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Multi-Criteria Analysis of Capesize Bulk Carrier Design Optimization Model

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Abstract

In engineering problems, the concepts of design and optimization are two basic topics that are related to each other. The problem owner should prioritize the design or optimization on each other. In this regard, two different ways can be followed in engineering problems: firstly designing and then optimizing or using optimized parameters in the design process. In this study, the basic design parameters of a capesize bulk carrier for a specific purpose were created and exemplified on a model. The prototype development problem is handled as a multi-criteria optimization problem by creating appropriate and pareto optimal solutions. Parameter Space Investigation method was used to solve this optimization problem, and this method was applied in a program called Multi-criteria Optimization Vector Identification. As a result of the study, the design parameters of the capesize bulk carrier sample were created and the objective function criteria were obtained better than the prototype and the value in the literature.

Keywords: Ship design parameters, Capesize bulk carrier, Parameter space investigation, Multi-criteria optimization vector identification

1. Introduction

Maritime transportation has played a significant role in the advancement of societies throughout history, facilitating increased commercial activities and contributing to their wealth and power [1]. In recent years, the importance of marine transport in the logistics sector has steadily increased. The cost is cheaper, many materials can be transferred at a party, and delivery conditions are more appropriate are reasons for growing demand in this sector. Increasing competition with globalization and the rapid development of international trade as a result of this have made maritime transportation an important mode of transportation that directly affects the foreign trade level and economic competitiveness of countries [2].

The Coronavirus disease-2019 (COVID-19) pandemic experienced recently has also revealed the importance of logistics and supply chain for countries. Although faced with applications such as restrictions and quarantines during the COVID-19 pandemic, maritime transport was relatively less affected by the pandemic process among all modes of transport. The "Review of Maritime Transport 2021" report prepared by the United Nations Conference on Trade and Development points out that although the coronavirus pandemic disrupted maritime transport, this decline was not as dramatic as expected. When maritime transportation was interrupted in the first half of 2020, it started to recover in the second half of the year and maritime trade increased by 4.3% in 2021 [3]. Ships provide more than 80% of world trade, so disruptions in ports and shipping routes mean that food, energy, medicine and other essentials do not reach those in need [4]. For this reason, marine transportation and platform needs are expected to grow.

As of January 1, 2022, the countries with the most ships in terms of dead weight tonnage and commercial value were Greece, China, and Japan. The maritime transport supply continues to be dominated by three countries (China, the Republic of Korea and Japan), which together hold 94 percent of the market in 2022 [5]. When examined in Türkiye

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using all modes of transport in foreign trade activities, the largest share in both imports and exports in the 10-year period covering the years 2011-2021 belongs to maritime transport, based on the value of the goods transported, as seen in Table 1.

The type and characteristics of the ships that make up the merchant fleet, which is the most important element in maritime transport, are of great importance. As can be seen in Table 2, when the DWT and number of ships of 150 GT and above in the Turkish merchant marine fleet are examined in the last 5 years, it is seen that 42 bulk carriers have been owned for 2022 and bulk carriers constitute 25% of the total deadweight [6].

Bulk carriers are used to transport goods (scrap, grain, logs, wood products, sand, etc.) iron ore, coal, and grain are the main cargoes of international bulk freight, as they are transported in large quantities. There are different types and capacities of ships in bulk cargo transportation. Generally, ships up to 10,000 DWT are known as small bulk carriers, while ships with larger payloads are known by some special names. In this context, Handysize (10,000-30,000 DWT), Handymax (30,000-50,000 DWT), Panamax (50,000-92,000 DWT), Post Panamax (92,000-120,000 DWT), Capesize (120,000-182,000 DWT) abbreviated the names of ships larger than 200,000 DWT as VLBC (Very Large Bulk Carrier) [7]. The design of ships and marine vehicles in general can be counted among the most complex engineering problems [8].

“Ship Design Optimization” is frequently used by designers and shipyards, and it causes different interpretations in the relevant parts of the sector, and its boundaries must be defined [9]. The use of optimization models in ship design dates back to the 1960s. Ship design problems have various conflicting objective functions. Both conventional methods are used in solving multi-criteria problems, and current multi-criteria approaches could be seen.

Table 1. *Percentage shares of transportation types in import and export by years (on a value basis)*

		Years										
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Road Transportation	Import	21.97	20.26	18.69	18.23	19.09	19.16	18.01	17.88	20.56	21.14	20.79
	Export	37.6	33.35	35.66	35.29	32.7	31.62	29.59	28	30.36	31.61	30.85
Airway Transportation	Import	10.62	12.23	15.21	12.07	11.11	12.83	16.33	14.4	16.17	19.82	11.08
	Export	6.42	14.4	8.61	9.01	12.1	12.54	10.98	8.25	8.28	7.58	8.4
Maritime Transportation	Import	65.85	66.31	65.28	69.11	69.14	67.22	65.1	67.09	62.47	57.96	66.91
	Export	55.05	51.57	55.1	55.11	54.64	55.39	58.99	63.31	60.82	60.04	60.01
Railway Transportation	Import	1.57	1.21	0.83	0.59	0.65	0.8	0.56	0.62	0.8	1.08	1.23
	Export	0.93	0.67	0.64	0.59	0.56	0.45	0.44	0.44	0.54	0.77	0.74
Source: [3]												

Table 2. *DWT and number development of the Turkish merchant fleet (vessels of 150 GT and above), 2018-2022*

The Type of Ship	**2018**		**2019**		**2020**		**2021**		**2022**	
	Number	**DWT**	**Number**	**DWT**	**Number**	**DWT**	**Number**	**DWT**	**Number**	**DWT**
Dry Bulk Carriers	323	1,245,588	298	1,148,389	278	10,71119	251	945,737	196	807,374
Bulk Carriers	64	2,636,897	56	2,225,010	46	17,14108	45	1,692,176	42	1,769,522
Container Ships	70	1,349,228	57	1,047,502	56	1,028,620	53	998,316	59	1,097,971
Tankers	184	2,023,011	178	2,085,755	181	2,188,978	185	2,179,130	190	2,452,630
Passenger Ships	308	89,923	311	90,924	308	86,697	306	81,458	445	128,165
Services Ships	151	101,339	151	110,122	154	178,484	161	194,784	164	361,413
Tugs	152	2,776	165	2,598	173	2,710	181	2,710	175	18,836
Sea Vessels	258	34,715	272	38,483	286	38,731	297	48,143	314	352,775
Fishing Ships	293	8,358	314	8,503	337	8,542	375	8,586	401	38,932
Sport and Entertainment Boats	222	3,297	222	3,223	234	3,300	246	3,300	116	3,983
Total	2.025	7,495,133	2024	6,760,509	2053	6,321,289	2100	6,154,340	2102	7,031,603
Source: [6]										

In prototype development problems, optimization is performed by considering multiple criteria [10]. To solve the prototype development problem, operational development of the prototype requires two phases [11].

Statnikov et al. [10] indicated that the first step is to determine the mathematical model of the object and its parameters based on different tests. To this end, it would be advantageous to solve the identification problem based on certain adequacy criteria (proximity). In the second step, an expert formulates and resolves the multi-criteria optimization problem using the mathematical model and the performance criteria determined in the first step. Depending on the optimization results, the prototype is improved and object tests are repeated. It is repeated until an expert decides to stop the operational development process.

The Parameter Space Investigation (PSI) method was used in multi-criteria analysis in this study, which constructed feasible and Pareto optimal solution sets while also improving the prototype's key performance criteria by altering the constraints of design variables, functional relations and criteria. The PSI method is applied with the Multi-criteria Optimization and Vector Identification (MOVI) program.

Multi-criteria analysis of a ship design model using the PSI technique was first performed at St. Petersburg State Naval Technical University by M. Berezanskii and Y. N. Semenov. A prototype ship (UT-704) was intended to improve performance benchmarks [12].

In this study, the PSI method which has been widely used for the solution of optimization problems related to manufacturing engineering, machine design, and mechanisms and it has been known for more than a quarter of a century, was employed [13].

In order to examine the surface texture of the Ti6Al4V titanium alloy following final turning under both dry and wet cooling conditions, Leksycki and Feldshtein [14] used the PSI method. They conducted research tests with the fewest possible test points. The test points were set sequentially in fixed positions. The steps involved positioning the points in a multidimensional space with their projection points equally spaced apart from one another on the X_1 and X_2 axes, respectively.

The study of Maruda et al. [15] described three cooling techniques for AISI-1045 steel turning: dry machining, minimum amount of cooling (MQC), and MQC with EP/AW (MQC + EP/AW) additives. The PSI method was applied to an increasing number of variables (variation of shear and emulsion mist generation parameters). A Kistler dynamometer type 9129AA was used to measure the shear force, and an MPS7 network parameter meter was used to measure the power consumption.

A novel approach for the development of force transducers based on strain gauges was put forth by Gavrilenkov et al. [16]. The approach depended on multi-criteria optimization techniques and PSI method.

Three elements of total cutting force and changes in chip shape when finishing turning 17-417-4 4 PH (precipitation hardening) stainless steel were analyzed by Leksycki et al. [17]. The cutting speed was 220 m/min, the depth of cut ranged from 0.2 to 1.2 mm, and the variable feed pattern ranged from 0.05 to 0.4 mm per rev. Minimum amount of lubrication was used during the studies which were conducted in both dry and wet cooling conditions. The PSI method was used to conduct this research.

Pagano et al. [18] examined the mechanism that causes the propagation of twist and sausage modes in the solar corona following the collision of counter-propagating flows and how the characteristics of the flows affect the characteristics of the waves produced. They used the PSI method to explain how the collision of coronal flows results in the generation of magnetohydrodynamic waves.

According to Maruda et al. [19], the condition of the machined surface of 1.4310 stainless steel after turning was examined in relation to the anti-wear additive Crodafos EHA-LQ-(MH) added to emulsion mist. In the tests conducted for the formation of emulsion fog, the emulsion's mass flow, the air's volumetric flow, the nozzle's distance from the shear zone range, and the PSI method were all used.

The PSI method was applied for the design of the L1 flight control system installed on the dynamically scaled GTM AirSTAR aircraft powered by two turbines, and the preliminary results were presented in Xargay and Hovakimyan's [20] study.

Anıl [21] investigated marine design engineering problems with PSI method. MIT Functional ship design optimization was conducted and pareto optimal solutions of design variables and criteria values were obtained.

In this study, the PSI method studies of Statnikov et al. [10-12] PSI studies, the study of Anıl [21] and optimization model of Cudina [22,23] and Zanic and Cudina [24] are taken as the main references for the optimal design of the model ship.

2. Ship Design Optimization

2.1. Motivation of the Study

The main purpose of ship design is to find the most economical alternative among the alternatives that provide the given design conditions. For this, many design calculations and controls need to be implemented for several alternative designs.

Brown and Salcedo [25] point out that there are three components necessary for a systematic approach to ship design, and these three components are;

- The creation of an effective and efficient design space, the objective function of containing well-defined measurable properties, and the use of an effective format for the expression of the design space.
- Maximizing effectiveness.
- Minimizing cost and risk are different characteristics and require different measurement methods.

These three different features cannot be combined into one function. It should be included in problem solving for simultaneous decision making and comparison. The effectiveness of ship designs can be analyzed using wargaming or other complex methods [25]. However, this approach is of little use when evaluating designs in a structured design space. The non-dominated solution represents a feasible solution in which the problem and the constraints are defined and there is only one best solution in the objective function. For example, in Figure 1 there is a problem solution in which cost is minimized and efficiency is maximized. Decision-making authorities will determine preferred concept designs as one of the non-dominated solutions to strike the balance between cost and effectiveness. Although ship design optimization is not new, it is a concept that contains several computational difficulties. The ship design space is non-linear, discrete and bounded by various constraints and thresholds. It is estimated that 80% of a ship's procurement cost remains unused during the design phase. Therefore, making critical design decisions is unable to be superficial. A methodology that will meet user needs, respect critical performance values, and integrate multiple factors into the objective function should be followed [25].

Ship designs were carried out using the basic ship design and the Evans-Buxton-Andrews spiral until the 1990s. In this spiral, it is assumed that the design process will be sequential, and the possibility of inclusion of life cycle issues is limited. Mistree et al. [26] proposed a new process for increasing ship design efficiency and effectiveness. This process emphasizes systems philosophy and simultaneous engineering in terms of the life cycle.

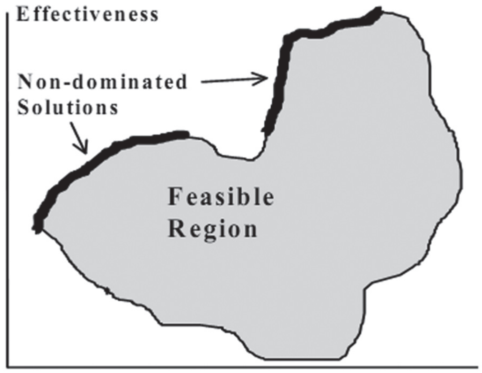

Figure 1. Cost-efficiency design space [25]

Mistree et al. [26] classify design processes in two groups as descriptive and predictive. Predictive methods include three main activities as analysis, synthesis, and evaluation and show a systematic approach. In this context, the Pahl and Bitz method in the literature is a systematic design approach developed in Germany. In this method, which is described as a predictive approach, product design is divided into functional stages. Thanks to the modules that can be designed independently, the design activity is simplified. On the other hand, design studies in the form of independent modules may cause some problems in the integration phase. It is possible to define the method in seven stages. In the first stage, the evaluation criteria are listed and in the second stage, these criteria are weighted. Then, operational measurement values are defined for the criteria, and then numerical values are assigned to each criterion. After finding the value of each criterion by multiplying the weights with the numerical values, the total value is reached. Alternatives are evaluated, with the highest value being the most optimal result. In the final stage, the results are checked to eliminate uncertainties and ensure consistency. On the other hand, descriptive approaches work under the leadership of a designer, and a solution is sought. The approach includes four activities as problem analysis, conceptual design, final design, and detail design. In addition, concurrent engineering design is an approach that considers the product life cycle from the conceptual design stage to inventory removal. It is an approach that focuses on the demands and priorities of the concurrent engineering needs authority, believes that quality occurs as a result of process improvement, and has the philosophy that process improvement is the unending responsibility of the entire enterprise. Although the concurrent design approach has a wide variety of application forms, three activities are generically valid in all of them. These; use of multifunctional teams for design, production and support processes; including computer-aided programs, and the search for solutions with various analytical methods to optimize product design, production and support processes [26].

Mistree et al. [26] state that Evans' spiral model forms the basis of ship design activities. Brinati et al. [27] also state that the most used one among the different design models is the one developed by Evans.

As can be seen in Figure 2, transactions take place in sequential order [28]. It is also a labor-intensive and

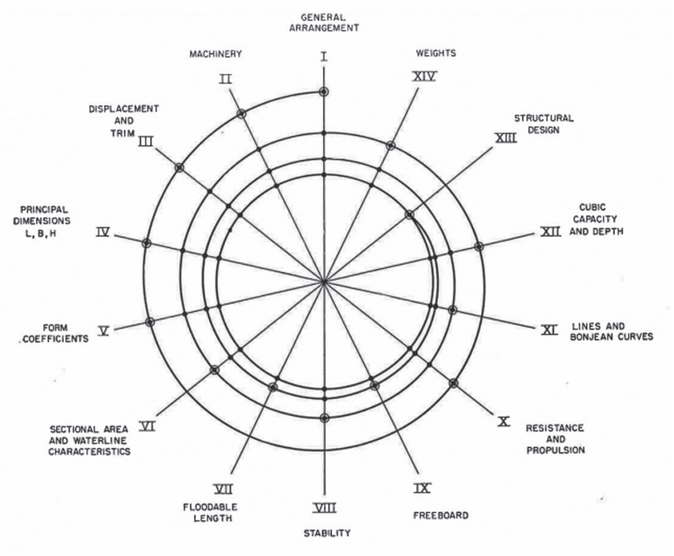

Figure 2. *Evans spiral model [27]*

expensive system. It is far from model information systems, which was used extensively in ship design in the past and has increased detail [26,27]. Although it is still used today, information systems are used for the solution. Optimization models are also used. According to Mistree et al. [26], optimization models shorten the calculations, the required amount of design variables and constraints can be included in the solution, and the optimal solution defined in the objective function can be found automatically. While single-criteria decision-making models were used in the past, multi-criteria decision-making models have been used. For example, an optimization model was developed by sequential linear programing by Mistree et al. [26]. Thus, simultaneous engineering applications took place in ship design optimization applications, similar to Figure 3.

As stated by Shin and Han [29], in ship design optimization models, designers' own variable spaces are formed and solution sets are created using very different programs. For example, while researchers were working with a computer-aided design program, McGookin et al. [30] used a genetic algorithm for cruise control system optimization. On the other hand, Diez and Peri [31] applied the stochastic study to the ship design, thus reflecting the differences in expected value and standard deviation to the objective function, and based on the worst-case scenario conditions for the constraints. Yaakob et al. [32] remodeled the durability of fishing boats to reduce their cost, achieving 12% fuel savings with a slight modification. Papanikolaou [33] sought a solution for ship design optimization by applying system approach.

Brinati et al. [27] stated that weight calculations such as structure, the machine group, and exterior design excluding cargo could be made with regression. Design models for other criteria were also presented by the researchers. Solutions of multi-objective combinatorial problems were examined by Ölçer [34] and it was indicated to use solution methods reached by evolutionary calculations. Ray et al. [35] developed a multi-criteria decision-making model and a ship design optimization model. Researchers using container design combined a general optimization tool, a decision-making model, and many ship architectural prediction models in this model. Structural design modeling requires the application of many more factors together than other modeling applications. For example, while range, speed, mobility, and control efficiency are important for missile capacity, speed, surface and underwater forms, dimensions, stabilization, and load status gain importance in ships [36]. Tanıl [36] derived an algorithm run in the MATLAB program to be used for missile exterior design. Thus, it is aimed to obtain the optimum configuration considering the parameters entered by the user during the conceptual design phase. Türkmen and Turan [37] used the multi-criteria decision-making methodology to improve the passenger ship structural design and achieved gains in terms of safety and economy. Arslan and Gürel [38] tried to find an optimal solution by applying fuzzy logic methodology. Along with these, a solution can be found using a genetic algorithm [27].

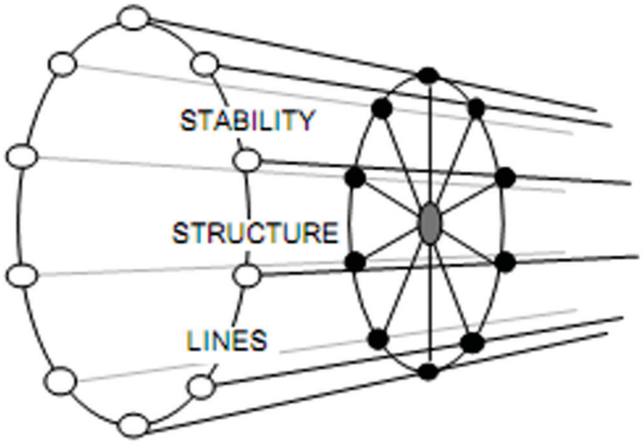

Figure 3. *Simultaneous design in a spiral model [26]*

Özdemir [9] states that the subject of ship design optimization, which is frequently used by designers and shipyards in recent years, is perceived as a subject that causes different interpretations in the relevant parts of the sector and whose boundaries need to be defined. The use of optimization models in ship designs dates back to the 1960s.

Ship design optimization problems have several conflicting objective functions. In the solution of multi-objective problems, classical methods can be used in the light of assumptions and current multi-criteria approaches. For example, the use of the analytic hierarchy process to combine the efficiency function for evaluating designs.

Lee and Lee [39] emphasize that designers can only design based on their experience and available data. The limited data available at the preliminary design stage further highlight the designer's freedom of knowledge. Lee and Lee [39], who refer to a wide variety of designs, especially in line with the wishes of the ship owners, mention the necessity of making comparisons with similar ships and using the values of their main characteristics at the conceptual design stage.

Tahara et al. [40] state that hull design is a multi-criteria decision-making problem. For example, reducing resistance, eliminating noise, minimal wave height, and increasing certain movements can be the goal of the design process. In addition, designers should consider values related to engine power or maintenance costs. Increasing some values may prevent others from reaching the desired values. Since it is generally impossible to create a perfect design in every respect, the main task of the designer is to provide a balanced integrity among the different functions expected from the ship [41]. Therefore, a multi-objective optimization approach is appropriate.

Genç and Özkök [42] focus on the sea trial stage in the ship production, which is the last phase of tests performed on ships before their delivery. Sea trial is optimized by planning and simulating the tests using computer programs. The objective is to suggest improvements that can shorten the duration of the sea trial, reduce costs, and expedite ship delivery. The results show that the new simulation model reduces the testing time by 2.75 hours (9.76%) compared to the initial model, indicating a more efficient sea trial process. The authors conclude that using simulation programs such as SImulation Modeling framework based on Intelligent Objects-SIMIO can help shipyards optimize their production processes, reduce costs, and improve on-time delivery performance.

A comprehensive examination of the literature reveals that the establishment of an effective design space is crucial in ship design. This entails creating a framework that allows for efficient exploration and evaluation of design alternatives for different ship types and sizes. Additionally, defining measurable objective functions with specific attributes is essential for accurate assessment and comparison of design solutions. By incorporating quantitative metrics such as efficiency, cost, and risk, designers can make informed decisions and optimize their designs.

2.2. PSI Method

It is necessary to mathematically formulate multi-criteria optimization problems to describe the "Parameter Space Investigation-PSI" method. In this method, the system relies on design variables. The vector of design variables is as follows [12,21].

$$\alpha = \alpha_1, \ldots \alpha_r \quad (1)$$

The Capesize bulk carrier optimization model's design variables are length between perpendicular (L_{pp}), breadth (B), draft (d_s), block coefficient (C_b), ship speed (v_{tr}), cargo volume (V_{car}), and the machine database number (I_{mei}). Design variable vector;

$$\alpha = (L_{pp}, B, d_s, C_b, v_{tr}, V_{car}, I_{mei}) \quad (2)$$

Every design variable has constraints. These constraints are;

$$\alpha_j^* \leq \alpha_j \leq \alpha_j^{**} \quad j = 1, \ldots, r \quad (3)$$

is displayed as α_j^* and α_j^{**} shows the lower and upper limit values of variable α [12,21].

When the model consists of two design variables, $\alpha = \alpha_1$, α_2 design variable constraints $\alpha_1^* \leq \alpha_1 \leq \alpha_1^{**}$ and $\alpha_2^* \leq \alpha_2 \leq \alpha_2^{**}$ is expressed [12,21].

Functional relationships that are functions of the design variables exist for every design optimization problem. These functional constraints are shown as;

$$C_l^* \leq f_l(\alpha) \leq C_l^{**}, \quad l = 1, \ldots t \quad (4)$$

is displayed as $f_l(\alpha)$ functional relations, C_l^* and C_l^{**} consist of lower and upper boundaries of this functional relations [12,21].

The design model has characteristics that should be minimized or optimized in performance criteria. The criteria restrictions determine the performance criteria. The criteria constraints can be written as;

$$\Phi_v(\alpha) \leq \Phi_v^{**}, \quad v = 1, \ldots, k. \quad (5)$$

Here $\Phi_v(\alpha)$ indicates performance criteria, Φ_v^{**} indicates the worst value of $\Phi_v(\alpha)$ and "≤" sign is used in equation (5) because minimization is the most common form for demonstration purposes [12,21].

Performance criteria,

$$\Phi(\alpha) = \left(\Phi_1(\alpha), \ldots, \Phi_k(\alpha)\right) \quad (6)$$

Expressed as vector. Functional constraints are sometimes not correctly identified. In practice, feasible solutions may remain beyond constraints. To include these feasible solutions in the feasible solution set, the constraints need to be rearranged. $\Phi_{k+1}(\alpha) = f_l(\alpha)$ expressed as pseudo-criterion instead of $f_l(\alpha) \leq C_l^{**}\ l = 1, \ldots, t$. To find constraint Φ_{k+1}, the test table containing $\Phi_{k+1}(\alpha)$ the must be compiled (There are test tables containing performance criteria $\Phi_v(\alpha) \leq \Phi_v^{**}, \ v = 1, \ldots, k$) [21].

Generally, all performance criteria and pseudo-criteria are considered when it is desired to find the feasible solution set (D). The problem is now

$\Phi_v(\alpha) \le \Phi_v^{**}$, $v = 1, \ldots, k$, $k + 1, \ldots$, $k + t$ solved with constraints. Thus, in order to define the feasible solution set, the problem should be considered with k+t criteria [11].

The Pareto optimal solution set (P) can be discovered by figuring out the optimal solution between the vectors in the feasible solution set (D). The Pareto optimal solution set in minimization problems can be defined as $\Phi(P) = \min_{\alpha \in D} \Phi(\alpha)$. $P \subset D$; is expressed as the Pareto optimal solution set. However, the pseudo criteria are not taken into account while creating this Pareto optimal solution set. They are the criteria values in the Pareto optimal solution calculated using P(Π). Φ^P is prototype is value, that is the current design or desired design that needs to be developed [21].

Uniformly distributed LP sequences or random number generators are used in the PSI approach to create vectors (points) in the design variable space. LP-Tau generates uniformly distributed sequences and supports up to 51 design variables and 2^{20} tests. These sequences are used to compute N test points $\alpha^1, \ldots, \alpha^N$ in the design variable space [43].

3. Mathematical Model of Capesize Bulk Carrier

Many approaches have been developed to solve multi-criteria optimization problems. In this study, the technique of “Parameter Space Investigation-PSI” developed in the former Soviet Union was used. PSI method studies conducted by Statnikov et al.’s [10-12,43] and Anıl [21] are taken as the main reference of this study. As a starting point, this study used the structure of Cudina [22,23] and Zanic and Cudina’s [24] optimization model. When solving optimization problems, the MOVI software uses a mathematical model that expresses the properties of the problem under consideration.

This research focuses on the optimization problem of bulk carrier design employing PSI technique to address the challenges posed by multiple and contradictory criteria. A prototype was developed based on existing ship designs found in the literature, and this prototype was further enhanced and refined. The design optimization model was examined using the PSI technique with MOVI software. Subsequently, the obtained results were compared with the findings from Zanic and Cudina’s [24] study as reported in the literature.

This study focuses on the optimization of ship design parameters. Design parameters identified in the literature were employed in the study. Note that the limitation of this study lies in the predefined set of ship design parameters. However, these parameters can be expanded or reduced based on specific needs and requirements. Furthermore, future research can involve the development of a prototype model to further explore and enhance the optimization of ship design parameters.

The problem has seven design variables, five functional relations, three criteria, and four pseudo-criteria. Functional constraints are sometimes not correctly identified. In practice, feasible solutions may remain beyond constraints. In order for these feasible solutions to be included in the feasible solution set, the constraints need to be rearranged. Instead of $f_l(\alpha) \le C_l^{**}$ $l = 1, \ldots, t$ the pseudo-criteria $\Phi_{k+1}(\alpha) = f_l(\alpha)$ is used.

Before solving an optimization problem, the properties of the objective function, constraints, and the state of the decision variables are important [44]. This mathematical model is valid only for the “Capesize” case. For other ship types, calculation factors, engine database, power, and cost parameters need to be rearranged in Appendix [24,45]. Also, the minimum freeboard calculation is calculated for the “Capesize (bulk carrier)” type [24]. It needs to be rearranged for other ship types.

Terms used in the mathematical model and their definitions:

Length Between Perpendiculars (Lpp): The horizontal distance between the front and rear perpendiculars is called the length between perpendiculars. It is fixed for a particular ship and does not depend on the ship’s loading condition [46].

Breadth (B): The breadth of the ship at its widest point is called the beam [46].

Draft (ds): The vertical distance at any point along the length between the waterline and the deepest part of the ship is the draft [46].

The block coefficient (C_B): C_B is the ratio of the displacement volume to the volume of a rectangular block whose sides are equal to the tip width, the average draft, and the length between perpendiculars [47].

Depth (D): The vertical length between the lowest point and the highest point of the ship [48].

Deadweight Tonnage (DWT): This weight measure shows the total weight a ship can carry [48].

Gross Tonnage (GT): It is a measure of the volume of all the spaces of the ship contained within the hull, bulkheads, and decks [48].

vtr: Trial speed is the speed measured at the ship’s sea trial [49].

$V_{service}$: It is the speed at which the ship performs while navigating its route determined in real weather conditions [49].

Cargo Volume (V_{car}): The cargo of a ship is the goods that it is carrying [50].

MCR: Maximum Continuous Service Rating is the maximum power output engine can produce while running continuously at safe limits and conditions [51].

SMCR: Specified Maximum Continuous Rating [52].

Freeboard: Freeboard is the distance from the waterline to the freeboard deck of a fully loaded ship [53].

Wst: Wst includes the weight of all elements of the ship's steel structure (tonnage) [54].

There are also some dimensionless ratios that are commonly used to describe ship geometry and in systematic analysis studies. These can be expressed as design parameters in modeling The main dimensions of the dimensionless ratios can be listed as follows [7]:

Length Between Perpendiculars - Beam Ratio: Lpp/B

Length Between Perpendiculars - Draft Ratio: Lpp/ds

Length Between Perpendiculars - Depth Ratio: Lpp/D

Breadth - Draft Ratio: B/ds

These ratios should be as low as possible and should not be correlated with each other in a way that defines the ship form in the model.

3.1. Design Variables and Constraints

There are seven design variables in this problem, and four of them are defined as main dimension design variables. The design variables that were developed from the model of Cudina [22] were listed as follows [45]:

Main Dimensions:

p1: L_{pp}	Length between perpendiculars (m)
p2: B	Breadth (m)
p3: d_s	Scantling draught (m)
p4: C_B	Block coefficient (-)

Other Design Variables:

p5: V_{car}	Volume of cargo space (m^3)
p6: v_{tr}	Required trial speed (kn)

p7: IME MAN B&W 6S70MC-C, mark 7, IME (Main engine identifier) = 1 (MCRi = 18660; (kW at 91 rpm) maximum continuous rating)

MAN B&W 5S70MC-C, mark 7, IME (Main engine identifier) = 2 (MCRi = 15550; (kW at 91 rpm) maximum continuous rating)

The design variable vector is shown as $\alpha = (L_{pp}, B, d_s, C_B, v_{tr}, V_{car}, IME)$ and design variable constraints are also shown as $\alpha^*_j \leq \alpha \leq \alpha^{**}_j$ j = 1,..., r. Constraints of design variables are defined in the range of minimum and maximum values.

$265 \leq p1 \leq 280$

$43 \leq p2 \leq 45$

$17.5 \leq p3 \leq 17.95$

$0.85 \leq p4 \leq 0.875$

$185000 \leq p5 \leq 195000$

$14.5 \leq p6 \leq 15.5$

p7 = 1 or 2

3.2. Functional Relations and Functional Constraints

The functional relations used in the model are expressed as follows. There are five functional relations in this model. These functional relationships and constraints were developed from Cudina's [22] model [45].

f1: L_{pp}/B	Length/Breadth ratio
f2: L_{pp}/d_s	Length/Scantling draught ratio
f3: B/d_s	Breadth/Scantling draught ratio
f4: L_{pp}/D	Length/Depth ratio
f5: $(D\text{-}ds)\text{-}F_{B60}$	Freeboard control

The freeboard (D-ds) should be at least "about minimum freeboard" (FB60).

The functional relationship constraints used in the model are shown as follows:

$5.8 \leq f1 \leq 6.5$	L_{pp}/B
$15.3 \leq f2 \leq 16.2$	L_{pp}/d_s
$2.3 \leq f3 \leq 2.7$	B/d_s
$11.0 \leq f4 \leq 11.9$	L_{pp}/D
$0 \leq f5$	$(D\text{-}ds)\text{-}F_{B60}$

3.3. Pseudo-Criteria and Pseudo-Criteria Constraints

At the beginning of the research, functional relationships that lack strict functional restrictions can be referred to as pseudo-criteria.

Pseudo-criteria used in the model are "engine power control, the volume of cargo space and the required trial speed". Pseudo-criteria used in the model and their features are as follows [22,45]:

f6: MCR_i - SMCR	MINIMIZE the "Engine Power Control"
f7: DWT	MAXIMIZE the deadweight (t)
f8: V_{car}	MAXIMIZE the volume of cargo space (m^3)
f9: v_{tr}	MAXIMIZE the required trial speed (kn)

Machine Power Control: The power of the selected machine should be more than the power requirement. In other words, the difference between the power of the selected machine and the power requirement must be greater than zero (0 < f6). On the other hand, f6 should also be minimized as the machine may be a lower powered machine supplying the power requirement in the database. Therefore, f6 will be included in the pseudo-criteria section, and the condition of being greater than zero will be evaluated as a "pseudo-criteria constraint", not a "functional constraint". The design variables Cargo Volume (p5) and Ship Speed (p6) are also pseudo-criteria.

3.4. Criteria and Criteria Constraints (Performance Criteria Constraints)

The “design” criteria, also called the “Objective Function”, used in the model were “the weight of steel structure”, “the power requirement”, “the cost of newbuilding”. These criteria are adapted from Cudina’s [22] model. The criteria included in the model have the feature of minimization. There are no criterion constraints in the model [45].

c1: W_{st} MINIMIZE the weight of steel structure (t)

c2: SMCR MINIMIZE the power requirement (kW)

c3: CNB MINIMIZE the cost of new building the (US DOLLAR)

3.5. Prototype

The prototype model was determined based on the characteristics of the ships produced in IHHI, Koyo Dock, Namura, NKK shipyards located in the Far East and the characteristics of the capesize bulk carriers. The specifications of the ships are shown in Table 3.

Based on the characteristics of the ships indicated in Table 3, a prototype model was created. The prototype values used in the model are as follows [45]:

p1: L_{pp} (m)= 279

p2: B (m)= 43

p3: d_s (m)= 17.5

p4: C_B (-)= 0.875

p5: V_{car} (m^3)= 185000

p6: v_{tr} (knots)= 15.27

p7: Ime i (-)= 1

4. Multi-Criteria Optimization of Capesize Bulk Carrier

Optimization is a discipline that helps to make managerial decisions by developing mathematical models for solving a problem [44]. In single-criteria optimization, it is tried to obtain a single design or decision that is best for a purpose, which is usually a global minimum or global maximum based on the minimization or maximization problem [66]. Almost all designs or challenges in the real world necessitate simultaneous optimization of several conflicting objectives. In the case of several objectives, there may not be a single optimal all-purpose solution. In this situation, selecting a solution from a limited number of consensus options is required of the decision-maker. The optimal solution ought to have performance adequate for all needs.

The Pareto optimum has been integrated into the development of multi-objective optimization algorithms. In this way, depending on its objective values, a feasible

Table 3. *Characteristics of ships produced in shipyards and their types*

		L_{PP} (m)	B (m)	d_s (m)	D (m)	The capacity of cargo (m^3)	DWT (t)	GT (t)	$V_{kn,}$ service	Main engine	SMCR (kw/rev)
Shipyards	IHHI	277	45	17.6	23.8	186,668	48,338	83,849	14.8	6RTA72	8160/124
	Koyo Dock	280	45	17.6	23.8	188,205	45,908	85,379	14.6	6S70MC	9267/110
	Namura	277	45	17.7	24.1	191,255	44,881	85,868	14.8	6S70MC	8240/122
	NKK	279	45	17.81	24.1	191,582	47,400	87,522	14.7	6S70MC	8310/123
Capesize Bulk Carriers	Cape Riviera	280	47	17.95	24.4	205,722	185,875	93,006	14.7	Kawasaki MAN B&W 6S70MC Mk VI diesel	16860 kW x 91 rpm
	Cape Heron	279	45	17.95	24.4	197,049	177,656	88,494	15	Mitsui MAN B&W 6S70MC diesel	16860 kW x 91 rpm
	Royal Chorale	279	45	17.95	24.4	197,050	177,544	88,491	15	Mitsui MAN B&W 6S70MC diesel	16860 kW x 91 rpm
	Ocean Comet	279	45	17.93	24.4	198,964	176,943	89,603	14.6	MAN B&W 6S70MC Mk VI diesel	16860 kW x 91 rpm
	Frontier Neige	288	45	18.2	24.7	203,226	182,737	93,288	15.3	Kawasaki MAN B&W 6S70MC-C7 diesel	17780 kW x 87 rpm

Source: [24,55-65]

solution may be the best, the worst, or indistinguishable from the other options. The phrase "optimal solution" refers to a solution that is not just better than the alternatives for at least one objective while not being worse for any of the goals. A solution that is not suppressed by any other solutions in the search space is the optimal solution. According to Osyczka [66], Dias and Vasconcelos [67], Sağ [68], and Deb [69], the collection of such optimum solutions is known as a pareto optimal solution set.

When solving optimization problems, MOVI software uses a mathematical model that expresses the properties of the problem under consideration. The mathematical model explains the relationships between output functions and input parameters (design variables) [21,45]. Model using MOVI software:

- Retrieves input parameters (design variables) created by MOVI.
- Calculates output functions based on input parameters.

In general, the model may contain data files, programs, etc.. No matter how complex the model structure is, the model interface provides the interaction between MOVI and the model, as shown in Figure 4. Dynamic Link Library (DLL file), Matlab M-function (M-file), and executable EXE file are supported for the model interface file. Matlab M-file was used in this study.

Matlab M-function (M-file): Output model functions are calculated with an M-function in a Matlab environment. Input parameters are passed to the M-function as input arguments. Output functions are expressed by the output vector of the M-function [21,45].

Once the M-file interface is generated, MOVI can begin optimization. In this study MOVI 1.4 and MATLAB R2009a software were used.

MOVI uses histograms to show the distribution of feasible and pareto optimal solutions. The intervals of the histograms are divided into 10 subintervals. Analysing the histograms elicits how feasible and pareto sets are distributed in the design variable set. Histograms play a major role in correcting constraints of design variables.

4.1. The First Run Optimization

The optimization model was defined in MOVI via the corresponding menus. LP Tau was chosen as the number generator for this optimization model. LP-Tau generated uniformly distributed arrays and supported 51 design variables and 220 tests. After the prototype values were entered, 8192 (2^{13}) tests were performed using the Run Test interface. This meant that 8192 design variable vectors could be generated by MOVI. As a result of these tests, 3069 of the vectors could enter the test table, while 5123 could not meet the constraints. Prototype values were expressed with the vector "0". To find better values than the prototype, the prototype value was taken as the constraint and 7 vectors were included in the feasible solution set. Only two of these seven feasible solutions (#7371, #5145) were Pareto optimal solutions. The vectors containing Pareto optimal solution were the 7371 and 5145 vectors. Table 4 shows the feasible and pareto optimal solutions for the first optimization.

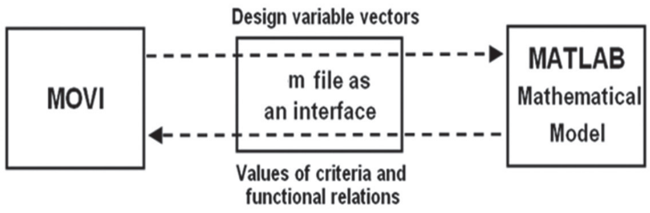

Figure 4. *Data exchange between MOVI 1.4 and the user model [21]*

By means of histograms, the analysis of the design variables in the feasible solution could be made. Histograms show the distribution of variables over certain intervals. Thus, to achieve a more uniform distribution, the lower and upper limits of variables could be determined again. In the histograms, the values of the pareto optimal solutions are shown as green circles, and the ranges in which the feasible solutions were collected are shown in the red circle. The prototype value is shown as ▽symbol in the optimization process. The feasible solution intervals of the design variables are shown in Figure 5.

According to the histograms of the design variables shown in Figure 5; the lower limit for the design variable p_1 (length between perpendicular) needed to be adjusted. The lower bound should also be adjusted for the design variable p_3 (draft). Both the upper and lower limits must be set for the design variable p_6 (ship speed).

4.2. The Second Run Optimization

The boundaries of the design variables were rearranged. Lower limit for p_1 was redefined as 273; lower limit for p_3

Table 4. *Feasible and pareto optimal solutions for the first run optimization*

	1st Run	2nd Run	3rd Run
Test Performed	8192	8192	8192
Test Table Contains	3069	4112	5162
Feasible Set Contains	7	102	282
The Number of Pareto Optimal Solutions	2	9	6
Numbers of Pareto Optimal Solutions Vectors:	#7371, #5145	#2794, #3220, #6096, #741, #3240, #3561, #903, #4307, #1935	#3240, #1944, #57, #4307, #1935, #207

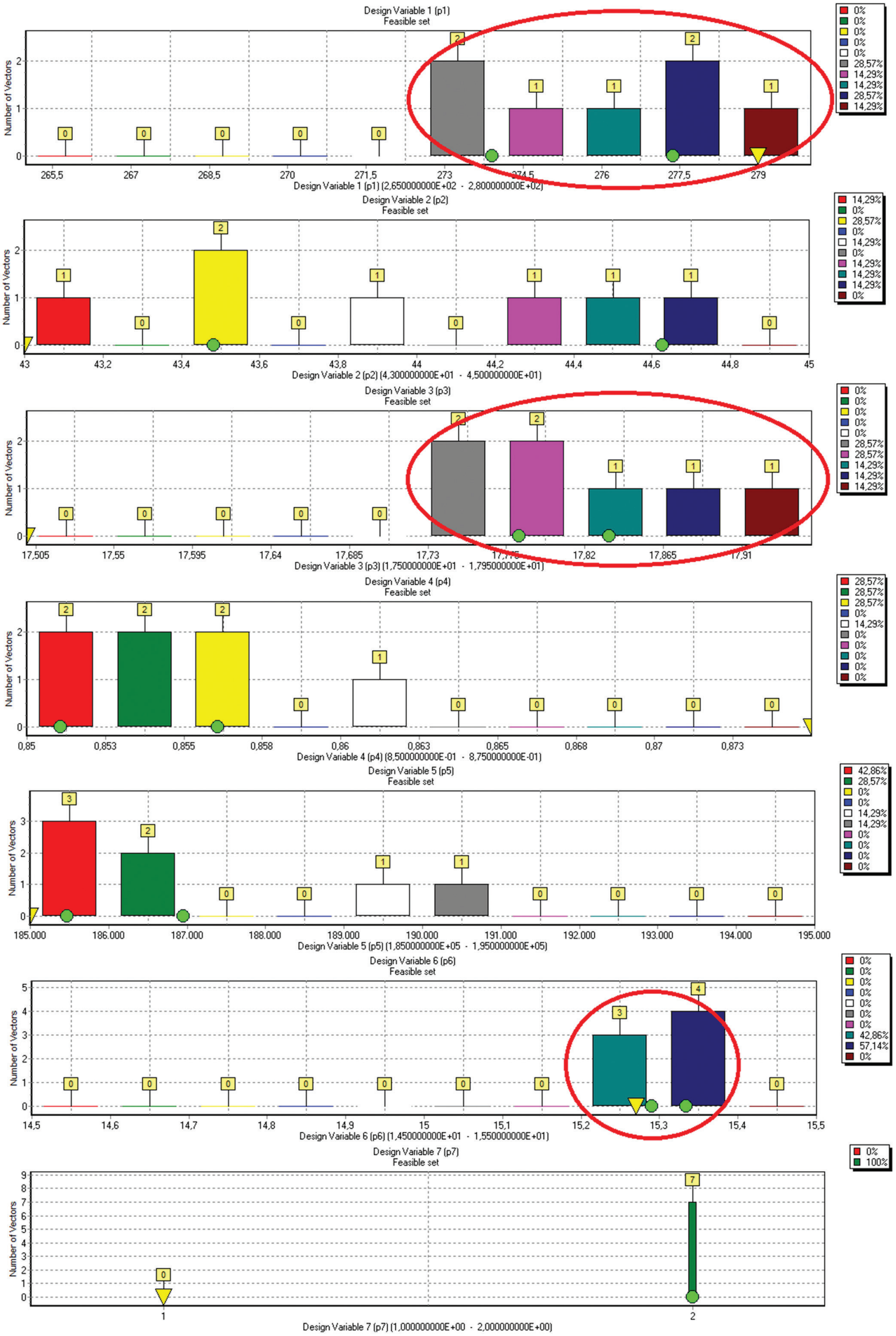

Figure 5. Feasible solution intervals of design variables for the first optimization

was redefined as 17.74; lower limit for p_6 was 15.26; and the upper limit was redefined as 15.4. For the second run of optimization, 8192 tests were performed using rearranged limits. As a result of this test, 4112 vectors could enter the test table. The 4080 vectors did not satisfy the constraints. Again, in order to find better values than the prototype, the prototype value was used as the constraint and 102 vectors were included in the feasible solution set. Only 9 of them were pareto optimal solutions in 102 feasible solutions. Table 4 shows the feasible and pareto optimal solutions for the second run optimization.

The lower and upper limit values of the variables should be determined again through histograms. Figure 6 indicates the boundaries that need to be rearranged. The upper bound for the design variable p_4 (block coefficient) and p_5 (cargo volume) needed to be rearranged.

After the second run optimization, pareto optimal values of design variables are listed in Table 5.

4.3. The Third Run Optimization

The boundaries of the design variables were rearranged. The upper bound for the design variable p_4 was changed to 0.864 and the upper bound for the design variable p_5 to 191,000. As a result of these tests, 5162 of 8192 tests could enter the test table, while 3030 could not. Prototype values were taken as constraints and 282 vectors were included in the feasible solution set. In the end of 8192 tests, 282 feasible solutions were found with better results than the prototype values, and 6 of them were pareto optimal solutions. Table 4 shows the feasible and pareto optimal solutions for the third run optimization.

By means of histograms, the lower and upper limit values of the variables are shown in Figure 7. When the histograms in Figure 7 are examined, there are no intervals in which the constraints of the continuous variables are defined, where there is no feasible solution. For this reason, the fourth round was not passed and the variable constraints were not rearranged.

As a result of of the first run optimization, vectors #7371 and #5145 contain the pareto optimal result. In the end of the second run of optimization, the pareto optimal vectors are #2794, #3220, #6096, #3741, #3240, #3561, #903, #4307, #1935. After the third run optimization, pareto optimal values of design variables are listed in Table 5. "0" number of vector has prototype values and "#57", "#207", "#1935", "#1944", "#3240", "#4307" number of vectors has pareto optimal values of design variables.

The prototype values and the values of Zanic and Cudina [24] found as a result of optimization and the pareto optimal values found as a result of the optimization process are shown in Table 5 for design variables, Table 6 for pseudo criteria, and Table 7 for criteria.

After the completion of the optimization process, pseudo-criteria values were calculated as Table 6.

When the pseudo-criteria in Table 6 are examined, it is seen that the values of the minimum feature f6 (Engine Power Control) criterion are lesser than the prototype value.

Considering the f7 (deadweight) and f8 (cargo volume) criteria which have maximum properties, it is seen that the values in the pareto optimal solution set values are higher than the prototype value.

When the f9 (required trial speed criterion), which is also in the maximum structure, is examined, it is seen that the values in the pareto optimal solution sets values are higher than both the prototype value and the value obtained by Zanic and Cudina [24] (15.03), which is used as a reference.

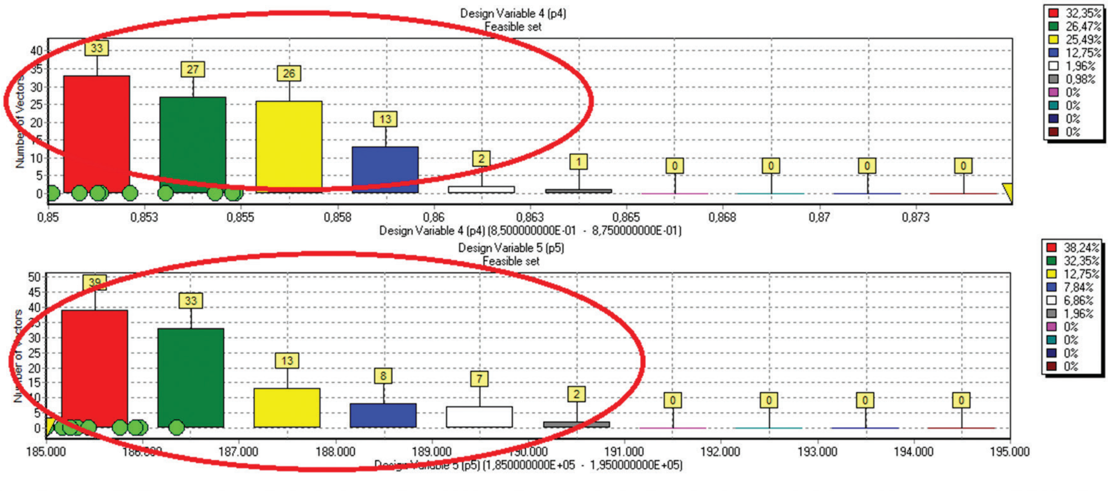

Figure 6. *The feasible solution intervals of design variable 4 and 5 for the second run optimization*

Table 5. *Pareto optimal values of the design variables obtained as a result of the first, second, third optimization runs and reference study*

	Design Variables	**p1 L_{pp}**	**p2 B**	**p3 d_s**	**p4 C_B**	**p5 V_{car}**	**p6 v_{tr}**	**p7 I_{ME}**
	Prototype Values # 0	**279**	**43**	**17.5**	**0.875**	**185,000**	**15.27**	**1**
1st Run	Lower Bounds	273.915	43.483	17.783	0.851	185,47	15.291	2
	Upper Bounds	277.376	44.626	17.834	0.856	186,95	15.334	2
	Pareto Optimal # 7371	277.376	43.483	17.783	0.856	185,47	15.334	2
	Pareto Optimal # 5145	273.915	44.626	17.834	0.851	186,95	15.291	2
2nd Run	Lower Bounds	273.326	43.124	17.763	0.850	185,002	15.274	2
	Upper Bounds	279.614	44.417	17.928	0.855	186,350	15.386	2
	Pareto Optimal # 2794	275.387	44.197	17.851	0.851	185,164	15.328	2
	Pareto Optimal # 3220	274.126	44.057	17.817	0.854	185,256	15.350	2
	Pareto Optimal # 6096	273.326	44.417	17.763	0.851	185,768	15.296	2
	Pareto Optimal # 3741	278.071	43.434	17.919	0.850	185,442	15.386	2
	Pareto Optimal # 3240	273.579	44.151	17.860	0.851	186,350	15.287	2
	Pareto Optimal # 3561	277.148	43.451	17.842	0.855	185,002	15.280	2
	Pareto Optimal # 903	279.173	43.744	17.782	0.852	185,322	15.300	2
	Pareto Optimal # 4307	278.552	43.168	17.925	0.855	185,919	15.274	2
	Pareto Optimal # 1935	279.614	43.124	17.928	0.853	185,981	15.287	2
3rd Run	Lower Bounds	273.579	43.124	17.813	0.850	185,026	15.274	2
	Upper Bounds	279.645	44.151	17.928	0.857	185,914	15.288	2
	Pareto Optimal # 3240	273.579	44.151	17.860	0.850	185,810	15.287	2
	Pareto Optimal # 1944	273.708	43.812	17.882	0.857	185,026	15.274	2
	Pareto Optimal # 57	277.266	43.406	17.881	0.854	185,094	15.289	2
	Pareto Optimal # 4307	278.551	43.168	15.925	0.853	185,552	15.274	2
	Pareto Optimal # 1935	279.614	43.124	17.928	0.852	185,589	15.287	2
	Pareto Optimal # 207	279.645	43.540	17.813	0.850	185,914	15.275	2
Reference [24]		274	44.4	17.85	0.865	189,670	15.03	2

The Pareto optimal values of the criteria obtained as a result of the first, second, and third optimization runs are listed in Table 7.

The prototype value for the minimized c1 = Wst ton (Steel Structure Weight) criterion is 18,911 tons, and the value that Zanic and Cudina [24] obtained as a result of the optimization is 19,001 tons. As a result of third run of optimization with MOVI, six solutions entered the Pareto optimal solution set. Looking at the c1 value of these six solutions, these values vary between 18,611 and 18,897. All six solutions are better than Zanic and Cudina's [24] result for c1 (steel structure weight). Also, the values of vectors 57, 1935, 1944, 3240 and 4307 are better than the value of c1 calculated using prototype values.

The prototype value for the minimized c2 = SMCR kW (Power Requirement) criterion is 15,670 kW, and the value that Zanic and Cudina [24] obtained as a result of the optimization is 15,268 kW. Considering the c2 value of the six pareto optimal solutions, these values vary between 14,744 and 15,431. Five of these six solutions are better than Zanic and Cudina's [24] result for the c2 - power requirement) (values of vectors 57, 207, 1935, 3240 and 4307). The c2 criterion value of all six solutions is better than the c2 value calculated using the prototype values.

For the minimized c3 = CNB US$ (New Shipbuilding Cost) criterion, the prototype value is 93,696,607 US$, result of Zanic and Cudina [24] optimization is 93.037.000 US$. As a result of the third run of optimization with MOVI, six solutions entered the pareto optimal solution set. Looking at the c3 value of these six solutions, these values are between 91.9 million and 92.19 million US$. All six solutions are better for c3 (new shipbuilding cost) than Zanic and Cudina's [24] value and prototype.

To find these criteria values, the design variables values in Table 5 should be taken as input parameters. The criteria values found in the end of the analysis were better than the prototype values and the values of Zanic and Cudina [24].

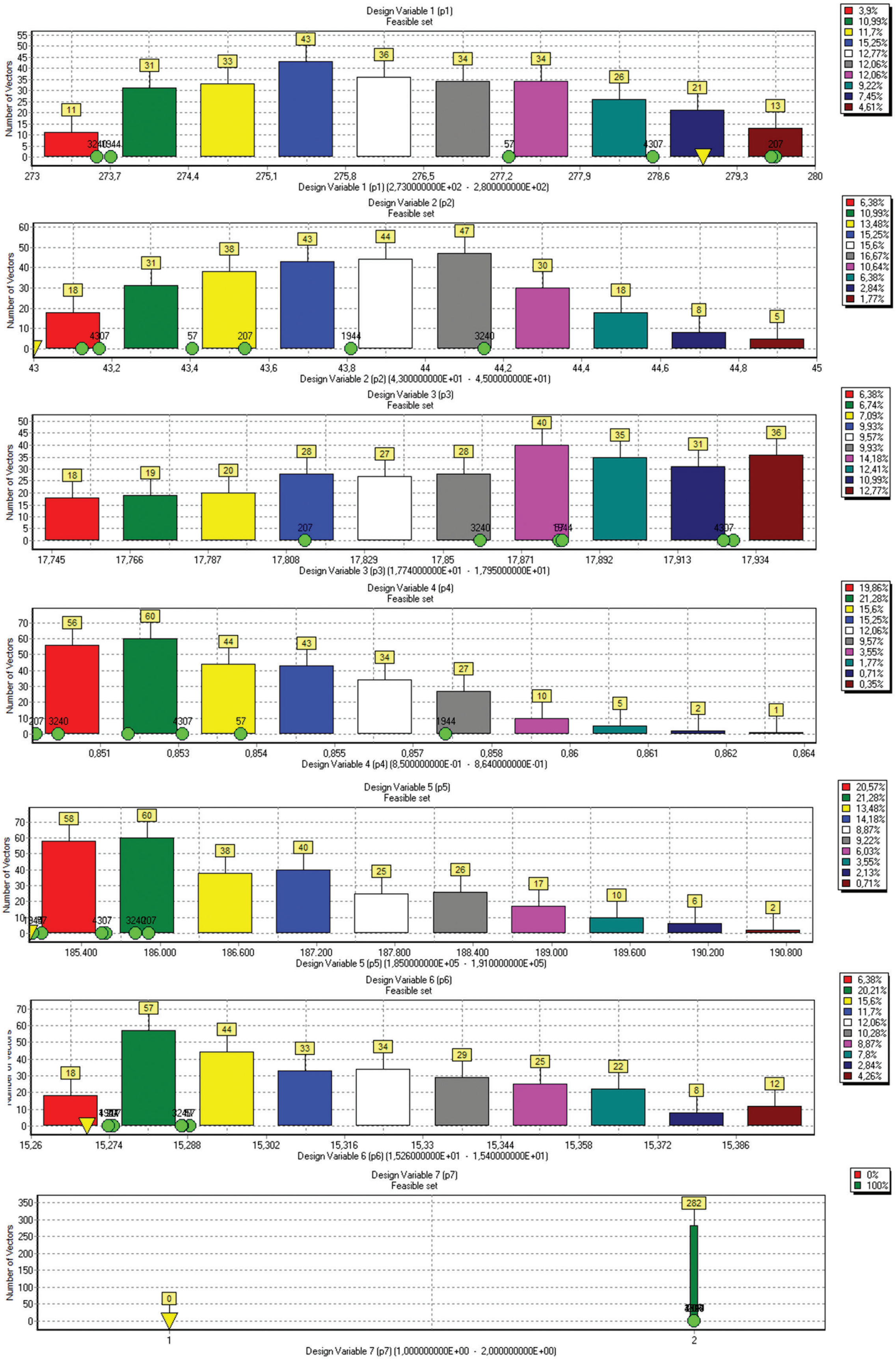

Figure 7. Feasible solution intervals of design variables for the third run optimization

Table 6. *Pareto optimal values of the pseudo-criteria obtained as a result of the third optimization run*

	Pseudo Criteria	f6: MCR_i - SMCR (Min)	f7: DWT (Max) (t)	f8: V_{car} (Max) (m^3)	f9: v_{tr} (Max) (kn)
	Prototype Values # 0	2,989.309	166,933.132	185,000.000	15.27000
3rd Run	Pareto Optimal # 57	497.926	167,178.378	185,093.750	15.28843
	Pareto Optimal # 207	806.262	167,696.279	185,914.062	15.27476
	Pareto Optimal # 1935	728.881	167,528.841	185,588.867	15.28700
	Pareto Optimal # 1944	119.429	167,370.242	185,026.367	15.27387
	Pareto Optimal # 3240	437.172	166,960.617	185,810.058	15.28689
	Pareto Optimal # 4307	687.037	167,233.339	185,551.513	15.27382

Table 7. *Pareto optimal values of the criteria obtained because of the first, second, third optimization runs and reference study*

	Criteria	c1 = Wst (Min)	c2 = SMCR (Min)	c3 = CNB US $ (Min)
1st Run	Prototype Values # 0	18,911	15,670	93,696,607
	Lower Bounds	18,778	15,322	92,162,223
	Upper Bounds	18,806	15,336	92,218,814
	Pareto Optimal # 5145	18,806	15,322	92,162,223
	Pareto Optimal # 7371	18,778	15,336	92,218,814
2nd Run	Lower Bounds	18,665	14,911	91,960,962
	Upper Bounds	18,898	15,540	92,218,230
	Pareto Optimal # 903	18,898	15,029	92,168,457
	Pareto Optimal # 1935	18,848	14,911	92,218,230
	Pareto Optimal # 2794	18,742	15,318	91,960,962
	Pareto Optimal # 3220	18,665	15,540	91,968,406
	Pareto Optimal # 3240	18,669	15,137	92,013,004
	Pareto Optimal # 3561	18,730	15,090	92,028,224
	Pareto Optimal # 3741	18,765	15,180	92,000,807
	Pareto Optimal # 4307	18,804	15,005	92,205,640
	Pareto Optimal # 6096	18,679	15,234	91,969,018
3rd Run	Lower Bounds	18,611	14,744	91,917,124
	Upper Bounds	18,897	15,431	92,191,529
	Pareto Optimal # 57	18,724	15,052	92,005,445
	Pareto Optimal # 207	18,897	14,744	92,191,529
	Pareto Optimal # 1935	18,819	14,821	92,115,028
	Pareto Optimal # 1944	18,611	15,431	91,956,770
	Pareto Optimal # 3240	18,643	15,113	91,917,124
	Pareto Optimal # 4307	18,770	14,863	92,082,947
Reference [24]		19,001	15,268	93,037,000

5. Conclusion

Decision making has always been exceptionally critical, particularly for the leading of different purposes. Deciding on ships and comparative plans with a life span of approximately 30-40 years, in terms of making them more economical, competitive and environmentally friendly, maintains and will preserve its significance as a subject that should be examined very well compared to numerous decisions.

The model used in this study will form the basis for ship designs using multi-criteria optimization methods.

The designs produced using the design spiral method have been transformed by the use of optimization methods. Finding the feasible solution and the Pareto optimal solution set in multi-criteria optimization problems is of great importance, especially when the prototype is being developed.

In this study, the prototype development problem of a Capesize-type bulk carrier was addressed by the PSI method using visualization techniques such as histograms and analysis methods.

The model was developed in MATLAB environment and solved again in MOVI. By finding the feasible solution set and pareto optimal solution set with MOVI, better results were obtained than the results of Zanic and Cudina [24] and the prototype.

At the end of this study, the prototype design of Capesize bulk carrier was developed. After analyzing the Pareto optimal results, the user can choose the model that suits him/her or continue the optimization process. This study presents a case study on the development of ship design problems.

For future studies, the design process can be improved by expanding databases of mathematical models specific to various ship types and sizes. The PSI method presented in this paper introduces a program that generates histograms and test tables, providing decision-makers with unprecedented opportunities for analyzing and synthesizing alternative designs.

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APPENDIX

A. Constants and Parameters

The following factors for computations, engine database, power parameters, cost parameters and constants are valid only for the Capesize (bulk carrier) model.

A.1. Factors for Computations [22,23,24,45]

ffc1 = 5 Impact of high-strength steel on reducing the weight of steel structures.

ffc2 = 0.0282 Empirical factor

ffc3 = 450 Addition of the mass of the steel structure

ffc4 = 800 Empirical factor

ffc5 = 0.9 CSR/SMCR ratio

ffc6 = 0.28 Empirical factor

ffc7 = 100 Addition of the weight of ship equipment

Af = 29 Compensation factors Af and Bf for calculation of cGT

Bf = 0.61

κ = 0.64 specific voluminosity of the ship

kappa = Vcar / (Lpp*B*D)

A.2. Engine Database [22,23,24,45]

MAN B&W 6S70MC-C, mark 7 MCR: 18660

CME: 8400000 $ KCSR: 1.022

MAN B&W 5S70MC-C, mark 7 MCR:15550

CME: 7400000 $ KCSR: 1.022

A.3. Power Parameters [22,23,24,45]

a1 = 0.00571

a2 = -0.1465

a3 = 1.072

a4 = 0.8145

a5 = 3.843

a6 = 3.589

a7 = 0.0006634

A.4. Cost Parameters [22,23,24,45]

cst = 1000 Average unit steel costs ($/tonne)

rWgst (Wgst/Wst) = 1.12 The ratio of the gross mass of steel to the weight of the steel structure

Cfix ($) = 26000000 Other costs, including costs related to other materials and equipment

PcGT = 35 Shipyard productivity (hrs/cGT) cGT: the gross tonnage accounted for, according to the OECD.

VL = 30 Unit hourly wage ($/hour of employment)

Coc = 7000000

Vcam = 5000 The volume of the camber (m^3)

Vsup = 11000 Volume of the accommodation (m^3)

Vfc = 0 The volume of the forecastle (m^3)

KCBD (CBD) = 0.005285 Constant for approximating the block coefficient to the molded depth.

A.5. Constants

γ_{tot} = 1.0279: Density of sea water, including influence of shell plating and ship appendages (t/m^3) [22,23,24,45].