nautical mile								
		8	10	12	8	10	12	8	10	12
Travel time	$T=2L/(24K_v \cdot V_s)$	12,06	9,65	8,04	12,06	9,65	8,04	12,06	9,65	8,04
Loading time	$T_l=P_{lc}\ (K_1+K_2)/M_1$	0,64	0,64	0,64	0,86	0,86	0,86	1,07	1,07	1,07
Unloading time	$T_u=P_{lc}\ (K_1+K_2)/M_2$	0,56	0,56	0,56	0,75	0,75	0,75	0,94	0,94	0,94
Parking time	$T_p=T_l+T_u+T_t$	2,21	2,21	2,21	2,61	2,61	2,61	3,01	3,01	3,01
Raise time	$Tr=T+T_p$	14,27	11,85	10,25	14,67	12,26	10,65	15,07	12,66	11,05
Number of trips	$\tau=T_d\ /T_u$	23,83	28,68	33,18	23,18	27,74	31,93	22,56	26,86	30,77
Standardized time	T_p/T	0,18	0,23	0,27	0,22	0,27	0,32	0,25	0,31	0,37
Number of ships on the line	$n=Q/((K_1+K_2) \cdot P_{lc} \cdot \tau$	11,19	9,30	8,04	8,63	7,21	6,26	7,09	5,96	5,20
	Accepted	12	10	9	9	8	7	8	6	6
Sailing time per year	$T_y=T \cdot \tau$	287,44	276,75	266,82	279,57	267,68	256,75	272,12	259,18	247,42
Staying time per year	$T_{py}=T_p \cdot \tau$	52,56	63,25	73,18	60,43	72,32	83,25	67,88	80,82	92,58
Inspection	$Q=P_{lc} \cdot (K_1+K_2) \cdot n \cdot \tau$	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000

3. Characteristics and elements of a ship

The displacement of a ship consists of two components: the lightship displacement D_0 and the deadweight DW

$$D = D_0 + DW \quad (1)$$

The lightship displacement in tons is determined by the following formula:

$$D_0 = q_h + q_{eq} + q_s + q_{mm} + q_{el} + q_{na} + q_{su} + q_d + q_{per} \quad (2)$$

$$P_i = q_i \cdot D \quad (3)$$

$$q_i = \frac{P_{ipr}}{D_{pr}} \quad (4)$$

P_i - is the mass of the corresponding load component in tons.

q_i - meter of the corresponding load article specified by the prototype.

P_{ipr} - weight of the i-th item.

D_{pr} - displacement of the prototype.

The basic data for the ship designed according to the theory of similarity is given by the formula:

$$L = \sqrt[3]{\frac{B}{\delta_\gamma} \cdot \left(\frac{L}{B}\right)^2 \cdot \frac{B}{T}} \quad (5)$$

$$B = \frac{L}{(L_{pr}/B_{pr})} \quad (6)$$

$$H = T \cdot \left(H_{pr}/T_{pr}\right) \quad (7)$$

$$T = \frac{B}{(Bpr/\mathrm{T}pr)} \quad (8)$$

The calculation of characteristics is presented in Table 3.

Table 3. Prototype load meters

Name	Notation	Value
Hull masses	q_h	0,136
Equipment masses	q_{eq}	0,014
Ship systems masses	q_s	0,024
Engines and mechanisms masses	q_{en}	0,079
Electrical equipment masses	q_{el}	0,009
Navigation armament masses	q_{na}	0,001
Supply masses	q_{su}	0,005
Displacement reserves	q_d	0,004
Permanent liquid cargo masses	q_{per}	0,003

Additional data accepted in the calculation methodology for calculating the deadweight of the vessel are given in Table 4.

Table 4. Additional data

Name	**Notation**	**Value**
Provision norm for 1 crew member	m_{pro}	5 kg/(per·day)
Average mass of 1 crew member with luggage	m_{cr}	120 kg/per
Fresh water norm for 1 crew member	m_w	150 kg/(per·day)
Sailing range	R	4000 m
Fuel consumption of main engines	q_c	200 g/(kW·h)
Sea stock coefficient	k	1,15
Admiralty coefficient (prototype)	$Ca=D^{2/3}\cdot V_s^3/N$	198,8
Lubricating oil consumption	q_{lo}	1,5 g/(kW·h)
Fuel reserve coefficient for auxiliary mechanisms	k_{am}	0,25

Table 5. Characteristics and elements of the ship

Name	Notation	Value								
Hull mass	P_h	802,5	824,3	856,2	***1063,5***	1090	1128,4	1323,9	1354,8	1399,1
Device mass	P_d	80,6	82,7	86,0	***106,8***	109,4	113,3	132,9	136,0	140,5
System mass	P_s	138,8	142,5	148,1	***183,9***	188,5	195,1	229,0	234,3	242,0
Mass of main engines and mechanisms	P_m	66,2	131,6	233,3	***79,9***	158,6	280,5	92,4	183,3	323,7
Electrical equipment mass	P_{el}	50,0	51,3	53,3	***66,2***	67,9	70,3	82,5	84,4	87,1
Navigation armament mass	P_{na}	5,9	6,0	6,3	***7,8***	8,0	8,2	9,7	9,9	10,2
Supply mass	P_{su}	29,4	30,2	31,4	***38,9***	39,9	41,3	48,5	49,6	51,2
Displacement reserve	P_{dr}	17,7	18,1	18,8	***23,4***	24,0	24,8	29,1	29,8	30,8
Permanent liquid cargo mass	P_{plcm}	23,5	24,2	25,1	***31,2***	32,0	33,1	38,8	39,7	41,0
Lightship displacement	$\boldsymbol{D_o}$	1214	1311	1458	***1602***	1718	1895	1987	2122	2326
Crew mass with provisions	P_{cr}	44	35	30	***44***	35	30	44	35	30
Cargo mass	P_{ca}	4500	4500	4500	***6000***	6000	6000	7500	7500	7500
Fuel and oil mass	Po	121	193	285	***146***	232	343	169	269	395
Ship's deadweight	$\boldsymbol{DW}$	4665	4728	4815	***6190***	6268	6372	7713	7804	7925
Total displacement	$\boldsymbol{D}$	5879	6039	6273	***7791***	7986	8267	9700	9926	10251
Main engine power	N	839	1668	2956	***1012***	2010	3554	1171	2323	4102
Endurance		21	17	14	***21***	17	14	21	17	14
Calculation check		0	0	0	***0***	0	0	0	0	0
Length of the ship	L	113,27	114,28	115,74	***124,41***	125,44	126,90	133,84	134,87	136,33
Breadth of the ship	B	13,96	14,09	14,27	***15,34***	15,46	15,64	16,50	16,63	16,80
Draught of the ship	T	3,75	3,78	3,83	***4,12***	4,15	4,20	4,43	4,47	4,51

4. Capital expenditures

The average serial construction cost of a ship can be determined by the formula:

$$K = \rho * K_h + (K_d + K_r)/n_c \tag{9}$$

$$K_d = (0.04 \cdot D + 600) \cdot i \tag{10}$$

$$K_r = 0.17 \cdot D \cdot i \tag{11}$$

K_d - cost of design

K_r - cost of rigging

K_c - construction cost of a serially produced ship

$$K_s = K_{mh} + K_{eq} + K_{pp} + K_{me} + K_{lc} \tag{12}$$

$$K_{mh} = \frac{P_h}{1000} \cdot \left[0.623 - 0.028 \cdot \frac{P_h}{1000} + 0.003 \cdot \left(\frac{P_h}{1000}\right)^2\right] \cdot i \tag{13}$$

$$K_{eq} = \frac{P_d}{1000} \cdot \left[5.507 - 3.182 \cdot \frac{P_d}{1000} + 0.003 \cdot \left(\frac{P_d}{1000}\right)^2\right] \cdot i \tag{14}$$

$$K_{pp} = \frac{N_{PP}}{10^6} \cdot \left[100.1 - 5.51 \cdot \frac{N_{PP}}{1000} + 0.048 \cdot \left(\frac{P_d}{1000}\right)^2 + 0.032 \cdot \left(\frac{P_d}{1000}\right)^3\right] \cdot i \tag{15}$$

$$K_{me} = \frac{P_{me}}{1000} \cdot \left(1.638 + 0.3156 \cdot \frac{1000}{P_{me}}\right) \cdot i \tag{16}$$

$$K_{lc} = \left[0.724 + 0.084 \cdot \frac{D}{1000} + 0.009 \cdot \left(\frac{D}{1000}\right)^2\right] \cdot i \tag{17}$$

K_{mh} - the cost of the metal hull

K_{eq} - hull equipment

K_{pp} - power plant

K_{me} - mechanical equipment and piping

K_{lc} - labor cost

Calculation of the cost of capital expenditures is presented in Table 6.

Table 6. Capital expenditure

Name	Notation	Value, mln. $								
Cost of design	K_d	0,902	0,909	0,919	0,985	0,993	1,005	1,067	1,077	1,091
Cost of rigging	K_r	1,079	1,109	1,152	1,431	1,466	1,518	1,781	1,822	1,882
Cost of the metal hull	K_{mh}	0,529	0,541	0,559	0,676	0,691	0,713	0,823	0,841	0,866
Hull equipment	K_{eq}	1,188	1,199	1,216	1,321	1,335	1,354	1,454	1,469	1,492
Power plant	K_{pp}	0,173	0,309	0,466	0,204	0,357	0,521	0,231	0,396	0,565
Mechanical equipment and piping	K_{MO}	0,222	0,388	0,646	0,257	0,457	0,766	0,289	0,519	0,876
Mechanical equipment and piping	K_{me}	0,313	0,373	0,448	0,508	0,550	0,603	0,627	0,658	0,699
Construction cost of a serially produced ship	K_c	2,426	2,811	3,335	2,966	3,389	3,957	3,424	3,884	4,497
Average series construction cost of the vessel	K	3,318	3,856	4,566	4,125	4,713	5,505	4,807	5,532	6,342

5. Crew maintenance expenses

The calculation of the monthly wage fund for the crew is presented in Table 7.

Table 7. Monthly crew wages fund

Position	Number of crew members	Salary ($/month)	Foreign currency daily subsistence allowance ($/day)	Total ($/month)
Captain	1	11020	155	11175
Chief Officer	1	8378	137	8515
Second Officer	1	6859	124	6983
Chief Engineer	1	8751	133	8884
Second Engineer	1	8102	123	8225
Third Engineer	1	7227	117	7344
Electrical Engineer	1	6895	114	7009
Bosun	1	4926	108	5034
Able Seaman	1	4524	111	4635
Motorman First Class	1	4972	118	5090
Cook	1	5987	108	6095
Steward	1	5923	103	6026
Ship's Doctor	1	6837	112	6949
Total for the crew per month:	13			91963

Calculation of crew maintenance costs is given in Table 8.

Table 8. Crew maintenance expenses

Name	Notation	Value
Coefficient of additional payments in operation	-	0,4
in repair	-	0,1
Coefficient of social insurance contributions	-	0,01
Annual crew salary	thousand $/year	1560,4
Payroll taxes	thousand $/year	593,0
Daily dining expenses for one crew member	thousand $/person*day	0,005
Crew dining expenses	thousand $/year	23,7
General ship foreign currency expenses	thousand $/year	275,9
Crew maintenance expenses	thousand $/year	2453,0

6. Ship operating costs

Ship costs are calculated by adding direct and indirect costs:

$$C_{ship} = C_{direct} + C_{indirect} \quad (18)$$

$$C_{indirect} = C_{direct} \cdot a \quad (19)$$

a-coefficient, for dry cargo ships it is taken equal to 0,055.

Direct costs are defined as the sum of:

$$C = C_{dc} + C_e + C_{se} + C_{cc} + C_{nc} + \mathrm{C}_t + C_{fc} \quad (20)$$

$$C_{dc} = 0.01 \cdot K \cdot dr \quad (21)$$

$$C_e = 200 \cdot (16.02 + 0.0029 \cdot DW) \quad (22)$$

$$C_{se} = 0.01 \cdot K \quad (23)$$

$$C_{nc} = \frac{C_{se}}{(7.8 \cdot 365)} \quad (24)$$

$$\mathrm{C}_t = 0.01 \cdot C_{dc} \cdot dr \quad (25)$$

$$C_{fc} = C_{fcp} + C_{fcm} \quad (26)$$

C_{dc} - depreciation charges

dr - depreciation rate

C_e - expenses on current repair

C_{se} - supply expenses

C_{cc} - Crew costs

C_{nc} - navigation costs

C_t - property tax

C_{fc} - fuel costs

C_{fcp} - fuel costs at the parking lot

C_{fcm} - fuel costs on the move

Calculation of ship operating costs is given in Table 9.

Table 9. Ship operating costs.

Name	Notation	Value								
Depreciation charges	million $	0,20	0,24	0,28	0,25	0,29	0,34	0,29	0,34	0,39
Expenses on current repair	million $	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Supply expenses	million $	0,03	0,04	0,05	0,04	0,05	0,06	0,05	0,06	0,06
Crew maintenance expenses	million $	2,45								
Navigation expenses	million $	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
Property tax	million $	0,05	0,06	0,08	0,07	0,08	0,09	0,08	0,09	0,10
Lighthouse dues	thousand $	0,20	0,21	0,22	0,27	0,28	0,29	0,34	0,35	0,36
Navigation dues	thousand $	0,20	0,21	0,22	0,27	0,28	0,29	0,34	0,35	0,36
including SHIP dues	thousand $	0,20	0,21	0,22	0,27	0,28	0,29	0,34	0,35	0,36
Environmental charge	thousand $	0,20	0,21	0,22	0,27	0,28	0,29	0,34	0,35	0,36
Port charges per port call	thousand $	0,82	0,84	0,87	1,08	1,11	1,15	1,35	1,38	1,43
Annual port charges	thousand $	19,50	24,11	28,98	25,14	30,84	36,75	30,46	37,11	43,91
Fuel costs at standstill	thousand $	88,98	107,09	123,90	102,31	122,45	140,94	114,93	136,83	156,75
Fuel costs on the move	thousand $	326,62	625,29	1068,44	383,28	728,61	1235,86	431,72	815,55	1374,50
Fuel costs	thousand $	415,60	732,37	1192,34	485,59	851,06	1376,80	546,65	952,38	1531,25
Direct costs	million $	3,25	3,62	4,15	3,40	3,82	4,42	3,53	4,00	4,66
Indirect costs	million $	0,14	0,16	0,18	0,15	0,17	0,19	0,16	0,18	0,21

7. Economic indicators of ship utilization

Economic indicators of ship utilization will be determined using the formulas provided below.

Annual ship transport volume:

$$Q_c = (K_1 + K_2) \cdot P_{su} \cdot \tau \tag{27}$$

The cost of transporting a ton of cargo:

$$S_1 = \frac{C_{ship}}{Q_c} \tag{28}$$

Cost of transportation:

$$S_2 = \frac{C_{ship}}{Q_c} \cdot L \tag{29}$$

Income per vessel:

$$I = Q_c \cdot f_{cm} \tag{30}$$

Transportation profitability level:

$$T_1 = \frac{I \cdot 100\%}{Q} \tag{31}$$

Fleet transport capacity:

$$F = n \cdot Q_c \tag{32}$$

Transport capacity reserve:

$$T_2 = \frac{(F - Q) \cdot 100\%}{Q} \tag{33}$$

Balance profit:

$$B_p = I - C_{ship} \tag{34}$$

Taxes:

$$T = 0.45 \cdot B_p \tag{35}$$

Net profit:

$$N_p = B_p - T \tag{36}$$

The calculation of economic indicators for ship utilization is presented in Table 10.

Table 10. Economic indicators of vessel utilization

Name	Notation	Value								
Annual transport volume per vessel	t/year	107242	129065	149322	139073	166445	191584	169207	201453	230772
Capital intensity of transport	$/(t*mile)	0,033	0,030	0,029	0,030	0,028	0,029	0,031	0,028	0,027
Transportation cost per ton of cargo	$/t	31,65	29,28	28,99	25,52	23,97	24,10	21,77	20,75	21,08
Transportation cost	$/(t*mile)	0,2794	0,2562	0,2505	0,2051	0,1911	0,1900	0,1626	0,1538	0,1547
Income per vessel	thousand.$	5091,5	6127,6	7089,3	6104,5	7306,0	8409,4	6408,5	7629,8	8740,3
Transport profitability level	%	150,0	162,1	163,8	172,0	183,1	182,1	174,0	182,5	179,6
Fleet transport capacity	t/year	1286907	1290651	1343901	1251658	1331564	1341087	1353653	1208717	1384632
Transport capacity reserve	%	7,2	7,6	12,0	4,3	11,0	11,8	12,8	0,7	15,4
Balance profit	thousand.$	1697,2	2348,6	2760,0	2555,4	3315,5	3791,4	2725,5	3449,9	3874,7
Taxes	thousand.$	763,7	1056,9	1242,0	1149,9	1492,0	1706,1	1226,5	1552,4	1743,6
Net profit	thousand.$	933,4	1291,7	1518,0	1405,4	1823,5	2085,3	1499,0	1897,4	2131,1

8. Economic criteria for justification of vessel design characteristics

Based on the economic indicators of ship utilization obtained in item 7, the economic criteria for justifying the design characteristics of vessels will be calculated.

Specific capital costs:

$$f_s = \frac{K \cdot E + C_{ship}}{Q_c \cdot L} \quad (37)$$

Return on investment

$$f_r = \frac{N_p \cdot 100\%}{K} \quad (38)$$

Profit margin

$$f_p = \frac{N_p}{C_{ship}} \quad (39)$$

Payback period

$$T_P = \frac{K}{N_p} \quad (40)$$

The calculation of economic criteria to substantiate the design characteristics of ships is given in Table 11.

Table 11. Economic criteria for justification of ship design characteristics.

№	**Specific capital costs, $/(t*mile)**	**Profitability of investments, %**	**Rate of return**	**Payback period,year**
1	0,3122	28,13	0,28	3,6
2	0,2876	33,50	0,34	3,0
3	0,2822	33,25	0,35	3,0
4	0,2337	34,07	0,40	2,9
5	***0,2182***	***38,69***	***0,46***	***2,6***
6	0,2171	37,88	0,45	2,6
7	0,1881	31,18	0,41	3,2
8	0,1783	34,30	0,45	2,9
9	0,1788	33,60	0,44	3,0

9. Conclusions

Analyzing the obtained results, it can be unequivocally concluded that the most advantageous option for operation on the given line is vessel type number 5 (Table 11). This option outperforms the opponents with the best indicators according to three out of four possible criteria. It provides the highest return on investment percentage, the highest rate of profit, and requires the shortest payback period.

The robust financial indicators of vessel type number 5 contribute to the economic resilience of the operating company. As the global economy faces uncertainties, having a vessel that ensures high profitability and quick investment recovery is crucial. This resilience will enable the company to withstand economic fluctuations, invest in innovation, and maintain a competitive edge in the maritime industry.

In conclusion, vessel type number 5 not only stands out as the most advantageous option for current operations but also holds significant promise for future developments. Its superior financial performance, coupled with potential advancements in technology, sustainability, and market expansion, positions it as a key asset for the company's long-term strategy. By continuously adapting to industry trends and regulatory requirements, vessel type number 5 can maintain its competitive advantage and contribute to the sustainable growth of maritime operations.

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