The efficiency of the Brazilian Navy's Riverine Captaincies from a Cost Perspective, based on Data Envelopment Analysis

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Abstract

This study measured and analyzed the efficiency of the Brazilian Navy's River Captaincies in carrying out their waterway traffic safety activities between 2021 and 2023. This is a descriptive, quantitative study employing a data envelopment analysis slacks-based model and input oriented. In order to achieve this, cost data and the net value of fixed assets related to the operational activity of waterway traffic safety were employed as inputs, in addition to the costs associated with the maintenance and operation of the units' infrastructure. The number of naval inspections and surveys conducted, and the extent of the area under the jurisdiction of each organization were considered as outputs. The findings revealed that the River Captaincies exhibited an average efficiency index of 0.8890, over the study period. Three units demonstrated consistent efficiency across all three years and were identified as benchmarks for the others. The discrepancies in inputs that led to the observed inefficiencies in the units and the optimal values for each cost element, which would enable the units to reach the efficiency frontier while maintaining the level of outputs, were also demonstrated. The results achieved are useful as parameters for the optimal distribution of resources, as well as for the potential establishment of annual cost reduction targets for these organizations. Consequently, the

Submetido em 24/09/2024 e aceito em 17/12/2024 por Marcelo Álvaro da Silva Macedo após o processo de Double Blind Review

assessment of public organization efficiency from a cost perspective represents a crucial indicator for the administrators of these units, providing guidance on the management of the limited resources under their purview. Academically, this research contributes to the existing literature on the efficiency of military organizations, particularly regarding the development of waterway traffic safety activities. From a practical standpoint, this research can inform improvements in cost management within the Brazilian Navy, which is a strategic naval objective included in the Force's Strategic Plan.
Keywords: Efficiency; Cost Systems; Data Envelopment Analysis; Captaincies; Brazilian Navy.

1 Introduction

In a globalized environment, production and consumption centers are increasingly distant from each other, leading to a complex network of commercial flows between various countries. In this context, maritime and river waterways emerge as an important alternative for trade and the economic sustainability of several nations worldwide.

Regarding river waterways, Brazil stands out for hosting approximately 21,000 km of navigable rivers under its jurisdiction, as well as several lakes, according to data from the National Agency for Waterway Transportation - ANTAQ (2024). These significant resources are utilized for a wide range of activities, including tourism, fishing, mineral exploration, nautical sports, military use, and waterway transportation (Moraes, 2020; Pimentel & Batista, 2021).

While the intense use of the country’s rivers and lakes has the potential to drive economic and social development, it also brings greater challenges and threats to navigation safety, such as accidents involving all types of vessels, as well as illegal fishing and exploration of Brazil's jurisdictional river resources. Therefore, state action to ensure waterway traffic safety (WTS) on river and lake waterways is of considerable importance. In this context, the Brazilian Navy (MB) has, as a subsidiary responsibility to its constitutional functions, the exercise of activities assigned to the Brazilian Maritime Authority (AMB), according to Law No. 9,537, dated December 11, 1997 (Waterway Traffic Safety Law - LESTA) (Brazil, 1997). Among the AMB's duties is the conduct of naval inspections and surveys to protect human lives, ensure navigation safety, and prevent environmental pollution in open seas or internal waterways (Barreto, 2019). In the river and lake environment, these tasks are carried out by the 14 River Captaincies (CF) and their directly subordinate agencies and delegations, which are distributed throughout the national territory.

To fulfill its legal responsibilities on river and lake waterways, the AMB uses public resources from the State budget to acquire assets for WTS activities. Additionally, annual costs are incurred related to the maintenance of these assets, fuel acquisition, maintenance of CF infrastructure, among other needs necessary for these Military Organizations (OM) to perform their primary activities. However, in a scenario marked by austerity and limitations, these resources must be applied more assertively to avoid waste, prioritizing efficiency.

In this sense, the Brazilian Navy developed the Navy Cost System (SCM), through which costs related to the various activities carried out by the Force are recorded, with the aim of conducting accounting analyses and providing information that can support a more efficient allocation of resources. However, although the SCM provides structured reports on the costs of the Naval Force's activities, Santos et al. (2023a) mention that, on their own, these reports are not sufficient to measure the efficiency of the various OMs in performing their duties. Additionally, the services of the Armed Forces are provided exclusively by the State, which leaves these institutions without price mechanism information for evaluating the efficient use of these resources (Hanson, 2016).

Thus, it is necessary to adopt approaches and methodologies, using data analysis tools, that can contribute to measuring the efficiency of public agencies (Alencar & Fonseca, 2016). Among the different models that use data for this purpose, Data Envelopment Analysis (DEA) stands out in the public sector due to its possibilities for measuring efficiency through a mathematical programming model (Ibáñez et al., 2020). This approach emerges as a management support tool, enabling evaluations that include the comparison and classification of efficiency among organizations in the same sector, based on the resources they use (inputs) and the products they generate (outputs) (Ferreira & Gomes, 2020).

However, few studies have been dedicated to measuring the efficiency of the operational activities of the Armed Forces. In the context of WTS, only the study by Santos et al. (2023a) was found, which measured the efficiency of naval inspections and surveys based on the district areas under the responsibility of the Brazilian Navy, encompassing OMs operating in both maritime and riverine/lacustrine areas.

Given the above, the following research problem is presented: how can the efficiency of River Captaincies in executing WTS activities be measured, based on DEA and from the perspective of SCM? Therefore, the general objective of this study is to measure and evaluate the efficiency of River Captaincies in carrying out their waterway traffic safety activities, based on the DEA approach, using data extracted from SCM.

The study proves relevant as measuring and evaluating the efficiency of public organizations from a cost perspective emerges as a significant indicator for the managers of these units to guide the administration of the limited resources under their responsibility. From a practical perspective, this research can contribute to improving the cost management of the Brazilian Navy, which is a strategic naval objective outlined in the Navy Strategic Plan 2040 - PEM 2040 (Brazil, 2020a).

Furthermore, in addition to contributing to the literature on measuring and analyzing efficiency in operational activities of military organizations, this study, by differing from the research by Santos et al. (2023a) in focusing specifically on the efficiency of a group operating exclusively in riverine and lacustrine waterways, also contributes to expanding the literature on measuring and analyzing the efficiency of waterway traffic safety activities conducted by the AMB.

2 Theoretical Foundation

This section aims to present the theoretical foundation underpinning this research, focusing on Efficiency in Public Administration, the Navy's Cost System, and Efficiency Measurement through the application of Data Envelopment Analysis.

2.1 Efficiency in Public Administration

Starting in the 1980s, a global restructuring process in public administration began, aiming to replace bureaucratic models with governance structures better equipped for economic, political, and social engagement. This shift sought to ensure citizens' social rights and address their needs (Oliveira & Paula, 2014).

In this context, the New Public Management (NPM) emerged, emphasizing key principles such as professional management, performance measurement, fostering competition, and the rational and moderate application of public resources, aiming for efficiency (Hood, 1995). In Brazil, the concept of efficiency is presented through different nuances. For instance, when defining the principle of efficiency in Brazilian public administration, Moraes (2016) asserts that managers should base their activities on the common good, prioritizing quality and the appropriate use of public resources to maximize social returns. Camargo and Guimarães

(2013) argue that efficient public management should focus on improving administrative processes, training its agents, and being open to adopting best practices in its field. According to Gomes (2009), efficiency in public management is related to adherence to regulations and cost reduction, aiming to ensure that a public service is delivered in the most competent manner. Similarly, Ferradaes (2019) states that efficiency entails the careful use of public resources, ensuring that the cost of public activities is strictly necessary for their execution, thus avoiding waste.

These definitions suggest that efficiency in public administration encompasses both social and economic dimensions. On the social side, efficiency is demonstrated by an institution's ability to serve a significant portion of society, thereby increasing the organization's utility within its environment (Mattos & Terra, 2015). From the perspective of social impacts, the efficiency of public entities is related to the effectiveness of public actions (Pacheco, 2009). Economically, efficiency includes the concepts of technical and allocative efficiency. Technical efficiency concerns the ability of units to achieve maximum output with the resources available (Rosano-Peña & Gomes, 2018). Allocative efficiency, on the other hand, refers to the ability of organizations to use resources in optimal proportions to fulfill their roles or provide services, following Pareto principles (Silva et al., 2011). Combining both concepts, Shaw (2009) suggests that economic efficiency is tied to maintaining cost levels while increasing output or, conversely, reducing costs while maintaining production capacity. Therefore, it can be inferred that in the social dimension, the efficiency of public management is evaluated based on the impacts of the services made available to society, while technical and allocative efficiency focus on analyzing the efficient use of resources in delivering services to society.

Focusing on efficiency from the economic dimension, specifically regarding the use of public resources to provide services to the community, NPM advocated for the adaptation of concepts, tools, instruments, and management models, established in private organizations, to the public sector (Aljuhmani et al., 2024). Among these tools, cost accounting stands out (Messias et al., 2018). According to Alqudah et al. (2022), implementing a cost management system provides continuous updates on the behavior and structure of public expenses, aiding the process of evaluating service efficiency for the collective. Alonso (2022) clearly highlights the relevance of these systems in relation to performance measurement in public management, asserting that without cost measurement, it is impossible to consider efficiency measures. However, Taj et al. (2012) caution that technical and allocative efficiency concepts are relative, as the ideal cost frontier can only be observed when comparing organizations operating in the same sector and using the same inputs. In this sense, Machado and Holanda (2010) mention that public administrators should use accounting information systems to compare the costs of similar services provided by different units.

In this regard, Santos et al. (2023b) highlight that in Brazil, recognizing the relationship between costs and efficiency has motivated several public sector entities, including the Brazilian Navy, to develop cost information systems. These systems aim to support managers in the administration of state resources, as will be discussed in the next section.

2.2 Brazilian Navy Cost System

In Brazil, although managerial public administration began in the 1980s, cost accounting in the public sector as a mandatory activity is not a recent topic. It was already prescribed by Law No. 4,320 of March 17, 1964 (Cardoso et al., 2011). Despite this legal obligation, the maintenance of cost systems was long neglected by many public agencies, becoming more established only in 2011 with the creation of the Federal Government Cost System (SIC) (Holanda et al., 2010).

Despite the slow adoption by a significant portion of state entities, the Brazilian Navy (MB) stands out as a pioneer institution in cost management (Mauss et al., 2015). According to Pereira et al. (2016), cost management in the Navy began in 1994 with the creation of the System of Military Organizations Providing Services (OMPS), aimed at managing costs in industrial, hospital, and science and technology areas. However, the managerial control provided by the OMPS system was not applied across all units of the institution. To expand the culture of cost management throughout the Navy, the High Naval Administration authorized, in 2017, the implementation of the Navy Cost System (SCM), based on the functionalities of the SIC (Albuquerque & Oliveira, 2017).

The adoption of the SCM allowed the Navy to broaden its cost assessments to encompass all its activities, providing a more detailed view of the distribution of the Force's resources (Santos et al., 2023a). Beyond understanding the costs of its activities, the SCM aims, according to the Navy Cost System Standards - SGM-307 (Brazil, 2020b), to provide information to the Navy's High Administration to promote more efficient resource allocation and support decision-making processes. The system operates as a data warehouse, consolidating and processing data from other federal government systems and Navy corporate systems, thus reducing the administrative workload required to generate information (Mello et al., 2021). Additionally, the SCM adopts the Activity-Based Costing (ABC) method, which assumes that activities consume organizational resources (Filgueiras, 2019). The SCM's structure is based on grouping similar activities into macro-activities, classified into two groups: final activities and support activities, according to their contribution to achieving the Navy's objectives (Filgueiras, 2019; Santos et al., 2023b).

To determine the costs of services related to the core activities of waterway traffic safety (WTS), the Brazilian Navy established the macro activity 04.00 – Ports and Coasts Service (Santos et al., 2023a). This macro-activity includes the cost centers related to the activities of the components of the waterway Traffic Safety System (WTSS) concerning compliance with maritime legislation, pollution prevention, traffic safety, and the training and qualification of merchant marine personnel (Brazil, 2020b). Another important macro-activity of the SCM is 59.00 – Administrative Activities, which, according to SGM-307 (Brazil, 2020b), includes all cost centers for the functioning and maintenance of infrastructure in all Navy units. The system also considers asset movements resulting from organizational activities, such as inventory consumption and asset depreciation, enabling effective resource application identification beyond mere budget execution (Filgueiras, 2019).

The importance of information systems like SCM is evident for managerial purposes, particularly in recording the costs of Navy activities. However, Hokkinen (2021) warns that the generic assessment of public activity costs is not sufficient, on its own, to identify the efficiency of entities. Additionally, some public services, such as STA, are exclusively provided by the state. Hanson (2016) argues that services provided solely by a state entity lack market price information, making it challenging to evaluate the efficiency of these institutions.

Thus, public cost records need to be analyzed from the perspective of the products generated and the availability of services provided to a segment of society, comparing similar units that operate in the same sector, using similar resources. For example, Carmo and Rosano-Peña (2019) analyzed cost efficiency in public georeferencing contracts using the serviced area size as the product. Lu (2011) studied the efficiency of Taiwan's transportation services based on costs, the number of people served, and the area covered by each bus line. Freitas (2020) measured the efficiency of public security at Brazil's borders using operational unit costs for various activities. Souza et al. (2018) used data on fixed assets and operational costs to measure the efficiency of 31 Brazilian hospitals in generating revenue and providing beds between 2006 and 2011.

In the Brazilian Navy, SCM data were used by Mello et al. (2021) to evaluate the efficiency of food supply services on the Navy's ships, based on the number of meals served in 2019. Similarly, Silva and Costa (2023) used SCM information and the average meals served to analyze the efficiency of food services in Navy units. Considering in-house and outsourced units, they found that in-house services were more cost-efficient in 2021. For hospital services, Santos et al. (2023b) used SCM data to analyze the efficiency of ten health-related units in conducting medical exams and consultations. Regarding operational activities, specifically STA, Santos et al. (2023a) analyzed the efficiency of Navy district areas based on the costs and investments made in 2021 for conducting inspections and naval surveys.

Beyond linking costs to generated outputs, further advancements in implementing tools for managing and analyzing cost efficiency in public sector units are needed to optimize the use of existing information systems (Pereira et al., 2018). The application of analytical methods, such as DEA, can enhance the managerial quality of information derived from cost systems.

2.3 Measuring Efficiency Using Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a mathematical tool that evaluates the relative efficiency of Decision-Making Units (DMUs) by considering multiple common input and output factors through a linear programming process (Neuenfeldt et al., 2015). In the process of converting inputs to outputs, the results provide efficiency indicators that range from 0 to 1, or 0% to 100%, where a DMU achieving a unitary value is considered efficient (Pereira & Tavares, 2020).

The purpose of DEA is to identify an efficiency frontier based on the data of the evaluated DMUs, classifying them as efficient or inefficient. Furthermore, the efficiency frontier serves as a benchmark from which guidelines and goals can be established to enable inefficient DMUs to achieve efficiency (Almeida et al., 2006).

For implementing DEA, Lins and Meza (2000) indicate three important steps. Initially, the DMUs to be analyzed must be defined and selected so that they are similar in terms of input usage and output delivery. Next, among the collected variables, the most appropriate ones for measuring the units' efficiency should be chosen. At this stage, Lorenzett et al. (2010) and Lu (2011) highlight that in DEA models, it is desirable for the variables used to meet the isotonicity assumption. This means that an increase in inputs should lead to an increase in desirable outputs or a decrease in undesirable ones. Finally, the linear programming model responsible for quantifying the efficiency score must be specified.

Regarding the models, there is a variety derived from the classical approaches developed by Charnes et al. (1978), known as constant returns to scale (CRS), and by Banker et al. (1984), known as variable returns to scale (VRS). The CRS model assumes that units are operating at optimal capacity, considering linear production growth, where an increase in input usage results in a proportional and constant increase in output, regardless of the DMU's size (Ferreira & Gomes, 2020). The VRS assumption, on the other hand, considers that the production scale of the units is not under the managers' control (Rosano-Peña & Gomes, 2018). Moreover, this model allows an inefficient unit to be compared with other efficient units of similar size or operating at similar scales, making it suitable for analyzing DMUs of different sizes (Lobo et al., 2014).

However, Tayebi et al. (2024) criticize traditional models for analyzing the relationship between inputs and outputs, as they are radial, presuming proportional changes, with remaining slacks not affecting efficiency scores. For this reason, a DMU located on the efficiency frontier, though considered efficient, may still exhibit input or output slacks (Profeta et al., 2021). Consequently, efficiency assessed by radial models is referred to as "weak efficiency" in DEA literature (Cooper et al., 2011).

With the advancement of research and new analysis needs, DEA began to be applied and expanded in a variety of models, such as the non-radial Slack Based DEA model (SBM), proposed by Tone (2001). In this model, given a set of n DMUs, where each consumes quantities $\{x_{i1}, x_{i2},...,x_{im}\}$ of m types of inputs and produces quantities $\{y_{i1}, y_{i2},..., y_{ip}\}$ of p types of outputs, the SBM model uses input slacks (s^-) and output shortfalls (s^+), in the calculation of the efficiency index ($0 \leq \theta \leq 1$) of the evaluated DMU j0, as illustrated in the mathematical programming model of Equation (1):

$$\begin{aligned}
&\min_{\lambda, s^-, s^+} \quad \theta = \frac{1-\frac{1}{m}\sum_{j=1}^{m}\frac{s_j^-}{x_{j0}}}{1+\frac{1}{p}\sum_{j=1}^{p}\frac{s_j^+}{y_{j0}}} \\
&s.t. \\
&\sum_{k=1}^{n} x_{jk}\lambda_k + s_j^- = x_{j0}\ \forall j = 1, m \\
&\sum_{k=1}^{n} y_{jk}\lambda_k - s_j^+ = y_{j0}\ \forall j = 1, p \\
&\lambda_k \geq 0\ \forall k = 1, n \\
&s_j^- \geq 0\ \forall j = 1, m \\
&s_j^+ \geq 0\ \forall j = 1, p
\end{aligned} \tag{1}$$

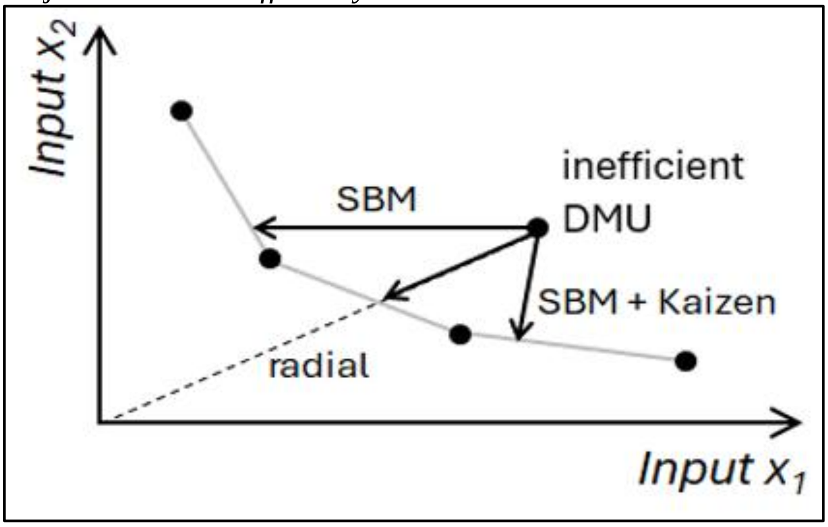
Based on the objective function, as shown in Equation (1), it can be concluded that the evaluated DMU *j0* is efficient if and only if the slack variables s^- (resource surplus) and s^+ (output deficit) are zero. By multiplying the constraints, the numerator, and the denominator of the objective function in Equation (1) by t (t>0), setting the resulting denominator equal to 1, and renaming $t\lambda_k$, ts_j^- and ts_j^+ as w_k, z_j^- and z_j^+, respectively, the linear programming problem in Equation (2) is obtained:

$$\begin{aligned}
&\min_{w, z^-, z^+} \quad \theta = t - \frac{1}{m}\sum_{j=1}^{m}\frac{z_j^-}{x_{j0}} \\
&s.t. \\
&t + \frac{1}{p}\sum_{j=1}^{p}\frac{z_j^+}{y_{j0}} = 1 \\
&\sum_{k=1}^{n} x_{jk}w_k + z_j^- = tx_{j0}\ \forall j = 1, m \\
&\sum_{k=1}^{n} y_{jk}w_k - z_j^+ = ty_{j0}\ \forall j = 1, p \\
&w_k \geq 0\ \forall k = 1, n \\
&z_j^- \geq 0\ \forall j = 1, m \\
&z_j^+ \geq 0\ \forall j = 1, p
\end{aligned} \tag{2}$$

Denoting the optimal solution of problem (2) by θ^*, t^*, w_k^*, z_j^{-*} and z_j^{+*}, the corresponding values of the multipliers and slack variables are, respectively, $\lambda_k^* = w_k^*/t^*$, $s_j^{-*} = z_j^{-*}/t^*$ and $s_j^{+*} = z_j^{+*}/t^*$. The DMU *j0* is efficient if and only if θ^*=1; in this case, the slack variables are zero ($s_j^{-*} = 0\ \forall j = 1, m$ and $s_j^{+*} = 0\ \forall j$=1,p). Otherwise, the DMU is inefficient and must reduce input consumption to $x_{j0} - s_j^{-*} \forall j$=1, m and increase output to $y_{j0} + s_j^{+*}\ \forall j$=1, p, to reach the efficiency frontier. Additionally, the reference set (peer set) or benchmarking of an inefficient DMU consists of the other DMUs analyzed with $\lambda_k^* > 0\ \forall k$=1,$n$.

In the classical DEA oriented models (CRS and VRS), the improvements an inefficient DMU can make to reach the efficiency frontier consist of a proportional reduction in all input quantities (input orientation) or a proportional expansion in all output quantities (output orientation). Thus, geometrically, the improved version of an inefficient DMU is given by its radial projection onto the efficiency frontier, as shown in Figure 1. However, unlike traditional DEA models, in the non-oriented SBM model, the improved version of an inefficient DMU is determined by its non-radial projection onto the efficiency frontier. This means the reductions (expansions) in input (output) quantities are not proportional. Nevertheless, as shown in Figure 1, the SBM model may project an inefficient DMU onto a point on the frontier that is excessively distant, which results in a lower efficiency score. To address this issue, Tone (2016) proposed the Kaizen algorithm, which projects an inefficient DMU onto a closer point on the efficiency frontier, ensuring the improved version of the DMU is achieved with smaller adjustments in input and output quantities.

Figure 1
Projections on the Efficiency Frontier



Source: Adapted from Tone (2016).

In the SBM model in Equation (2), inputs and outputs are controllable, but the model can accommodate inputs or outputs that are uncontrollable by the DMU. For example, in the case of an uncontrollable input ($x_k^{NC} \forall k = 1, n$), Equation (3) should be included as a constraint of the model:

$$\sum_{k=1}^{n} x_k^{NC} \lambda_k = x_0^{NC} \tag{3}$$

Furthermore, the DEA-SBM model, as given by Equation (2), assumes constant returns to scale (CRS). However, the consideration of variable returns to scale (VRS) can be implemented by including Equation (4) as an additional constraint in the model:

$$\sum_{k=1}^{n} w_k = 1 \tag{4}$$

By solving the equations of the DEA-SBM model, the efficiency scores of each DMU are obtained. For the units considered inefficient, the slack in resources or products is provided, as well as the ideal input and output targets determined by the projections of the inefficient DMUs onto the efficiency frontier.

It is important to mention that the DEA-SBM non-oriented model, as defined in Equation (2), can be adapted for input or output orientation, depending on the desired objectives (Tone, 2016). Thus, due to its approach, which takes into account input excesses and output shortages, where non-zero slacks are included in the efficiency evaluation (Tone et al., 2020), and its ability to accommodate non-discretionary and uncontrollable variables (EsmaeIli, 2009), Profeta et al. (2021) consider the DEA-SBM model more robust compared to traditional models, as it offers greater discriminatory power between the efficiency scores of DMUs, in addition to indicating which inputs have excesses or which products have shortages, providing more accurate managerial information for decision-making.

3 Methodology

According to Silveira (2011), this research is characterized as descriptive and quantitative in nature, as it aims to demonstrate the process used to measure the efficiency of the Fluvial Captaincies (CF) in the exercise of STA activities from a cost perspective, through a mathematical model.

To obtain the efficiency measurement model, the annual costs of macroactivities 04.00 (port and coastal services) and 59.00 (administrative activities) were considered as inputs for the CFs. These macroactivities represent the most relevant costs associated with the CF activities, such as fuel, maintenance of equipment, vehicles, and vessels, daily allowances for military personnel, and the maintenance and operation of CF infrastructure. Additionally, the net value of fixed assets (AIL), consisting of equipment, vehicles, and vessels that support the capacity of the CF to carry out their duties, recorded at the end of each year, was also considered. The data source for the inputs was the Tesouro Gerencial system, from the federal government, access to which was granted by the Navy's Finance Directorate. It is noted that the net book value of the fixed assets of the equipment is a non-discretionary input, as its reduction is subject to possible transfers, disposals, or, more commonly, depreciation.

As outputs, the jurisdictional area (AJ) of each CF was considered, obtained from the Norms and Procedures of the Fluvial Captaincies, available on the Directorate of Ports and Coasts (DPC) website, as well as the quantitative data of inspections and naval inspections (IN/VST) conducted annually by the units, obtained from the Brazilian Navy's Inspection and Survey Management System (SISGEVI), through provisional access granted by the DPC. The choice of these outputs is based on studies mentioned in the theoretical framework, such as the one by Santos et al. (2023a), which used the IN/VST variable and mentioned that the territorial scope of the OM’s operations can create considerable differences between them regarding the development of STA activities. It is noted that the AJ variable is not easily controllable by the CF, as it depends on regulatory changes and involves strategic aspects of the Navy’s operations.

It is important to highlight that, during data collection, inconsistencies were observed in one CF, which required its exclusion from the study. Therefore, the target population will consist of 13 CFs. To ensure transparency and accuracy of the information obtained for this study, the names of the CFs evaluated will be kept confidential.

According to Hanson (2016), DEA models require the number of DMUs to be at least three times greater than the number of variables in order to avoid dimensionality issues. Thus, given the number of variables selected and assuming no technological change in CF management between 2021 and 2023, panel analysis was chosen (Pessanha & Mello, 2021). This procedure helps to mitigate any dimensionality issues, as each CF will be treated as a separate DMU in each year, generating 39 observations and allowing for an analysis of CF efficiency over time. Therefore, the data were consolidated by CF, with the total values of each variable recorded at the end of each year.

Considering that the objective of this study is to measure efficiency from the SCM perspective, the proposed DEA model aims to set targets for reducing inputs of the DMUs, so the DEA-SBM input-oriented model will be used, with the specification indicated by Equation (5):

$$
\begin{array}{ll}
\underset{w, S^-}{Min} & \theta = 1 - \frac{1}{m}\sum_{j=1}^{m}\frac{S_j^-}{x_{j0}} \\
s.t. & \\
& \sum_{k=1}^{n} x_{jk}\lambda_k + S_j^- = x_{j0} \; \forall j = 1, m \\
& \sum_{k=1}^{n} y_{jk}\lambda_k \geq y_{j0} \; \forall j = 1, p \\
& \lambda_k \geq 0 \; \forall k = 1, n \\
& S_j^- \geq 0 \; \forall j = 1, m \\
& z_j^+ \geq 0 \; \forall j = 1, p
\end{array} \tag{5}
$$

Finally, considering the nature of the required mathematical calculations, the deaR package (Coll-Serrano et al., 2023) in the R software (R Core Team, 2024) was chosen as the tool for processing the data collected, throughout this research.

4 Results and Analysis

The analysis of the efficiency of the CF was based on the values of the inputs and outputs consolidated by year, from 2021 to 2023. In this regard, Table 1 provides the averages of the costs incurred in macroactivity 04.00 (MA 04.00), in macroactivity 59.00 (MA 59.00), the net value of fixed assets recorded in the accounting accounts for equipment, vehicles, and vessels used in the execution of STA activities (AIL), the number of inspections and naval inspections (IN/VST), as well as the extent of the jurisdictional area under the responsibility of each CF in km² (AJ), in order to preliminarily observe the structure of inputs and outputs of each OM.

Table 1

Average values of inputs and outputs of the CF 2021 - 2023

DMU	***Inputs***			***Outputs***	
	MA 04.00	**MA 59.00**	**AIL**	**IN/VST**	**AJ**
CF-1	352,707.97	1,813,926.07	1,747,259.38	1,488	586,513.99
CF-2	63,531.52	17,011.29	922,435.22	1,863	115,066.58
CF-3	573,597.57	1,007,660.57	2,976,050.07	4,988	434,339.51
CF-4	333,232.49	1,570,007.96	2,122,828.25	504	135,114.95
CF-5	408,828.78	24,179.76	3,270,389.67	3,090	357,142.08
CF-6	169,321.43	136,312.59	2,674,880.51	3,419	99,136.01
CF-7	71,462.73	41,828.07	1,284,057.66	1,382	246,867.64
CF-8	249,603.35	78,579.61	3,131,374.47	3,561	277,423.63
CF-9	383,235.40	1,351,602.08	4,586,066.58	2,440	139,500.68
CF-10	553,065.86	400,954.07	2,333,402.86	1,612	156,482.43
CF-11	3,908,754.89	1,455,528.61	15,112,077.09	8,228	594,184.98
CF-12	1,077,711.21	1,604,135.77	9,212,471.02	6,681	237,754.17
CF-13	958,640.61	504,058.10	3,536,972.54	13,543	201,156.30

Source: Research data (2024).

In order to verify the isotonicity between the variables, a Pearson correlation test was performed between the input and output variables (Lorenzett et al., 2010 and Lu, 2011). As shown in Table 2, all the correlation coefficients between the variables are positive, and therefore, the variables used in the study meet the isotonicity assumption for DEA models.

Table 2
Pearson Correlations between Inputs and Outputs

Variables	MA 04.00	MA 59.00	AIL
MA 59.00	0.399	-	-
AIL	0.930	0.458	-
IN/VST	0.541	0.073	0.509
AJ	0.563	0.424	0.456

Source: Research data (2024).

Next, regarding the assumption of the scale returns to be adopted, the descriptive statistics of the inputs and outputs of the CF over the three-year period were verified, as detailed in Table 3.

Table 3
Descriptive statistics

Variables	Mean	Standard Deviation	Minimum	Maximum	Coefficient of variation
MA 04.00	700,284.14	1,011,109.69	63,531.52	3,908,754.89	1.4439
MA 59.00	769,675.73	708,889.07	17,011.29	1,813,926.07	0.9210
AIL	4,070,020.41	3,910,002.21	922,435.22	15,112,077.09	0.9607
IN/VST	4,061.38	3,611.35	504,00	13,543.00	0.8992
AJ	275,437.15	170,091.28	99,136.01	594,184.98	0.6175

Source: Research data (2024).

The high values of the ranges (Maximum value - Minimum value) and the coefficients of variation of the variables point to significant differences between the CFs. For example, regarding the costs of macroactivity MA 04.00 and the values of the AIL, CF-11 is the unit with the highest average during the period, with R$ 3,908,754.89 in MA 04.00 and R$ 15,112,077.09 in AIL, while CF-2 reported an average cost of R$ 63,531.52 in MA 04.00 and an average AIL of R$ 922,435.22. Regarding macroactivity MA 59.00, CF-1 has the highest average, with R$ 1,813,926.07, while CF-2 is the OM with the lowest average cost for maintenance and operation of administrative infrastructure, R$ 17,011.29.

In the outputs, the significant difference in the observations remains. While CF-4 is the unit with the lowest average number of inspections and visits during the period, with 504, CF-13 stands out as the OM with the highest average, with 13,543. Regarding the extension of the jurisdictional area, CF-11 covers an area of 594,184.98 km², a considerably larger area than CF-6, which operates in an area of 99,136.01 km².

The heterogeneity in the size of the CFs, similar to what was observed by Santos et al. (2023a) and Santos et al. (2023b), suggests a DEA-SBM model oriented to inputs, under the VRS assumption. However, the VRS model classifies as efficient any DMU with the maximum value in an output variable or the minimum value in an input variable. In this case, CF-11, for example, would be classified as efficient simply for having the largest jurisdictional area, without considering the levels of the input variables, resulting in an inadequate evaluation. Therefore, the assumption of constant returns to scale (CRS) was adopted.

Additionally, the Kaizen algorithm, as per Tone (2016), was employed to ensure that the projection of any inefficient CF is achieved with minimal modifications to the input quantities. Table 4 presents the results, with the annual efficiency indices and the overall average for each CF during the period.

Table 4

Efficiencies of River Captaincies 2021-2023

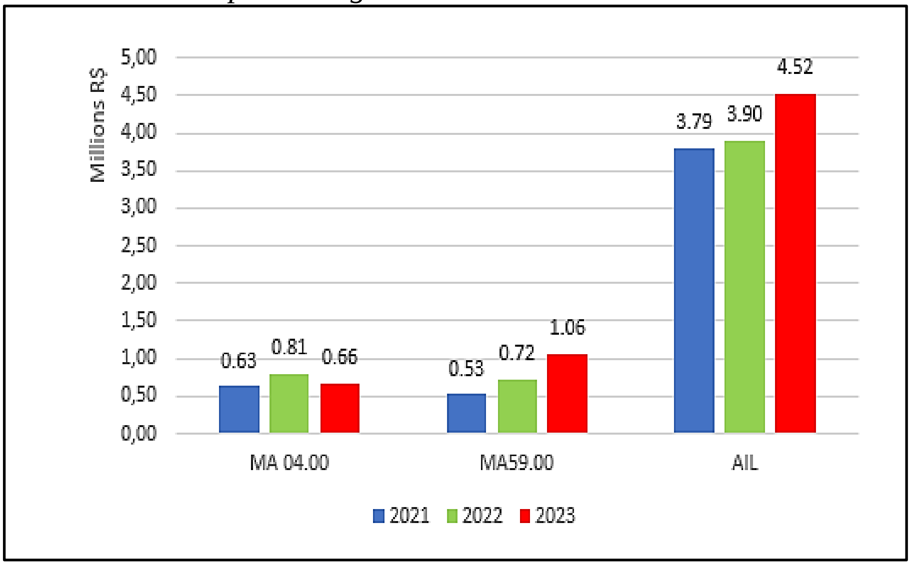
DMU	Year			Mean per CF
	2021	2022	2023	
CF-1	1.0000	1.0000	0.8670	0.9557
CF-2	1.0000	1.0000	1.0000	1.0000
CF-3	0.8147	0.8271	0.7430	0.7949
CF-4	0.7237	0.7209	0.7763	0.7403
CF-5	1.0000	0.8914	1.0000	0.9638
CF-6	1.0000	1.0000	0.9334	0.9778
CF-7	1.0000	1.0000	1,0000	1.0000
CF-8	1.0000	0.9312	0.9200	0.9504
CF-9	1.0000	0.6658	0.6272	0.7643
CF-10	0.8715	1.0000	0.9574	0.9430
CF-11	0.7856	0.8607	0.8021	0.8161
CF-12	0.7918	0.5726	0.5862	0.6502
CF-13	1.0000	1.0000	1.0000	1.0000
Annual Average	0.9221	0.8823	0.8625	0.8890

Source: Research data (2024).

The set of the 13 River Captaincies (CF) presented an average overall efficiency index of 0.8890, but with a decreasing trend over the three-year period. In this context, it is interesting to analyze the variations in the averages of inputs and outputs over time, in order to verify the possible influence of these changes on the decline in the overall efficiency indices of the CF.

As illustrated in Figure 2, macroactivity MA 04.00 showed an increase of 29% from 2021 to 2022, making 2022 the year with the highest average costs during the period. In 2023, there was a reduction in costs for this macroactivity, but it was still approximately 6% higher than in 2021. On the other hand, increases in the average values of the net value of fixed assets (AIL) were observed throughout the period, with a variation of 3% from 2021 to 2022 and 16% from 2022 to 2023. Considering that assets tend to depreciate over time, these increases indicate that the CF made investments in the acquisition of equipment, vehicles, or vessels supporting their STA activities during the three years. Most notably, a constant and significant growth in MA 59.00 was observed. In this macroactivity, there was a 36% increase in 2022 compared to 2021, and a 47% increase in 2023 compared to the previous year. As a result, the average costs related to the maintenance and operation of the CF infrastructure in 2023 were almost double the amount from 2021.

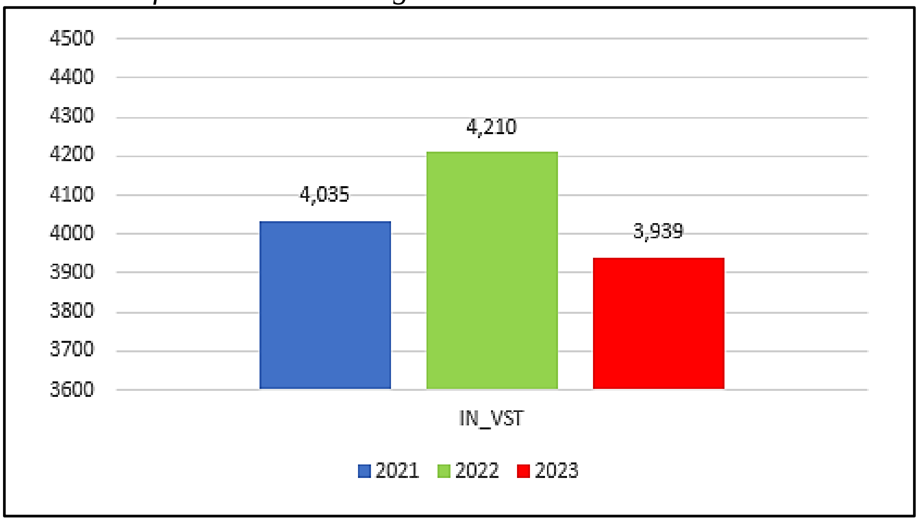
Figure 2
Variation in CF input averages



Source: Research data (2024).

Regarding the outputs, it is noteworthy that the jurisdictional areas (AJ), under the responsibility of the River Captaincies (CF), did not undergo any changes during the period. However, concerning the average number of inspections and surveys (IN/VST) conducted, a distinct pattern was observed compared to the inputs, as there were no significant variations over the three-year period. As shown in Figure 3, the largest recorded variation was a 6% decrease in 2023 compared to the average number recorded in 2022. However, it is interesting to note that the lowest average number of IN/VST conducted occurred in 2023, the year when, overall, the highest input values for the CF were recorded. Therefore, in general terms, it can be inferred that the significant increase in inputs, especially the costs for MA 59.00 and the investments made, did not result in a proportional increase in the outputs of the CF.

Figure 3
Variation of CF IN/VST averages



Source: Research data (2024).

Regarding the individual performance of each unit, CF-3, CF-4, CF-9, and CF-12 are the units that show the highest inefficiencies during the period, with averages of 0.7949, 0.7403, 0.7643, and 0.6502, respectively. Among these units, CF-9 stands out, as it was efficient in 2021 but saw a decline in efficiency, reaching 0.6272 in 2023. It is worth mentioning that this unit experienced significant increases in its costs in 2022 and 2023 compared to 2021. In the macroactivity MA 04.00, CF-9 incurred costs of R$ 69,003.11 in 2021, R$ 575,804.26 in 2022, and R$ 504,898.84 in 2023. In macroactivity MA 59.00, the costs in the first year were R$ 1,095,400.92, and in the last year of the analysis, R$ 1,559,199.72. In addition to the increase in costs, this unit recorded R$ 4,125,529.24 in AIL in 2021 and R$ 5,387,728.83 in 2023, representing a 30% increase in this variable. At the same time as these increases in costs and AIL, the number of IN/VST decreased from 2,872 in 2021 to 2,366 in 2022, reaching 2,083 in 2023, while maintaining its jurisdictional area.

On the other hand, CF-2, CF-7, and CF-13 stood out the most during the period, as they achieved the highest efficiency levels in all three years analyzed. These results indicate consistency in the costs incurred in the macroactivities MA 04.00 and MA 59.00, as well as in the values of the net fixed assets used in the STA activities of these units, with the volume of inspections and naval surveys conducted and the extent of their jurisdictional areas over time. Interestingly, among the CF with the highest average efficiency scores, CF-2 has the lowest average in all three inputs during the period, but it ranks fifth in the lowest average number of IN/VST and second in the lowest jurisdictional area. On the other hand, CF-13 is among those with the highest costs and AIL in the period, while it has the highest average of IN/VST and is only the eighth unit in terms of jurisdictional area. Thus, it becomes clear that SCM data alone are not sufficiently adequate to demonstrate the efficiency of the CF, which supports the considerations of Hokkinen (2021) and Santos et al. (2023a). Regarding efficiency indices, it is also worth mentioning CF-1, CF-5, CF-6, CF-8, and CF-10, which achieved high average indices, above 0.9. Despite the high indices, these units were not efficient during the analyzed period, as they had slack in at least one of their inputs in one or more of the years analyzed.

Based on the year 2023, the most recent data used in this research, Table 5 presents the slacks and ideal input values for the CFs, considered inefficient, to reach the efficiency frontier while maintaining their respective jurisdictional areas and average inspections and surveys conducted.

Table 5

Slacks and ideal values of the River Captaincies in 2023

DMU	Efficiency	Slacks			Ideal		
		MA 04.00	**MA 59.00**	**AIL**	**MA.04.00**	**MA 59.00**	**AIL**
CF-1	0,8670		894.227,16		229.499,52	1.347.396,33	2.139.079,33
CF-2	1,0000				73.067,47	27.210,60	1.036.004,35
CF-3	0,7430		1.605.968,53		552.220,96	476.803,89	3.410.766,03
CF-4	0,7763		1.012.070,53		427.913,79	496.274,44	2.529.837,80
CF-5	1,0000				536.578,06	15.106,70	3.260.138,16
CF-6	0,9334			620.006,43	142.451,11	199.522,97	2.483.467,29
CF-7	1,0000				104.386,24	28.588,85	1.183.732,67
CF-8	0,9200			711.084,32	247.696,85	21.326,49	2.251.997,94
CF-9	0,6272		949.869,79	2.743.218,68	504.898,84	609.329,93	2.644.510,15
CF-10	0,9574	105.256,35			718.152,32	388.609,67	2.605.179,95

DMU	Efficiency	Slacks			Ideal		
		MA 04.00	**MA 59.00**	**AIL**	**MA.04.00**	**MA 59.00**	**AIL**
CF-11	0,8021	834.814,10		5.481.361,56	2.362.938,38	2.460.138,60	10.990.612,28
CF-12	0,5862		1.480.142,96	6.573.695,89	1.057.332,60	841.461,71	4.313.500,93
CF-13	1,0000				743.028,49	905.606,42	3.763.649,20
Total		940.070,45	5.942.278,97	16.129.366,89	7.700.164,63	7.817.376,60	42.612.476,07

Source: Research data (2024).

In aggregate terms, the proposed reductions for expenses in the macroactivities MA 04.00 and MA 59.00 represent 10.88% and 43.19%, respectively, of the amounts recorded in 2023. As for the values of fixed assets (AIL), the proposed reduction is around 27.46%.

CF-1 was not considered efficient in 2023 due to excess inputs, but only in the macroactivity MA 59.00. A similar situation is observed in CF-3 and CF-4, which also incurred higher costs than necessary in this macroactivity. Regarding CF-6 and CF-8, the inefficiency is due to excess AIL, while in CF-10, it is due to the slack in macroactivity MA 04.00. In the other CFs, inefficiency is generated by slacks in two input variables.

In general, it can be observed that the inputs with the highest absolute and relative slacks are those related to the costs of macroactivity MA 59.00, as well as the net value of fixed assets for STA activities. In addition to indicating a substantial need for reduction, these inputs impacted most of the inefficient CFs in 2023, as well as in 2021 and 2022, as shown by the significant negative correlations (Table 6) between the efficiency scores obtained by the CFs over the three years and their inputs, indicating that higher input levels are associated with lower annual efficiency levels.

Table 6

Correlations between efficiency scores and inputs

	MA 04.00	MA 59.00	AIL
Efficiency	-0.303	- 0.676*	- 0.482*

Note: * $p < .05$
Source: Research data (2024).

Despite the results generated by the DEA-SBM model, it is important to highlight that before making any decision about reducing inputs, it is essential to analyze and consider in detail the operational specificities of each unit.

Thus, taking into account the specific peculiarities of each River Captaincy’s operational area, as well as the strategic aspects inherent to the Brazilian Navy's actions that may influence the efficiency scores achieved, the results presented point to the inputs that require greater attention, so that the units can improve their processes by optimizing their applications, avoiding waste, in order to achieve efficiency, as mentioned by Ferradaes (2019). One of the measures to be adopted by the River Captaincies that did not achieve the highest level of efficiency is the use of Benchmarking, as suggested by Camargo and Guimarães (2013). In this regard, the units that did not achieve efficiency during the period can base themselves on the management models of CF-2, CF-7, and CF-13, which maintained consistency in their costs and AIL with their outputs throughout the entire analyzed period, in order to identify which elements of these units' management can be replicated to contribute to the optimization of inputs in their activities.

Moreover, the ideal values indicated by the DEA-SBM model can be used by the Brazilian Naval High Command to set annual cost reduction targets for the River Captaincies, as well as parameters for resource allocation to these units.

5 Final Considerations

The main objective of this study was to measure and assess the efficiency of the River Captaincies in their maritime traffic safety activities, based on the DEA approach, using data extracted from the Brazilian Navy's Cost System. Based on the results presented, it can be concluded that this objective was achieved.

The analysis of the correlations between the variables showed that the combination of costs related directly to maritime traffic safety activities (MA 04.00), administrative infrastructure maintenance (MA 59.00), and the net values of assets directly employed in the main activities (AIL), with the number of naval inspections and surveys conducted (IN/VST) and the jurisdictional area covered by each Captaincy (AJ), are adequate indicators for measuring the efficiency of these units. The panel data analysis, in addition to improving the robustness of the DEA model by reducing dimensionality issues regarding the number of variables and DMUs, enabled a more comprehensive analysis of the River Captaincies' cost management, demonstrating the evolution of their efficiency indices over time. Despite the data heterogeneity suggesting the use of a variable returns to scale (VRS) assumption, the DEA-SBM model, oriented to inputs and based on the constant returns to scale (CRS) assumption, was found to be suitable for obtaining efficiency indices, as the VRS approach tends to classify as efficient those DMUs that have the lowest inputs or the highest outputs in the sample, which could bias the analysis.

With the results of this research, it was possible to identify the River Captaincies that showed the greatest consistency between the costs incurred and the products generated. In this case, CF-2, CF-7, and CF-13 were indicated as benchmarks for inefficient units to improve their cost management processes, specifically in the development of maritime traffic safety activities.

The results also specifically pointed out which inputs are being excessively applied by the River Captaincies, which could guide these units to focus on management aspects generating these additional costs, so they can implement strategies to optimize the use of these resources without compromising their ability to carry out naval inspections in their respective jurisdictional areas. Thus, the results are useful as parameters for resource allocation and for setting annual cost reduction goals for these units.

There is no doubt that the creation of the Brazilian Navy's Cost System (SCM) was a significant advance for the Naval Force, allowing for monitoring and recording of its activity costs, expanding the managerial scope of this branch of accounting to all its units. However, the results of this study align with the observations of Hokkinen (2021) and Santos et al. (2023), who mention that cost reports alone may not clearly indicate the efficiency of the units in applying scarce public resources from the state budget. Therefore, it is concluded that the efficiency of the units does not depend solely on the amount of costs incurred, but on how they optimize the use of their inputs to generate outputs, regardless of the values employed.

Thus, it is clear that efficiency, when analyzed in a broader context using mathematical models that integrate the data provided by cost management systems with the products generated by the units, can significantly aid in generating more robust information for managing organizations. This study demonstrated that the use of DEA can be an interesting tool to enhance the managerial data provided by SCM, as it can offer insights that allow managers to compare units with similar duties and resources, highlighting specific areas that require attention.

It is important to note that, despite its potential managerial utility, the results presented by the DEA-SBM model used in this study are limited to the input and output data of the thirteen River Captaincies analyzed from 2021 to 2023. Therefore, the results are not intended to be generalized to other Navy units or to other periods not covered in this research. Additionally, the proposed cost reductions should not be analyzed in isolation, particularly because it involves the operational activity of a Military Force, which encompasses environmental, strategic, and national security aspects beyond the scope of this work. Therefore, the results may be used as one of the guiding tools for the Navy's management of these units.

Finally, future research is suggested to apply DEA to analyze the Port Captaincies, which operate in the maritime environment, to expand studies on efficiency measurement from a cost perspective for the Brazilian Navy's operational units, especially those dedicated to maritime traffic safety activities in Brazil.

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