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Optimization of the Number of Boat Passengers Using the Intact Stability Survival Approach

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***Abstract*— Passenger ship accidents in Indonesia's domestic waters are frequently linked to overloading and stability failures, particularly on non-classed vessels with open decks. This study proposes an analytical method to determine the optimal passenger capacity based on intact stability survival criteria. The method begins with hydrostatic calculations of the hull to generate the KN curve, which is then adjusted for the mass distribution of the vessel and passengers to produce the actual GZ curve. Optimization is performed iteratively by comparing the calculated righting moment (Mst) with the regulatory criterion moment (Mkr), following both BKI and ISO 12217-1:2015 standards, while also accounting for the limiting condition at the downflooding angle. A case study on a V-hull boat (L = 10.5 m; B = 3.2 m; H = 1.4 m) reveals a substantial divergence between the two regulatory frameworks. Under light displacement (LWT = 1 ton), ISO permits up to 138 passengers, whereas BKI limits capacity to only 17. Conversely, at a high LWT of 8 tons, ISO does not allow any passengers, while BKI still permits approximately 29. Validation against Maxsurf software demonstrates excellent agreement (R^2 = 0.9993), confirming the reliability of the developed program. These findings establish that the proposed method is both valid and practical, offering a technical guideline for determining the safe passenger capacity of non-classed open-deck vessels operating in domestic waters.**

Keywords:— Passenger capacity optimization, Intact stability, Downflooding angle, BKI, ISO 12217-1:2015, Non-class vessels.

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I. INTRODUCTION

Maritime transportation plays a vital role in mobility and economic development, particularly in coastal and archipelagic regions. Within this domain, non-class boats are widely utilized due to their relatively low cost and accessibility. However, these boats often operate outside established classification systems and regulatory supervision. Unlike larger ships that undergo rigorous inspections and certification, non-class boats are typically built with simple or open deck configurations and receive minimal oversight. As a result, their safety standards—especially with respect to passenger capacity estimation and stability performance—are frequently inadequate [1].

Stability-related accidents, including capsizing and sinking, remain a persistent issue and highlight the vulnerability of non-class boats. In Indonesia, where traditional boats serve as essential transport for remote islands and coastal populations, the problem is particularly severe. Reports from the Transportation Agencies of South Sumatra and South Sulawesi recorded 22 accidents in the Musi River and Lake Matano between 2021 and 2024, largely attributed to stability deficiencies compounded by adverse weather, resulting in 70 casualties [2], [3]. A major incident occurred in June 2018, when KM Sinar Bangun sank in Lake Toba; overloading combined with poor weather conditions caused more than 160 fatalities [4].Similarly, in August 2024, a wooden boats on Lake Matano suffered hull failure that led to capsizing, once again underscoring the critical role of stability in accident causation, although 12 passengers survived [5].

Although general maritime safety regulations exist, their enforcement and practical application for non-class boats remain limited [6]. Small-scale operators often lack straightforward guidelines or operational tools to calculate safe passenger capacity based on stability requirements. Consequently, reliance on rough estimates or informal practices persists, which significantly increases the risk of stability loss, particularly under challenging environmental conditions [7].

To bridge this gap, the present study introduces the research entitled "Analytical Method for Optimizing the Number of Boat Passengers Based on Stability Criteria." In addition to presenting a theoretical foundation, this study aims to establish an innovative, user-friendly analytical approach for determining optimal passenger capacity grounded in fundamental stability principles. The method is intended to provide a practical reference, empowering traditional boat operators to evaluate and mitigate overloading risks independently. Ultimately, this research aspires to strengthen maritime safety, reduce accident-related fatalities, and support sustainable and responsible inland water transportation.

II. METHOD

A. Stability Concept

The static stability of a boats is defined as its inherent ability to return to an upright position after being subjected to an initial heel caused by steady external forces such as cargo shift or wind pressure. This property is fundamental to navigational safety, as it prevents

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capsizing when the boat is stationary or moving slowly in relatively calm waters [7]. The concept of static stability involves the interaction of three key geometric points of the boat, illustrated in Figure 1.

In the left panel of Figure 1, the boat is shown upright, without heel. Several principal elements that govern stability can be identified. The first is the center of gravity (G), which is the point through which the total weight of the boat acts. Its location varies dynamically depending on loading conditions and internal weight distribution. A lower center of gravity improves stability, whereas an excessively high G greatly reduces stability and increases the risk of capsizing. The coordinates of G are determined using Equations (1)–(3) [8]:

$$G_X = \frac{W_{boat} \cdot x_{boat} + W_{load} \cdot x_{load}}{W_{boat} + W_{load}} \quad (1)$$

$$G_Y = \frac{W_{boat} \cdot y_{boat} + W_{load} \cdot y_{load}}{W_{boat} + W_{load}} \quad (2)$$

$$G_Z = \frac{W_{boat} \cdot z_{boat} + W_{load} \cdot z_{load}}{W_{boat} + W_{load}} \quad (3)$$

These equations yield the combined center of gravity of the boat, representing the weighted mean position of all components. Here, W denotes the weight of each element, while x,y,z are the corresponding coordinates of its centroid. The resulting coordinates are expressed as G_X (longitudinal), G_Y (transverse, ideally zero for an upright ship), and G_Z (vertical, measured above the keel). In transverse stability analysis, G_Z is especially critical: a low value enhances stability, while a high value weakens it [9].

The second point is the center of buoyancy (B), defined as the centroid of the displaced water volume. In equilibrium, B lies on the centerline; however, when the boat heels, the submerged geometry changes and B shifts laterally toward the immersed side. This lateral shift generates the restoring moment. Its coordinates, denoted as B_X,B_Y, and B_Z, are obtained through integration of the submerged volume [10]. Here, B_Z is equivalent to KB, the distance from the keel to the buoyancy center. The variables x,y,z represent the coordinates of each elemental volume dV, and V is the total displacement [11].

The third reference point is the metacenter (M), an imaginary yet crucial concept. As the boat heels, the vertical line through the shifted buoyancy point $B1$ intersects the centerline at M. The distance between M and G is the transverse metacentric height (GM), a primary indicator of initial stability at small heel angles. A positive GM (M above G) indicates stable equilibrium, with a restoring moment returning the boat upright. Larger positive GM values produce quicker righting responses but may result in uncomfortable rolling motions. A negative GM (G above M) indicates instability, as no restoring moment exists and the heel progresses to capsizing [12].

When the boat heels, as shown in the right panel of Figure 1, the waterline shifts from WL to WL1. While G remains fixed (assuming no weight shift), the buoyancy point moves to a new position $B1$. The buoyant force acts upward through $B1$, while the weight acts downward through G. Since these forces no longer coincide, a righting lever is generated. The displacement volume at heel ($Vheel$) must equal the upright displacement (V), which is represented by the wedge of buoyancy (WoB): one wedge of emergence and one of immersion [13].

$$V_{heel} = V_{upright} \quad (4)$$

For ships with vertical hull walls, the geometric properties of the WoB can be calculated using Equations (8)–(9) [14]:

$$dv_k = \frac{y_k}{2} . y_k . \tan(\emptyset)\, dx \quad (5)$$

$$dv_k = \tan(\emptyset) \int \frac{y_k}{2} . y_k . dx \quad (6)$$

Here, Vk is the emerged wedge volume, yk is the transverse waterplane distance, $\tan(\phi)$ represents the wedge height projection, and dx is the elemental length. Since $ykdx$ corresponds to a waterplane area element, it also serves as a static moment when multiplied by its centroidal distance [14]:

$$v_k = M_k . \tan(\emptyset) \quad (7)$$

$$M_k . \tan(\emptyset) = M_m . \tan(\emptyset) \quad (8)$$

where Mk and Mm represent the static moments of the emerged and immersed wedges, respectively. This leads to the formulation for buoyancy shift from B to $B1$ [14]:

$$\Delta B_x = \frac{I_{yF}}{V} . \tan(\emptyset) \quad (9)$$

$$\Delta B_y = \frac{I_{xx}}{V} . \tan(\emptyset) \quad (10)$$

$$\Delta B_z = \frac{I_{xx}}{2V} . tan^2(\emptyset) \quad (18)$$

The combined interaction of G, B', and M defines the righting arm (GZ), the horizontal distance between the verticals through G and B'. A larger GZ indicates a stronger restoring moment. This mechanism is shown in Figure 1 [15].

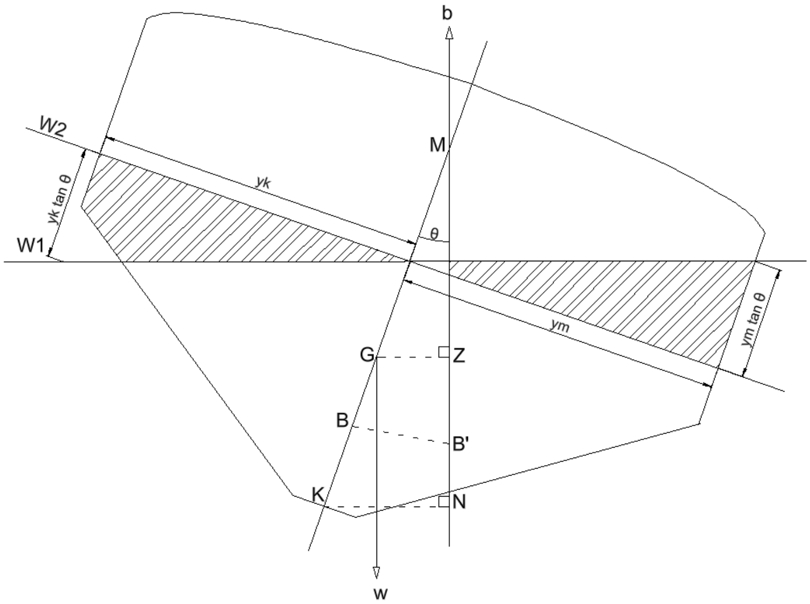

Figure. 1 Components of Statical Stability.

Furthermore, the KN curve (cross curves of stability) is introduced. KN is the perpendicular distance from the keel (K) to the buoyant line through B' at each heel angle. KN depends solely on hull geometry and is independent of G. For small heel angles, GM provides sufficient accuracy, but for large angles, KN curves are required to capture stability behavior [16] The KN curve is derived under the assumption KG=0, making KN equivalent to GZ in the idealized case. Practically, the actual GZ is obtained by correcting KN using the true KG value [17]

$$GZ = KN - KG. \sin(\emptyset) \quad (11)$$

This equation accounts for the vertical position of G above the keel. A higher KG reduces the righting arm and thus weakens transverse stability. Accordingly, KN-based formulations provide reliable predictions of stability over the entire range of heel angles, from upright to capsize [18]

B. Stability for Open Deck Boats

While the fundamental principles of static stability apply universally, open-deck boat—such as fishing boats, barges, and workboats—require additional consideration. Their primary limitation stems from downflooding, the condition in which water enters non-watertight openings once the boat heels beyond a certain angle [19]

For boats with fully watertight integrity, stability is generally limited by the angle of vanishing stability, the point at which the righting arm (GZ) becomes zero. In contrast, for open-deck boats the critical limit is often the angle of downflooding. At this angle, openings such as hatches, vents, or deck fittings submerge, allowing water ingress that increases weight, raises the center of gravity (G), and rapidly diminishes or eliminates the righting moment, thereby creating a significant risk of capsize [20]

As a result, the GZ curve of an open-deck boat terminates at the downflooding angle. Even though the theoretical righting moment may remain positive beyond this point, the presence of water ingress renders such conditions unsafe and operationally irrelevant. For this reason, stability criteria—such as maximum GZ and the area under the curve—must be evaluated only up to the downflooding angle or the angle of maximum GZ, whichever occurs first [21]

Figure 2 illustrates this difference: the stability curve of an open-deck boats rises to a maximum before ending abruptly at the angle of flooding, whereas the curve of a watertight boat (dotted line) continues to exhibit positive stability at much larger heel angles, often up to 60–90° or more, before ultimate capsize. The exact limiting angle for an open-deck boat depends on hull geometry, loading condition, and distribution of weights [22].

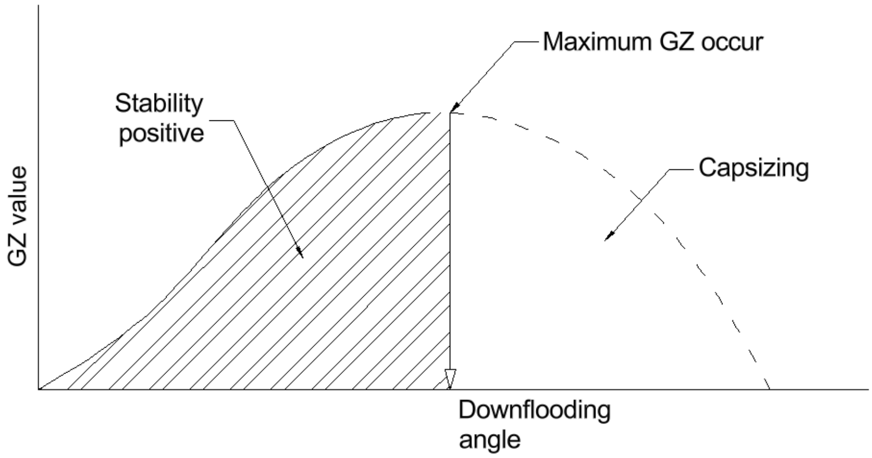

Figure. 2 Stability Curve for Open Deck Boats.

Accordingly, the stability assessment of open-deck boats must explicitly account for the downflooding angle as a governing parameter. From a design standpoint, naval architects must ensure that potential downflooding points retain adequate freeboard or are equipped with effective watertight closures. From an operational perspective, careful management of loading and ballast is essential to minimize the likelihood of reaching the downflooding angle under adverse sea conditions.

C. Validation of Stability Calculations in the Optimization Process

The design of a safe and efficient open-deck boat requires not only accurate stability calculations but also thorough validation against the governing criteria. Within the context of passenger distribution optimization, this validation is critical to confirm that proposed seating arrangements comply with recognized stability standards. The optimization framework seeks the most favorable passenger configuration by incorporating variables such as passenger number, average body mass, and seating distribution [23]

For each optimized layout, the boat's center of gravity (G) must be recalculated and combined with the Cross Curves of Stability (KN) to generate the corresponding righting arm (GZ) curve. These GZ curves are then assessed against established stability benchmarks for open-deck boats. Internationally, ISO 12217-1:2015, Small Craft – Stability and Buoyancy Assessment and Categorization – Part 1: Non-sailing Boats of Hull Length 6 m to <24 m, provides comprehensive stability criteria, including environmental categories (A–D). For open-deck boat, the standard places particular emphasis on preventing downflooding, requiring minimum freeboard to non-watertight openings and truncating the GZ curve at the downflooding angle. Figure 1 illustrates the stability principles in upright and inclined conditions [24].

In addition to ISO requirements, national regulations must also be considered. In Indonesia, the Bureau of Classification Indonesia (BKI) prescribes stability rules for vessels up to 24 m, with special provisions for boat under 15 m. Similar to ISO, BKI sets minimum thresholds for stability indices, such as the area under the GZ curve (up to the downflooding or limiting angle) and minimum metacentric height (GM), tailored to small open-deck vessels [25].

Validation is generally expressed through mathematical formulations, requiring that calculated stability parameters exceed prescribed limits. For example, ISO 12217-1:2015 defines quantitative stability criteria based on heel angle and maximum righting arm, as shown in Equation (12):

$$\theta = 11.5 + \frac{(24 - L_H)^2}{520} \quad (12)$$

where LH is the hull length. The corresponding GZ stability requirements are:

- If θGZ max ≥ 30°; GZ ≥ 0.2 , or
- If θGZ max < 30°; GZ ≥ 6/θGZ max

Additionally, BKI rules define stability requirements involving specific moments or operational parameters, as expressed in Equation (13):

$$M = 0.25D\frac{v^2}{L}(0.7H - 0.5T) + n(0.2B + 0.1) \quad (13)$$

Here, M represents the righting moment, v the vessel speed, L the length, H the height, T the load, n the number of passengers, and B the beam. The parameter D is explicitly defined in the standard to reflect the vessel's design and operational characteristics.

The calculated results, including GZ curves and related indices, are then compared against the prescribed thresholds in ISO and BKI. This validation ensures that the optimized passenger arrangement not only meets the required stability performance but also complies with regulatory standards. By aligning the computed stability parameters with ISO 12217-1:2015 and BKI rules, designers can rigorously demonstrate that passenger placement does not compromise vessel safety.

III. RESULTS AND DISCUSSION

A. Optimization Model for Determination of Boat Passengers

Determining the optimal passenger capacity and distribution on open-deck vessels is a central challenge in naval architecture, as it directly affects both safety and compliance with stability regulations. To address this issue, an optimization model was developed with the objective of maximizing vessel stability performance while ensuring conformity with established regulatory criteria. The model is designed to identify the most effective passenger number and seating arrangement that maintain stability requirements.

The objective function is derived from Equation (21), which, after substitution with Equations (1–3), results in Equation (14):

$$GZ = KN - \frac{W_{boat} \cdot y_{boat} + W_{load} \cdot y_{load}}{W_{boat} + W_{load}} . \sin(\emptyset) \tag{14}$$

Here, the load is expressed as the total passenger mass, defined as the product of average passenger weight (m) and passenger number (n), yielding Equation (15). Since KN is obtained from Equation (11), it can be substituted into Equation (15), producing the optimization formulations (16–18):

$$GZ = KN - \frac{W_{boat} \cdot z_{boat} + m.n.z_{load}}{W_{boat} + m.n} . \sin(\emptyset) \tag{15}$$

$$GZ = \left((Y_{B1}\cos(\emptyset) + Z_{B1}\sin(\emptyset)) - \frac{(W_{boat} \cdot z_{boat} + m.n.z_{load})}{(W_{boat} + m.n)} . \sin(\emptyset) \right) \tag{16}$$

$$M_{st} = \Delta.g.\left((Y_{B1}\cos(\emptyset) + Z_{B1}\sin(\emptyset)) - \frac{(W_{boat} \cdot z_{boat} + m.n.z_{load})}{(W_{boat} + m.n)} . \sin(\emptyset) \right) \tag{17}$$

$$M_{st} = (W_{boat} + m.n).g.\left((Y_{B1}\cos(\emptyset) + Z_{B1}\sin(\emptyset)) - \frac{(W_{boat} \cdot z_{boat} + m.n.z_{load})}{(W_{boat} + m.n)} . \sin(\emptyset) \right) \tag{18}$$

The optimization objective is then formulated as:

$$Objective\ Function = Minimum\ (M_{st} - M_{kr}) \tag{19}$$

Two sets of rules are applied for the criterion moment Mkr. Under BKI regulations, Mkr follows Equation (13). Under ISO regulations, it refers to Equation (12) and its derivatives, yielding Equations (20–21):

- If θGZ max ≥ 30°

$$M_{st} = (W_{boat} + m.n).g.(GZ \geq 0.2) \tag{20}$$

- If θGZ max < 30°

$$M_{st} = (W_{boat} + m.n).g.(GZ \geq 6/\emptyset) \tag{21}$$

Thus, the optimization model determines the maximum permissible passenger number (n) by comparing the actual restoring moment (Mst) with the criterion moment (Mkr) across different heel angles (φ), while ensuring that the righting arm curve (GZ) satisfies the minimum thresholds.

In this formulation, the main decision variable is passenger number (n), which is iterated until reaching the critical stability condition. Dependent variables such as total displacement (Δ) and the vertical center of gravity (KG) vary with n, thereby influencing the GZ curve. Constants include average passenger mass (m), gravitational acceleration (g), and hydrostatic parameters such as length (L), beam (B), depth (H), and the $KN(\varphi)$ curve.

The optimization process is subject to three principal constraints:

- Restoring moment constraint: the actual restoring moment must satisfy

$$M_{st} \geq M_{kr} \tag{22}$$

- Evaluation angle constraint: stability assessment is limited to the smaller of the downflooding angle φdf or the evaluation angle $\varphi eval$

$$\varphi \leq \min(\varphi_{df}, \varphi_{eval}) \tag{23}$$

where φdf is the downflooding angle and $\varphi eval$ is the regulatory evaluation angle..

- Constraint arm enforcement (GZ): the righting arm must exceed the minimum prescribed value

$$GZ(\varphi) \geq GZ_{kr} \tag{24}$$

where $GZkr$ differs between BKI and ISO criteria (e.g., BKI adopts moment-based values considering turning moment and asymmetric load, while ISO applies GZ-based thresholds at the downflooding angle).

B. Optimization Model Working Logic Scheme

The optimization process for determining passenger capacity on an open-deck vessel, illustrated in the flow scheme of Figure 3, follows a structured and iterative framework to achieve a safe yet efficient solution. The methodology balances two objectives: maximizing the number of passengers while ensuring compliance with strict stability criteria.

The process begins with the Hull Model and Initial Calculation stage, where the vessel's geometric characteristics are digitally defined and the first hydrostatic analyses are performed. This step produces fundamental data, including the KN curve, which forms the basis for stability assessment under various heel and loading conditions. In parallel, Input Parameters are defined, such as the weight and center of gravity of the light ship, along with the average passenger mass and estimated vertical center of gravity. These parameters serve as critical inputs for subsequent stability evaluations.

The core of the methodology lies in the Optimization Calculation module. Here, stability is assessed iteratively by varying the number of passengers, starting from zero and progressing until the design displacement is approached. At each step, the total displacement and the combined center of gravity (ship plus passengers) are recalculated, from which the actual GZ curve is derived. The corresponding stability moment (Mst) is then computed.

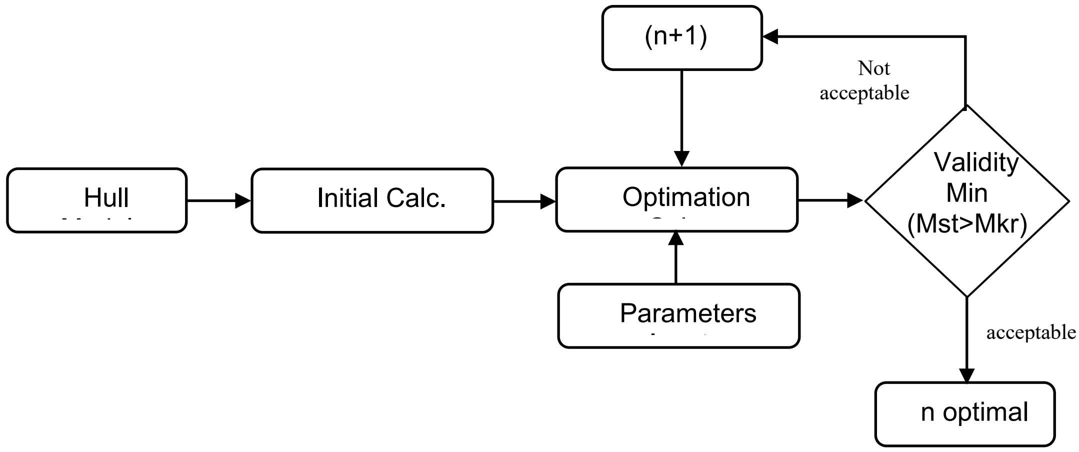

Figure. 3 Optimization Flow System.

Results are validated in the Minimum Validity module by comparing Mst against the regulatory criterion moment (Mkr), as prescribed in standards such as BKI or ISO 12217-1:2015. The condition $Mst \geq Mkr$ indicates compliance, while the optimization seeks to minimize the difference between the two values. If this condition is not satisfied, the iteration proceeds by incrementally increasing the passenger number (n+1) and repeating the calculation loop.Furthermore, the results of the Mst were evaluated on the Validity Min module (Mst > Mkr). This is a crucial decision point in the optimization loop.

The process continues until the maximum passenger number is reached for which Mst still satisfies the regulatory threshold without exceeding acceptable limits. At this point, the solution is considered acceptable, and the resulting passenger count ($noptimal$) is identified as the safe capacity for the vessel. Importantly, the optimization inherently incorporates limiting factors such as the downflooding angle, which truncates the effective GZ curve (Figure 6-13). Through this iterative strategy, the model identifies the "tipping point" at which the vessel can safely carry the maximum number of passengers without compromising stability or violating safety standards.

C. Validation of Stability Calculations in Optimization Programs

Validation represents a critical stage of this study to ensure that the stability curves (GZ curves) generated by the developed program achieve an acceptable level of accuracy. This step was performed by comparing the program's results with those produced by a widely recognized commercial software package used in the maritime industry for hydrostatic and stability analysis. Both calculations were conducted under identical loading conditions, with heel angles ranging from 0° to 26.4°. As illustrated in Figure 4, Validity of Intact Stability Calculation for Optimization Program, the comparison demonstrates a high degree of consistency between the two approaches.

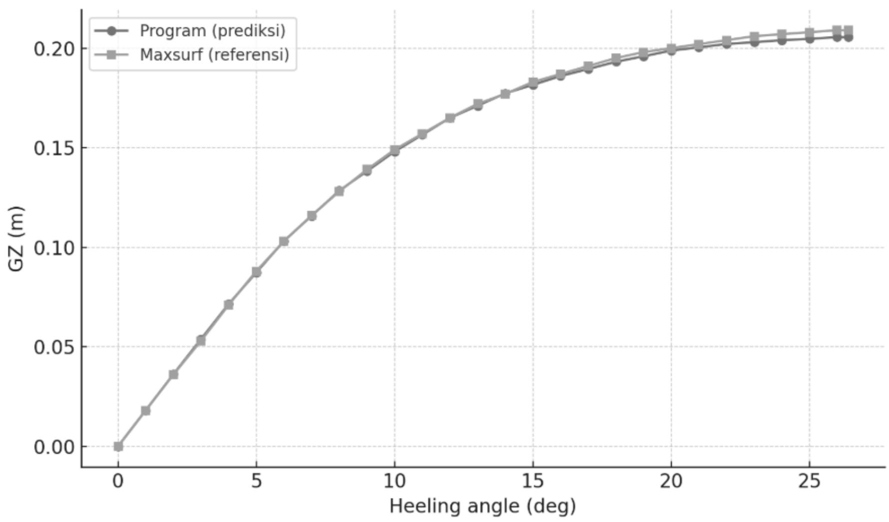

Figure. 4 Validity of Intact Stability Calculation for Optimization Program.

Overall, the GZ curves obtained from both methods exhibit similar trends. The righting arm increases with heel angle until reaching its maximum value, then decreases as the angle of vanishing stability is approached. This consistency demonstrates that the algorithm implemented in the developed program is capable of replicating the physical phenomena in accordance with the principles of ship hydrostatics. Quantitatively, the differences between the two methods are minimal across both low and high heel angles.

Statistical evaluation further supports this conclusion. The Mean Absolute Error (MAE) was found to be 0.00127 m, the Root Mean Square Error (RMSE) 0.00168 m, and the maximum deviation 0.00349 m. These differences are on the order of millimeters, which is negligible in practical stability analysis. In addition, the coefficient of determination ($R^2 = 0.9993$) indicates a correlation exceeding 99%, confirming the high reliability of the program in reproducing GZ curves.

The small discrepancies identified are most likely attributable to technical factors, including variations in interpolation methods for heel angles, numerical rounding, or differences in hydrostatic calculations, as the commercial software employs a panel or mesh-based approach. Nevertheless, these differences remain within accepted tolerances and do not compromise the validity of the results.

The validation outcomes confirm that the developed program performs effectively as an alternative to commercial software for stability assessment. This is particularly valuable in research and design contexts, as it provides flexibility for algorithm modification without exclusive dependence on third-party tools. With demonstrated accuracy, the program can be confidently applied to stability analyses across different loading conditions and integrated into optimization frameworks for vessel design.

In conclusion, the validation against commercial software establishes that the developed program is consistent with the fundamental principles of ship hydrostatics and can be reliably utilized for design evaluation and stability assessment.

D. Evaluation of Passenger Optimization with Ship Weight Difference

1. Boat Model for Optimization

Evaluating passenger capacity optimization by considering variations in ship weight (Light Weight Tonnage, LWT) is a fundamental aspect that cannot be overlooked in the design and operation of small passenger vessels. The light weight of a vessel forms the basis for hydrostatic calculations, as it strongly influences the stability characteristics. Changes in LWT directly affect the vertical center of gravity (KG), the total displacement, and the shape of the righting arm curve (GZ). In general, a higher LWT increases the vessel's own weight, which often reduces the GZ curve and consequently diminishes stability margins. Conversely, a lower LWT provides greater flexibility for accommodating passengers but may reduce the reserve margin of stability against the criterion moment.

For this study, a V-hull boat with principal dimensions of L = 10.5 m, B = 3.2 m, and H = 1.4 m was selected as the case study object. This hull type is widely employed for passenger transport in coastal regions of Indonesia due to its advantages in maneuverability and comfort in open waters. However, the V-hull form requires careful consideration of stability performance, particularly when passenger loading approaches the maximum capacity. To examine these effects, LWT was varied from 1 ton to 8 tons, representing a range of vessel conditions—from lightweight configurations to heavier conditions resulting from additional structures, equipment, or operational modifications commonly found in practice.

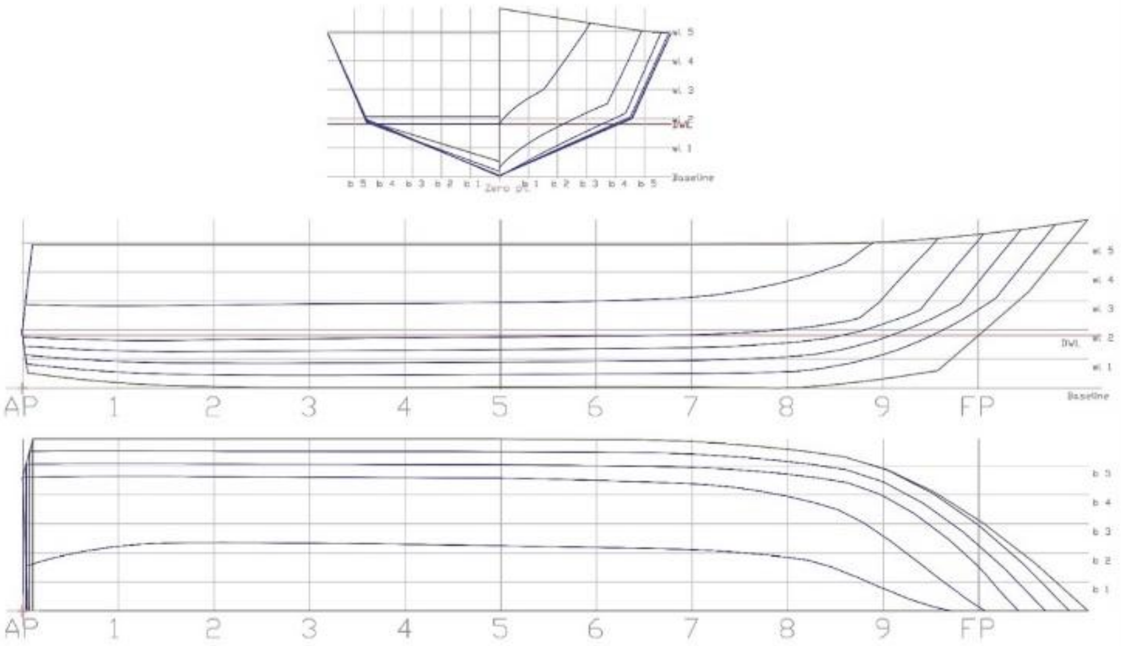

Figure. 5 Linesplan of Boat Model.

Figure 5 presents the lines plan of the selected V-hull, showing the body plan (top), profile view (middle), and plan view (bottom). The hull form is characterized by a relatively fine entry and a moderate deadrise angle, which provide good seakeeping qualities while maintaining structural simplicity. This figure serves as the geometric reference used for hydrostatic and stability calculations in the optimization study.

2. GZ Curve Identification

Figures 6 through 13 present the GZ curves of the vessel across a range of loading conditions, with Light Weight Tonnage (LWT) varied from 1 ton to 8 tons. For readability, each figure displays a selected set of GZ curves, where each curve represents the ship's stability profile for a given passenger number (n). The solid point on each curve marks the maximum GZ value, while the curve terminates at the corresponding downflooding angle, beyond which water ingress occurs and the condition is deemed unsafe.

At low LWT conditions (1–2 tons), the GZ curves exhibit relatively high maximum values with broad stability margins. The maximum GZ is reached at moderate heel angles, indicating strong initial stability. The downflooding angle is comparatively wide, which suggests that the vessel can tolerate larger heeling before the onset of flooding. This explains why ISO criteria tend to allow significantly higher passenger numbers at low LWT, as the righting arms remain well above the regulatory minimum.

In the intermediate range (3–6 tons), the shape of the curves begins to change. The peak GZ values decrease gradually as the ship's weight increases, and the angle at which maximum stability occurs shifts toward smaller values. This reflects the influence of a rising vertical center of gravity (KG) as additional passengers are included, reducing the effective lever arm. The downflooding angle also decreases slightly, limiting the effective operational margin. In this range, ISO criteria show a marked reduction in allowable passenger numbers, while BKI calculations tend to permit more capacity, as displacement increases the calculated recovery moment (MGZ).

At high LWT conditions (7–8 tons), the reduction in stability becomes more pronounced. The maximum GZ values are significantly lower, and the downflooding angle occurs earlier, truncating the stability curve. For LWT = 8 tons, some curves terminate at very small positive margins, and in several cases the GZ curve falls below the ISO criterion, indicating that the vessel would no longer satisfy ISO stability requirements. By contrast, under BKI evaluation, the MGZ values remain positive due to the contribution of higher displacement, resulting in a more conservative yet constant allowable capacity.

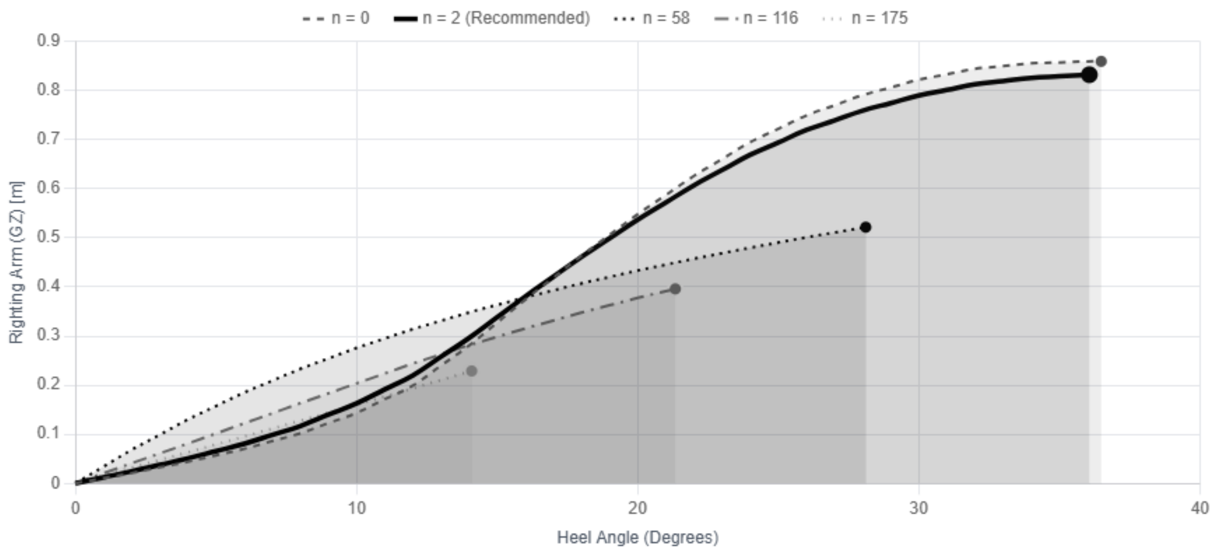

Figure. 6. GZ Curve Properties at Boat Load 1 ton.

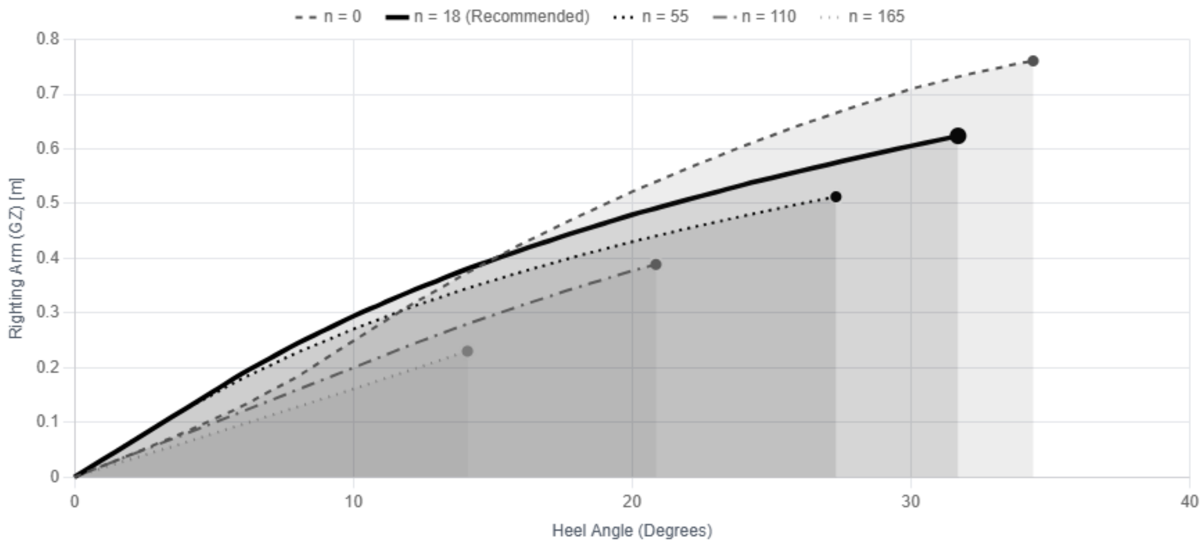

Figure. 7. GZ Curve Properties at Boat Load 2 tons.

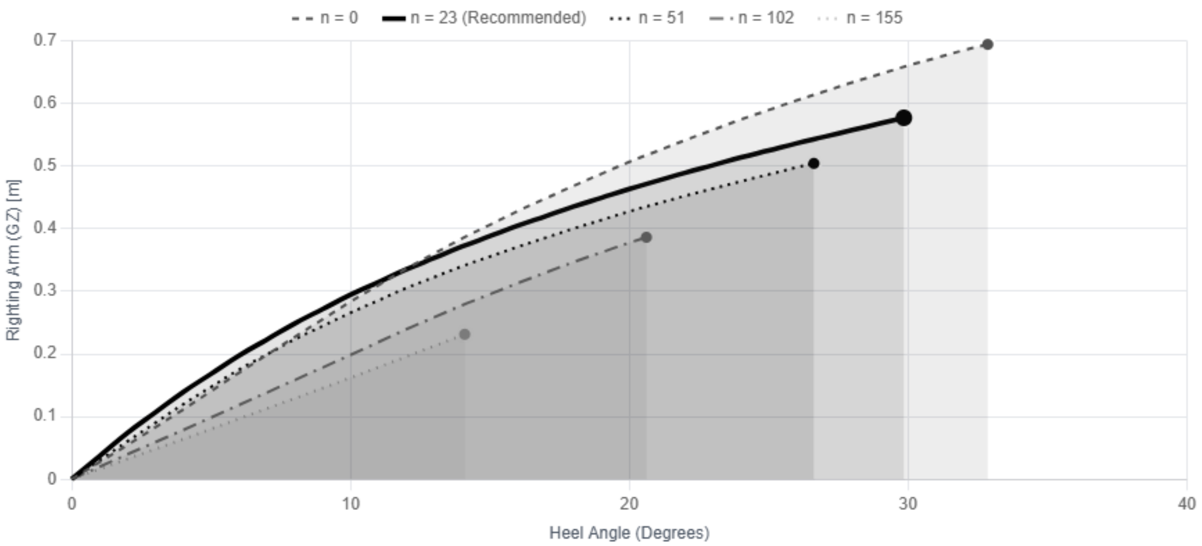

Figure. 8 GZ Curve Properties at Boat Load 3 tons.

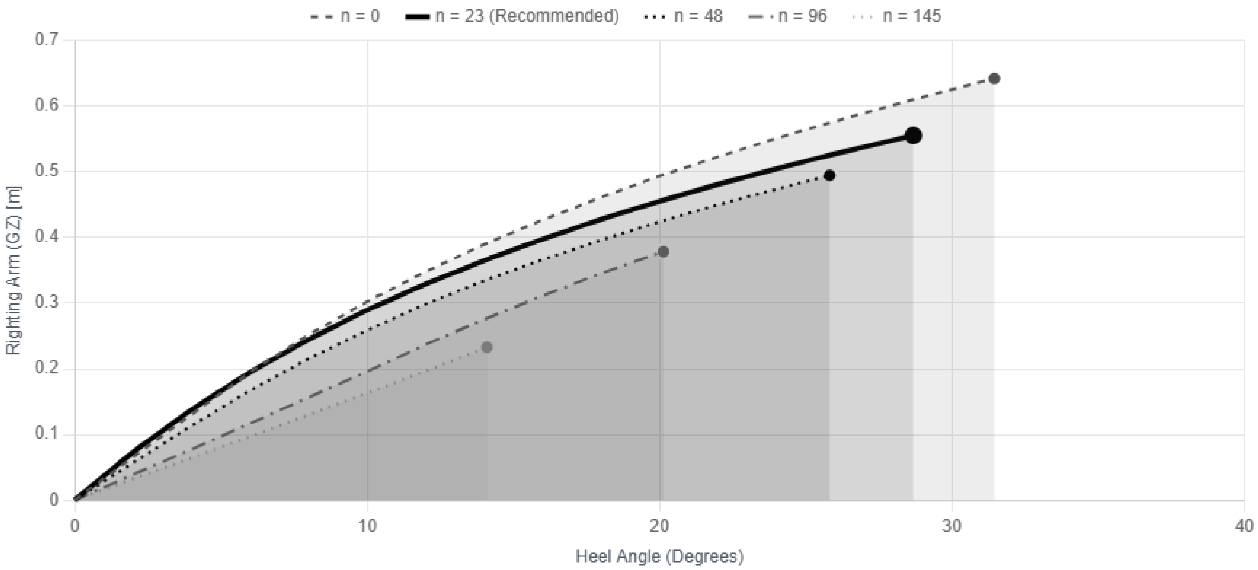

Figure. 9 GZ Curve Properties at Boat Load 4 tons.

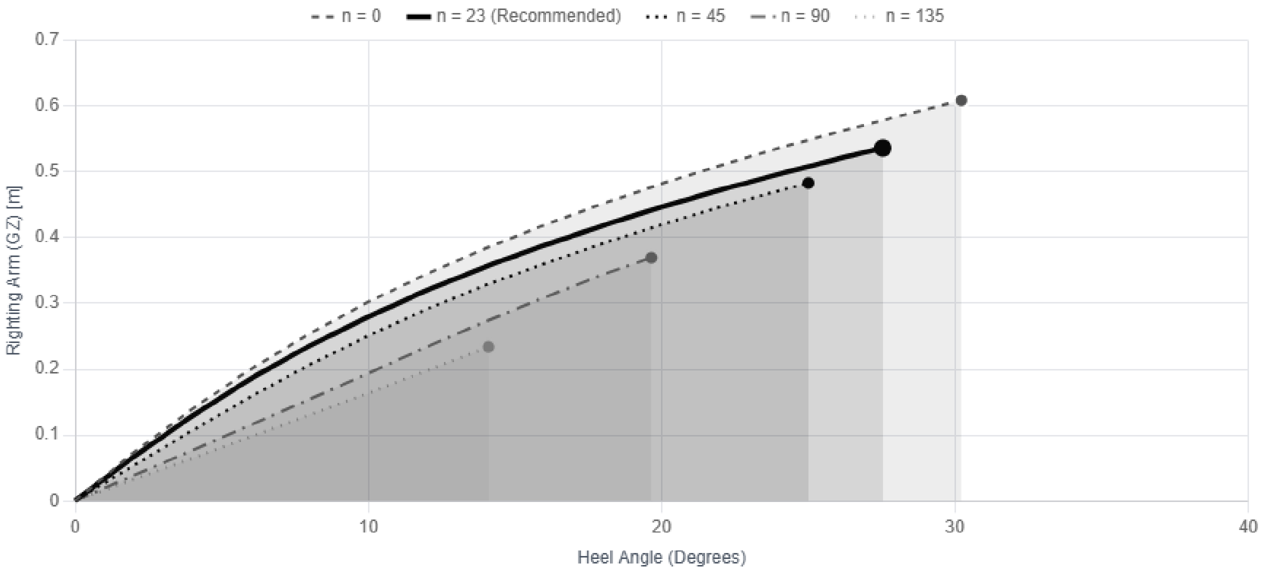

Figure. 10 GZ Curve Properties at Boat Load 5 tons.

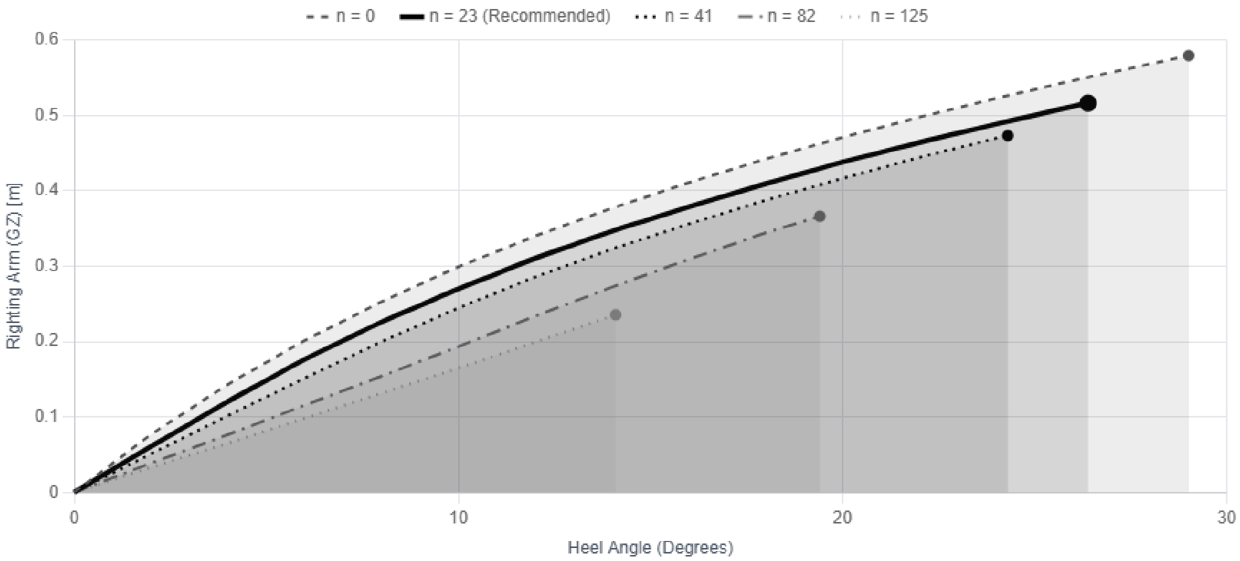

Figure. 11 GZ Curve Properties at Boat Load 6 tons.

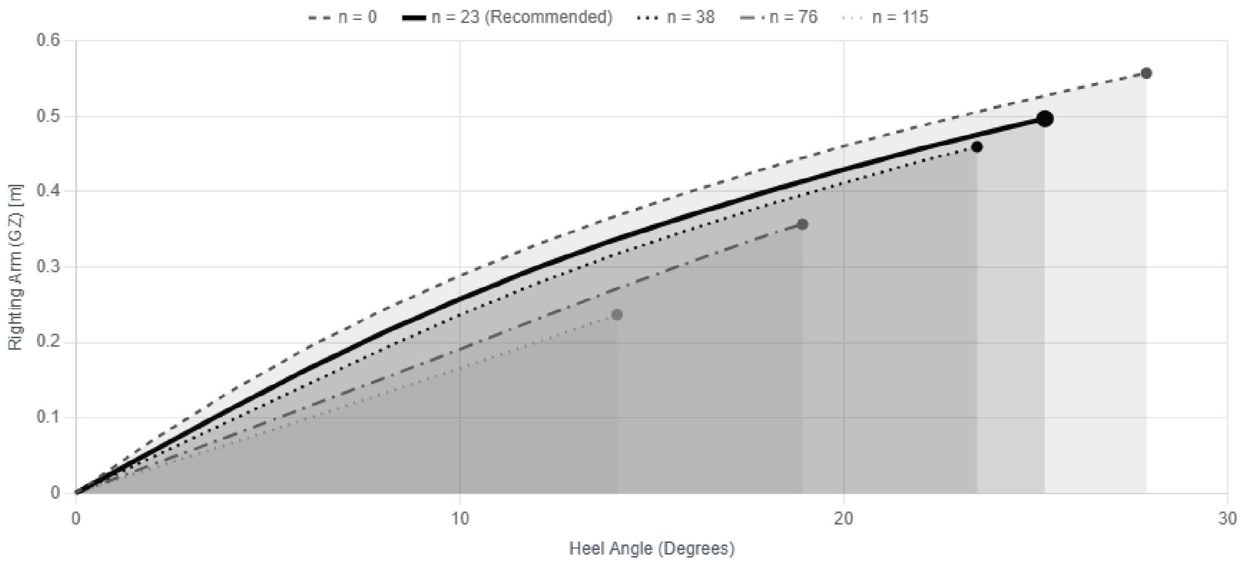

Figure. 12 GZ Curve Properties at Boat Load 7 tons.

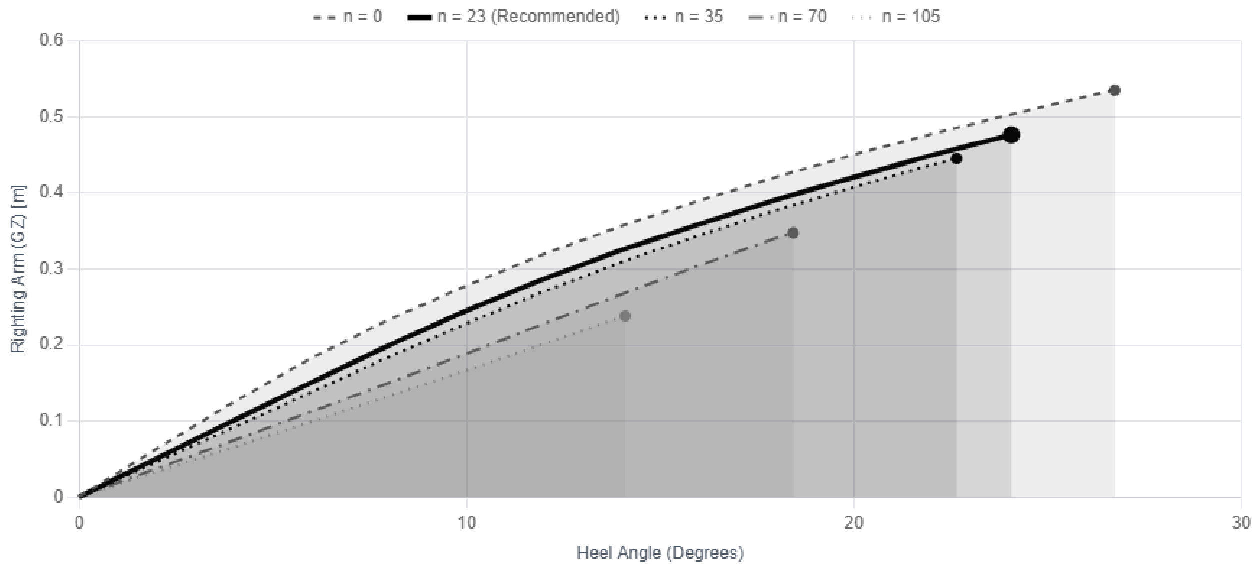

Figure. 13 GZ Curve Properties at Boat Load 8 tons.

Overall, the GZ curve analysis highlights the opposing interpretations of the two standards. BKI reflects an upward trend in stability with increasing displacement, while ISO emphasizes the loss of stability associated with higher vertical weight positions. The practical implication is that ISO captures the sensitivity of small passenger vessels to passenger distribution and vertical loading, whereas BKI maintains stricter limits through displacement-driven calculations. The shaded compromise zone between both criteria therefore provides the most balanced reference, ensuring that stability margins are not overestimated while also preventing unnecessary underutilization of vessel capacity.

3. Optimization Results

Table 1 summarizes the optimization results of the maximum number of passengers across the 1–8 ton LWT variations based on two stability criteria, namely BKI and ISO. The table provides a clear overview of how changes in the vessel's light weight influence safe passenger capacity. Several key findings can be highlighted:

- Low LWT Condition (1–2 tons)

At the lowest displacement (LWT = 1 ton), the results show a striking disparity: ISO permits up to 138 passengers, whereas BKI allows only 17. This difference—nearly sevenfold—illustrates the contrasting philosophies of the two regulations. A similar outcome occurs at LWT = 2 tons, where ISO permits 124 passengers compared to only 19 under BKI. The explanation lies in the mathematical approaches: under low LWT, ISO produces relatively large GZ values since the vessel weight is small, allowing the GZ curve to remain above the criterion line even with many passengers. Conversely, BKI applies a more conservative MGZ formulation that accounts for total displacement, thereby limiting passenger capacity at low weight conditions.

- Medium LWT Condition (3–6 tons)

In the medium range, the trends of the two standards diverge further. ISO results show a steady reduction in passenger capacity, from 111 (3 tons) down to 65 (6 tons), due to the rise in KG that diminishes GZ values. In contrast, BKI permits more passengers as displacement increases, from 22 (3 tons) to 28 (6 tons), consistent with the logic that greater displacement enhances MGZ. Thus, ISO becomes increasingly restrictive with added weight, while BKI grows more permissive. This reflects the fundamentally different interpretations of weight effects: ISO views additional weight primarily as detrimental to stability, whereas BKI interprets it as a factor that strengthens the righting moment.

TABLE 1.
SUMMARY OF OPTIMATION ANALYSIS FOR PASSENGER NUMBER.

LWT	n (BKI)	n (ISO)	MGZ (BKI)	GZ (ISO)	MKR (BKI)	MKR (ISO)	Margin (BKI)	Margin (ISO)
1	17	138	13.960	46.659	13.880	46.572	+0.08	+0.0006
2	19	124	15.990	45.398	15.850	45.314	+0.14	+0.0040
3	22	111	18.590	44.453	18.570	44.370	+0.01	+0.0014
4	24	97	20.600	43.191	20.490	43.111	+0.11	+0.0009
5	26	82	22.550	41.615	22.370	41.537	+0.18	+0.0006
6	28	65	24.290	39.408	24,21	39.335	+0.07	+0.0018
7	29	45	25.400	36.256	25.260	36.188	+0.13	+0.0013
8	29	0	25.890	25.221	25.520	25.174	+0.37	-0.0330

- High LWT Condition (7–8 tons)

At heavy displacement, the contrast becomes sharper. ISO allows only 45 passengers at 7 tons and none at 8 tons, indicating that the actual GZ curve has fallen below the criterion line at maximum LWT, disqualifying the vessel from carrying passengers. On the other hand, BKI results remain steady at 29 passengers for both 7 and 8 tons, reflecting its conservative consistency—maintaining passenger capacity regardless of increasing structural weight.

Margins of Stability.

The margin between the actual stability moment (Mst) and the required criterion moment (Mkr) offers additional insight. Under BKI, the margin is consistently positive (0.07–0.37), signifying a reliable reserve of stability even at maximum passenger load. In contrast, ISO margins are extremely small (0.0006–0.004) and become negative (–0.033) at LWT = 8 tons. A margin near zero suggests the vessel is approaching a critical limit, while a negative value confirms non-compliance with ISO standards, making passenger carriage unsafe.

4. Characteristics of Optimization Charts

The analysis of optimization charts reveals two contrasting approaches to evaluating passenger capacity and vessel stability, as reflected in the BKI and ISO criteria. On the BKI chart, the curve consistently increases as the number of passengers grows. This occurs because the BKI formulation incorporates the ship's total displacement—comprising the lightship weight (LWT) and passenger load—into the enforcement moment calculation. As displacement rises, the recovery moment (Mst) also increases, creating the impression that additional passengers enhance stability, provided that the actual moment remains above the criterion line (Mkr). In this context, the BKI framework suggests that ships appear more stable with increasing passenger numbers, reinforcing a mathematically upward trend.

In contrast, the ISO chart exhibits the opposite behavior, showing a decreasing trend as the number of passengers increases. ISO calculations focus on the enforcement arm (GZ), which is highly sensitive to the ship's vertical center of gravity (KG). When more passengers are added, the KG rises due to their distribution above deck. This elevation reduces the GZ arm length, leading to weaker stability despite the increase in displacement. Consequently, ISO emphasizes the physical vulnerability of ships under heavier loads, demonstrating that stability declines as passenger numbers grow.

This difference in curve patterns highlights the distinct philosophical foundations of each standard. BKI emphasizes the effect of increasing mass and its contribution to recovery moments, leading to stability curves that trend upward. ISO, however, highlights the destabilizing influence of a rising vertical center of gravity, producing downward-sloping curves that better reflect real-world phenomena.

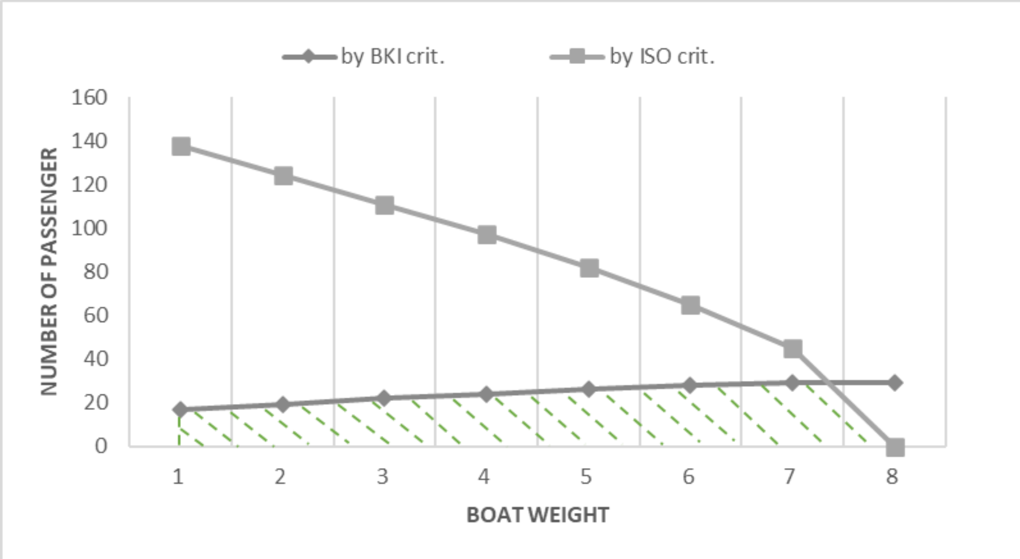

Figure. 15 Safety Number of Passenger Based on Optimization Proccess.

Figure 15 further illustrates this contrast by comparing the optimal passenger capacity across variations in LWT under both criteria. The BKI chart shows an upward trend, suggesting that heavier vessels can generate greater enforcement moments and thus accommodate more passengers. Meanwhile, the ISO chart reveals a downward trend, indicating diminishing stability as the ship's KG increases. The shaded area between the two curves represents a compromise, balancing BKI's conservative safety margin with ISO's sensitivity to passenger distribution and vertical loading effects.

This compromise is especially important in practice, as relying solely on one standard may lead to either overestimation or underutilization of capacity. For instance, at an LWT of 4 tons, ISO permits 97 passengers, while BKI allows only 24—a nearly fourfold difference. Such extremes highlight the risks of depending exclusively on one regulation. ISO may allow unsafe overloading at low LWT, while BKI may impose unnecessarily strict limits, reducing operational efficiency. Thus, the shaded compromise zone in Figure 15 serves as a realistic and balanced reference, ensuring both passenger safety and operational viability.

IV. CONCLUSION

This research succeeded in developing a method of optimizing the number of boat passengers with a validated survival intact stability approach to commercial software with a very high level of accuracy. This method is not only able to accurately represent the hydrostatic behavior of the ship, but also provides a systematic analytical way to determine the maximum passenger capacity based on applicable regulatory criteria.

The results of the analysis show that passenger capacity is greatly influenced by the weight of the empty ship (light tonnage). In low LWT conditions, ISO 12217-1 regulations tend to be permissive by producing a much larger passenger capacity than BKI. However, when the LWT increases, the ISO becomes so strict that it can even eliminate passenger capacity, while BKI still provides relatively constant and conservative results. This illustrates the difference in the stability evaluation philosophy between the two rules, where BKI emphasizes more on the moment of enforcement due to total displacement, while ISO is more sensitive to the increase in the weight point due to additional passengers.

Thus, the optimization method developed is not only valid and applicable, but can also be a practical technical guide for designers and operators of non-class ships. Its implementation is expected to help prevent cases of overloading, improve shipping safety standards, and provide a strong scientific basis in determining the passenger capacity of river and lake ships in Indonesia.

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