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MODELAGEM ESTOCÁSTICA DE ECLUSAS DE NAVEGAÇÃO INTERIOR: UMA ESTRUTURA DE MONTE CARLO PARA AVALIAÇÃO DA CAPACIDADE E DA OPERAÇÃO DE COMBOIOS EM ECLUSAS

STOCHASTIC MODELING OF INLAND NAVIGATION LOCKS: A MONTE CARLO FRAMEWORK FOR CONVOY LOCKAGE AND CAPACITY ASSESSMENT

MODELADO ESTOCÁSTICO DE ESCLUSAS DE NAVEGACIÓN INTERIOR: UN MARCO DE MONTE CARLO PARA LA EVALUACIÓN DE LA CAPACIDAD Y EL BLOQUEO DE CONVOYES

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Resumo

As eclusas são elementos críticos de infraestrutura em sistemas de navegação interior, pois regulam o movimento de embarcações e influenciam diretamente a

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vazão do canal. A variabilidade operacional durante os procedimentos de passagem pelas eclusas pode afetar significativamente o tempo de trânsito dos comboios, o consumo de energia e a capacidade efetiva da eclusa. Este estudo desenvolve um modelo estocástico para operações em eclusas interiores baseado em simulação de Monte Carlo. O processo de passagem pelas eclusas é decomposto em etapas operacionais elementares, incluindo manobras, atracação, operação das comportas, processos hidráulicos e reconfiguração dos comboios. O modelo é aplicado à eclusa de Bariri, na hidrovia Tietê-Paraná, Brasil, onde comboios padrão BP2×2 precisam ser temporariamente divididos em duas unidades BP1×2 devido às limitações de largura da câmara. Os resultados da simulação mostram que o tempo total de passagem pelas eclusas varia aproximadamente de 6 a 7 horas, dependendo das condições operacionais, e que a capacidade efetiva anual da eclusa pode variar em cerca de 15 a 17 % entre os cenários analisados. A análise de sensibilidade identifica o tempo de amarração como o principal fator operacional que controla a variabilidade do tempo de travessia das eclusas. Além disso, as diferenças entre os cenários mais e menos eficientes correspondem a aproximadamente 120 L de combustível por travessia, o que pode representar uma economia anual de cerca de 3.6×10^5 L de combustível e quase 960 t de CO_2 em condições operacionais típicas. A estrutura proposta demonstra como a variabilidade operacional se propaga dos procedimentos locais de travessia das eclusas para indicadores de nível de sistema, como confiabilidade, consumo de energia, emissões e capacidade de processamento da infraestrutura. A metodologia é transferível para outros sistemas hidroviários interiores e apoia o planejamento operacional baseado em evidências e a avaliação da capacidade.

Palavras-chave: transporte hidroviário interior; simulação de Monte Carlo; modelagem estocástica; capacidade de eclusas; Hidrovia Tietê-Paraná**.**

Abstract

Locks are critical infrastructure elements in inland navigation systems because they regulate vessel movement and directly influence corridor throughput. Operational variability during lockage procedures may significantly affect convoy transit time, energy consumption, and effective lock capacity. This study develops a stochastic modeling framework for inland lock operations based on Monte Carlo simulation. The lockage process is decomposed into elementary operational stages, including maneuvering, mooring, gate operations, hydraulic processes, and convoy reconfiguration. The model is applied to the Bariri lock on the Tietê-Paraná Waterway, Brazil, where standard BP2x2 convoys must be temporarily dismembered into two BP1x2 units due to chamber width limitations. The simulation results show that total lockage time ranges approximately from 6 to 7 h depending on operational conditions, and that effective annual lock capacity may vary by about 15-17 % across the analyzed scenarios. The sensitivity analysis identifies mooring time as the dominant operational factor controlling lockage-time variability. In addition, differences between the most and least efficient scenarios correspond to approximately 120 L of fuel per lockage, which may represent annual savings of about 3.6×10^5 L of fuel and nearly

960 t of CO_2 under typical operating conditions. The proposed framework demonstrates how operational variability propagates from local lockage procedures to system-level indicators such as reliability, energy consumption, emissions, and infrastructure throughput. The methodology is transferable to other inland waterway systems and supports evidence-based operational planning and capacity assessment.

Keywords: inland waterway transport; Monte Carlo simulation; stochastic modeling; lock capacity; Tietê-Paraná waterway.

Resumen

Las esclusas son elementos de infraestructura críticos en los sistemas de navegación interior, ya que regulan el movimiento de las embarcaciones e influyen directamente en el flujo del corredor. La variabilidad operativa durante los procedimientos de esclusaje puede afectar significativamente el tiempo de tránsito de los convoyes, el consumo de energía y la capacidad efectiva de la esclusa. Este estudio desarrolla un marco de modelado estocástico para las operaciones de esclusas interiores basado en la simulación de Monte Carlo. El proceso de esclusaje se descompone en etapas operativas elementales, que incluyen maniobras, amarre, operaciones de compuertas, procesos hidráulicos y reconfiguración de convoyes. El modelo se aplica a la esclusa de Bariri en la vía fluvial Tietê-Paraná, Brasil, donde los convoyes estándar BP2x2 deben dividirse temporalmente en dos unidades BP1x2 debido a las limitaciones de ancho de la cámara. Los resultados de la simulación muestran que el tiempo total de esclusaje oscila aproximadamente entre 6 y 7 horas, dependiendo de las condiciones operativas, y que la capacidad efectiva anual de la esclusa puede variar entre un 15% y un 17 % en los escenarios analizados. El análisis de sensibilidad identifica el tiempo de amarre como el factor operativo dominante que controla la variabilidad del tiempo de esclusaje. Además, las diferencias entre los escenarios más y menos eficientes corresponden a aproximadamente 120 L de combustible por esclusaje, lo que podría representar un ahorro anual de alrededor de 3.6×10^5L de combustible y casi 960 t de CO_2 en condiciones operativas típicas. El marco propuesto demuestra cómo la variabilidad operativa se propaga desde los procedimientos locales de esclusaje hasta indicadores a nivel de sistema, como la fiabilidad, el consumo de energía, las emisiones y el rendimiento de la infraestructura. La metodología es transferible a otros sistemas de vías navegables interiores y respalda la planificación operativa y la evaluación de la capacidad basadas en evidencia.

Palabras clave: transporte fluvial; simulación de Monte Carlo; modelado estocástico; capacidad de las esclusas; vía fluvial Tietê-Paraná.

1 Introduction

Inland waterway transportation offers several advantages compared with road and rail modes, including lower fuel consumption, reduced greenhouse gas emissions, and higher cargo capacity per unit of energy. In Brazil, the Tietê–Paraná Waterway (TPW) constitutes a strategic logistics corridor connecting agricultural and industrial production regions in the interior of the country to intermodal terminals and export routes.

The waterway includes important logistics nodes, such as the Pederneiras intermodal terminal, which integrates waterway transport with road and rail networks and serves as a major hub for cargo operations in the region (Felipe Junior; Silveira; Cocco, 2023; Mendonça; Amorim; Rezende, 2025; Silva, 2015; Toloi *et al.*, 2016).

Among the infrastructures that regulate navigation along the TPW, locks play a critical role because they enable vessels to overcome elevation differences created by hydroelectric dams. However, these facilities also impose operational constraints that influence vessel flow and the effective capacity of the navigation corridor (Carroll; Bronzini, 1971; Dantas, 2023; Hammedi *et al.*, 2022; Rogers; Hofseth; Adams, 2012; Wu; Ji; Yu, 2024).

A representative example is the Bariri lock, whose chamber dimensions impose restrictions on convoy configurations. Convoys operating on the TPW typically adopt two configurations. The Double Tietê formation (BP2x2) consists of a pusher and four barges arranged in two rows, with an overall length of approximately 137 m and a beam of 21.34 m. The reduced Tietê formation (BP1x2) is composed of a pusher and two barges, maintaining the same length but with a beam of 10.67 m. Because the Bariri lock chamber measures approximately 142 m in length and 12 m in width, BP2x2 convoys cannot transit in a single lockage and must be temporarily dismembered into two BP1x2 units that pass sequentially through the chamber.

The lockage process at Bariri therefore involves a complex sequence of operational stages, including convoy approach and mooring, gate opening and closing, chamber filling or emptying, vessel entry and exit maneuvers, and the uncoupling and recoupling of barges. Among these stages, mooring procedures represent a particularly sensitive component of the operation, since their duration depends on several operational factors—such as crew experience and equipment condition—as well as environmental conditions including wind, currents, and visibility (Daggett; Ankeny, 1975; Silva, 2015; Toloi *et al.*, 2016).

As pointed out by Rogers, Hofseth, and Adams (2012), such operational variability limits the applicability of purely deterministic models for analyzing lock performance and capacity, since these models do not capture the dispersion of cycle times or allow the estimation of risk percentiles relevant for infrastructure planning.

Previous studies have investigated lock operation modeling in waterways in the United States and Europe (Adhikari *et al.*, 2014; Carroll; Bronzini; Hayward, 1972; Daggett; Ankeny, 1975; Smith, L. D.; Sweeney; Campbell, 2009; Wang, 2007; Wilson, 1978). However, relatively few studies have addressed the Brazilian inland waterway context. The operational characteristics of the TPW—including convoy dismemberment procedures, infrastructure constraints, and regional environmental conditions—limit the direct applicability of models developed for other waterway systems.

In the Brazilian case, the available literature has focused predominantly on macroeconomic feasibility studies and environmental analyses, while detailed stochastic modeling of lock operations remains limited. Operational factors such as vessel maneuvering, mooring procedures, water levels, and traffic patterns may generate variability in lockage times, potentially leading to queues and increased waiting times in the navigation corridor (Brinatti; Ramalho; Tonon, 1981; Caljouw, 2015; Silva, 2015).

Monte Carlo simulation provides a suitable framework for analyzing systems characterized by multiple sources of uncertainty and operational variability, since it allows the generation of stochastic realizations of the lockage process and the estimation of probability distributions and percentile-based indicators relevant for capacity planning and operational management (Bandy, 1996; Campbell *et al.*, 2007; Guan *et al.*, 2021).

In this context, the objective of this study is to develop and apply a Monte Carlo simulation model for stochastic analysis of the push-barge convoy lockage

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process at the Bariri lock, quantifying operational variability and its impacts on system capacity and efficiency.

Specifically, this study aims to: (i) decompose the lockage process into its elementary operational components; (ii) develop a deterministic reference model for lock transit time; (iii) implement a Monte Carlo simulation framework incorporating stochastic variability; (iv) estimate probability distributions of lock transit time and fuel consumption; (v) compare stochastic and deterministic results for capacity planning; and (vi) identify operational improvement opportunities for the TPW.

The present study contributes to this gap by proposing a stochastic modeling framework for lockage operations at the Bariri lock. The methodology explicitly represents operational variability and enables the estimation of transit time distributions and associated risk percentiles. The approach is transferable to other locks in the TPW and in other Brazilian waterways, providing a methodological basis for capacity analysis and evidence-based operational management.

This article is organized as follows. Section 2 presents the literature review on lock operations modeling and stochastic simulation. Section 3 describes the proposed methodology and modeling framework. Section 4 presents the Bariri lock case study and the model parameters. Section 5 discusses the simulation results and their implications for operational performance and capacity assessment. Finally, Section \ref{sec:conclusion} presents the conclusions and directions for future research.

2 Literature review

The modeling of lock operations in inland waterways has been an established research topic in transportation engineering for several decades, with foundational studies dating back to the 1970s. A central theme in this literature concerns the analysis of lockage time and lock scheduling, both of which are critical for improving operational efficiency and system throughput in navigation locks. Recent research has explored these topics through analytical modeling, simulation approaches, and statistical analyses of operational factors affecting lock performance (Ji *et al.*, 2022; Pan, 2019; Tian *et al.*, 2024).

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Lockage time generally refers to the period required for a vessel to complete the locking process. According to Caljouw (2015), it corresponds to the vessel transit time within the chamber, whereas Kreis *et al.* (2014) and Brinati, Ramalho, and Tolou (1981) define it more broadly as the interval between the beginning of the locking procedure and the vessel's exit from the facility. In practice, lockage time is often decomposed into operational components such as vessel approach and mooring, gate opening and closing, chamber filling or emptying, safety inspections, and vessel movement through the chamber (Carroll; Bronzini, 1971; Rogers; Hofseth; Adams, 2012). This decomposition facilitates the identification of operational bottlenecks and the evaluation of improvement strategies (Segovia *et al.*, 2022).

Early analytical approaches frequently applied queueing theory to estimate lock capacity and waiting times. However, Wilson (1978) demonstrated that classical queueing assumptions—such as independent arrivals and exponentially distributed service times—are often violated in real inland navigation systems. Convoy arrivals, highly variable service times, and complex operational priorities may therefore lead to biased estimates of waiting times and system capacity. These limitations motivated the adoption of simulation-based approaches capable of representing operational variability more realistically.

Simulation techniques subsequently became widely used in lock operations research. One of the earliest computational models was proposed by Carroll and Bronzini (1971), who applied Monte Carlo techniques to simulate convoy arrivals and vessel movements through locks using stochastic interarrival times and probabilistic lock operation processes. Later, Carroll, Bronzini, and Hayward (1972) expanded this line of research by addressing transient periods, validation of Poisson arrival assumptions, and treatment of autocorrelated simulation data. These studies established simulation as an important tool for representing the stochastic nature of lock operations.

Research has also addressed the concept of lock capacity. Daggett and Ankeny (1975) distinguished between physical capacity—defined as the theoretical maximum throughput under minimum cycle times—and economic capacity,

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corresponding to utilization levels beyond which waiting costs become excessive. More recent work has examined the influence of operational variability on capacity estimates. For example, Liu and Cao (2023) showed that randomness in vessel speeds may reduce estimated capacity by approximately 1.5-1.7 %, whereas variability in departure intervals has negligible effects.

Discrete-event and Monte Carlo simulation have been widely applied to evaluate operational decision rules, congestion management, and waterway performance. The Navigation System Simulation (NaSS) framework developed by Rogers, Hofseth, and Adams (2012) enabled the simulation of vessel movements, lock policies, and interactions across waterway networks, making it possible to evaluate operational strategies and estimate delays and costs. Similarly, Smith, Sweeney, and Campbell (2007) analyzed lock management policies on a congested reach of the Upper Mississippi River and showed that optimized vessel sequencing can significantly reduce waiting times without requiring infrastructure expansion. Building on this approach, Campbell *et al.* (2007) developed decision-support tools combining multi-lock simulation, traffic management policies, and GIS-based vessel tracking.

Several studies have focused on detailed simulation of specific waterway systems. Bandy (1996) modeled the Illinois Waterway lock system by incorporating heterogeneous vessels and chamber allocation rules, while Adhikari *et al.* (2014) analyzed the Ohio River system to evaluate the effects of maintenance interruptions and equipment failures. These studies highlight the vulnerability of inland waterways to disruptions at critical locks.

Recent research has incorporated additional operational features into lock simulation models. For example, Zheng *et al.* (2024) introduced chain navigation processes into lock modeling, while Di Chiachio *et al.* (2021) explored scheduling approaches for vessel arrival management. Data-driven models have also been proposed. Wang (2007) developed a waterway simulation model representing the network as a large-scale queueing system with bidirectional traffic and convoy operations. Likewise, Smith, Sweeney, and Campbell (2014) integrated discrete-event simulation with a random utility model of shipper modal choice, capturing

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endogenous demand responses to congestion.

Optimization of lock operations has received increasing attention in recent years. Guan *et al.* (2021) proposed a mixed-integer programming model combined with large neighborhood search heuristics for vessel arrival scheduling and lock allocation in multi-lock systems. Likewise, Hengeveld (2012) investigated speed control strategies to regulate vessel arrivals at locks, demonstrating significant reductions in waiting times under moderate to high traffic conditions. Caljouw (2015) further compared different sequencing policies, showing that simple prioritization rules may perform well under moderate demand levels, whereas more advanced optimization methods become advantageous under high utilization conditions.

Overall, the literature on lock operations modeling can be broadly categorized into three complementary research streams. The first focuses on analytical and statistical approaches for estimating lock capacity and identifying determinants of lockage time (Daggett; Ankeny, 1975; Kreis *et al.*, 2014; Wilson, 1978). The second emphasizes simulation-based modeling of inland waterway systems, including Monte Carlo and discrete-event simulation methods designed to capture operational variability and system interactions (Carroll; Bronzini, 1971; Rogers; Hofseth; Adams, 2012; Smith, L.; Sweeney; Campbell, 2007). The third stream addresses operational optimization, developing scheduling algorithms, traffic management strategies, and decision-support tools aimed at reducing congestion and improving system efficiency (Caljouw, 2015; Guan *et al.*, 2021; Hengeveld, 2012).

Despite the extensive international literature on lock operations modeling, relatively few studies have addressed the Brazilian inland waterway context. The operational characteristics of the Tietê–Paraná Waterway (TPW)—including specific convoy configurations, infrastructure restrictions requiring convoy dismemberment, and regional environmental conditions—limit the direct applicability of models developed for North American and European waterways. Moreover, Brazilian studies have predominantly focused on macroeconomic feasibility analyses, environmental assessments, and modal competitiveness, with limited attention to detailed stochastic modeling of lock operations (Oliveira, 2019;

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Rezende; Kaiser; Peixoto, 2018; Toloi *et al.*, 2016). Table 1 summarizes the main approaches used in lock operations modeling. This gap motivates the development of a stochastic framework tailored to the operational characteristics of the TPW and, more specifically, to the Bariri lock case.

Table 1 - Main approaches used in lockage operations modeling.

Approach	Key references	Main focus
Queueing models	Wilson (1978); Daggett (1975)	Capacity estimation
Simulation models	Carroll (1971); Rogers (2012)	Operational variability
Optimization models	Guan (2021); Caljouw (2015)	Lock scheduling

Source: Own elaboration

3 Methodology

In Europe and the United States, there is a high volume of vessels on the waterway, and for this reason, the problem of queues at the locks is a significant issue, and convoys are not split up. This is evident in the number of studies that address this issue. In Brazil, particularly on the Tietê-Paraná waterway, the flow of vessels through the Bariri lock is low; however, due to the lock's spatial limitations, there is a need for convoy splitting, which is the main issue, not the problem of queues. Considering the existing gap in research on the problem of Brazilian locks, this is the major methodological contribution of this work.

The proposed framework was developed to represent the complete lockage process of a BP2x2 convoy at the Bariri lock, from mooring at the upstream waiting buoy to final release at the downstream buoy after convoy reassembly. The model combines operational, geometric, navigation, and propulsion information in order to estimate lock transit time, fuel consumption, CO2 emissions, and annual lock capacity under deterministic and stochastic assumptions.

The input data were compiled from four main sources: (i) lock chamber characteristics and operational procedures, (ii) convoy geometry and propulsion

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characteristics, (iii) navigation rules applicable to the waterway, and (iv) vessel speed records obtained from Automatic Identification System (AIS) data, obtained in real time from the VesselFinder website[1] and nautical-chart distances. AIS observations were used to define representative operating speeds. For loaded convoys navigating upstream, recorded speeds ranged from 5.74 to 7.59 km/h, and a nominal value of 7 km/h was adopted. For empty vessels navigating downstream, typical speeds of approximately 13 km/h were observed. In the vicinity of the lock and within the Mandatory Communication Point, lower safety speeds were adopted in accordance with Brazilian inland navigation procedures (Brazilian Navy Regulations) (Marinha do Brasil - CFTP, 2023).

The lock transit of a BP2x2 convoy requires temporary dismemberment into two BP1x2 units, since the complete convoy cannot pass through the lock chamber in a single operation. The overall procedure was decomposed into 54 elementary operations, including maneuvering, mooring, inspection, gate operation, chamber filling or emptying, and final convoy reassembly.

Figure 1 summarizes the main stages of the process. First, the complete convoy arrives and moors at the upstream buoy. The pusher then disconnects part of the convoy, changing the configuration from BP2x2 to BP1x2. The first BP1x2 unit is guided to the lock, enters the chamber, is secured to the floating bollards, and undergoes inspection. After gate closure, the chamber is filled or emptied depending on the navigation direction. Once level equalization is completed, the downstream gate is opened, the unit is released, and it proceeds to the downstream buoy. The pusher then returns to collect the remaining barges and repeats the same sequence for the second BP1x2 unit. After both lockages are completed, the barges are recoupled at the downstream side, restoring the original BP2x2 configuration.

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[1] https://www.vesselfinder.com/

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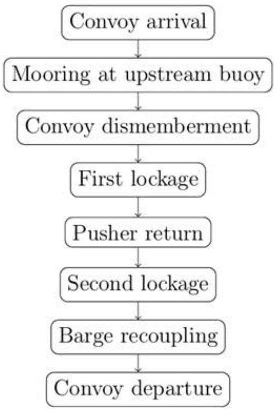
Figure 1 - Simplified operational flow of the BP2x2 convoy lockage process at the Bariri lock, including dismemberment, sequential lockages, and downstream recoupling



Source: Own elaboration

The deterministic model divides the lockage process into two classes of operations: stationary operations, in which the convoy or the pusher remains stopped, and movement operations, in which the vessel system is in motion. Nominal times for stationary operations were assigned on the basis of operational procedures, technical references, and observed practice. The adopted operational time parameters are summarized in Table 2, while the navigation speeds used in the model are presented in Table 3.

Table 2 - Operational time parameters adopted in the lock transit model.

Parameter	Description	Adopted value
t_{ACB}	Convoy mooring/release at buoy	0.10 h
t_{AEB}	Pusher–barge mooring/release	0.17 h
t_{POS}	Pusher repositioning maneuver	0.10 h
t_{ABB}	Barge–barge mooring/release	0.13 h
t_{LB}	Release from floating bollard	0.07 h
t_{INS}	Lock operator inspection time	0.004 h
t_{FE}	Lock gate opening/closing time	0.07 h
t_{E}	Lock chamber filling/emptying time	0.17 h

Source: Own elaboration

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Table 3 - Operational navigation speeds adopted in the model

Parameter	Description	Value
u_{AC}	Berthing/approach speed	1 km/h
u_s	Safety speed near the lock	5.58 (loaded) – 6.98 (empty) km/h
u_n	Normal navigation speed	13 km/h

Source: Own elaboration

Accordingly, the total lock transit time is expressed as

$$t_t = \sum_{i\in S} n_i\, t_i + \sum_{j\in M} \frac{d_j}{u_j}, \tag{1}$$

where S is the set of stationary operations, M is the set of movement operations, n_i is the frequency of stationary operation i, t_i is its characteristic duration, and d_j/u_j is the duration of movement segment j.

Fuel consumption was modeled consistently with the same operational decomposition. Thus, total fuel consumption was divided into contributions from stationary and movement operations:

$$C_t = \sum_{i\in S} \alpha_i\, n_i\, t_i + \sum_{j\in M} \beta_j \frac{d_j}{u_j}, \tag{2}$$

where α_i is the fuel consumption rate associated with stationary operation i, and β_j is the consumption coefficient associated with movement operation j. The propulsion-engine fuel consumption parameters adopted in this study were obtained from the manufacturer's technical manual and used as reference values in the simulations.

The proposed model was developed based on the representation of typical operational conditions, grounded on plausible scenarios observed in inland navigation practice. It is therefore characterized as a theoretical-exploratory mathematical model, whose primary objective is not the exact reproduction of a specific empirical dataset, but rather the systematic analysis of system behavior under different operational conditions.

In this context, factors such as variability associated with crew experience, extreme weather events, or high-frequency operational fluctuations were not explicitly incorporated. These simplifications are deliberate and consistent with classical approaches in the modeling of complex systems, where the initial goal is to isolate the dominant mechanisms governing the phenomenon under investigation.

The absence of direct calibration with empirical data does not invalidate the model, since its purpose lies in the *evaluation of scenarios and the identification of trends, sensitivities, and potential critical points in the mooring process*. In particular, the model enables:

a) the investigation of the influence of mean parameters and dispersion associated with mooring time.
b) the comparison of different operational configurations.
c) the identification of regimes of higher efficiency or increased operational risk.

From a methodological perspective, the model can be classified as a decision-support model, whose value lies in generating structured knowledge and supporting the proposition of operational strategies, rather than in the deterministic prediction of specific events.

3.1 Stochastic model and uncertainty propagation

The deterministic lockage model can be written as

$$T_{lock} = f(\boldsymbol{x}, \boldsymbol{\theta}),$$

where $\boldsymbol{x}$ represents the stochastic parameters and $\boldsymbol{\theta}$ denotes the deterministic parameters, including navigation speeds, fixed operation times, and maneuvering distances.

The stochastic component of the model is associated with mooring-related activities, represented by

$$\boldsymbol{x} = (t_{ACB}, t_{AEB}, t_{ABB}, t_{LB}).$$

These parameters were assumed to follow normal probability distributions,

$$t_i \sim N(\mu_i, \sigma_i^2),$$

where μ_i is the nominal mean duration of operation i and σ_i its standard deviation.

The adoption of the normal distribution to represent the stochastic behavior of operational times was primarily motivated by its analytical simplicity and its suitability for exploratory scenario analysis. The normal distribution allows straightforward

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parameterization through mean and standard deviation, facilitating the generation of scenarios with distinct dispersion levels and enabling a consistent sensitivity analysis framework. In addition, under the assumption that operational durations result from the aggregation of multiple independent or weakly dependent factors—such as crew actions, equipment response, and local environmental conditions—the use of a normal distribution is consistent with the Central Limit Theorem, which states that when a large sample of independent observations is collected from any distribution, the mean of those observations will approximate a normal distribution.

The corresponding dispersion level is represented by the coefficient of variation,

$$CV_i = \frac{\sigma_i}{\mu_i}. \tag{3}$$

The total lock transit time is therefore written as

$$T_{lock} = f(\boldsymbol{x}),$$

and the resulting variability propagates to fuel consumption, CO_2 emissions, and annual lock capacity according to

$$\boldsymbol{x} \sim \mathcal{P} \Rightarrow T_{lock} = f(\boldsymbol{x}) \Rightarrow \begin{cases} F = g(T_{lock}), \\ E = \gamma g(T_{lock}), \\ C = \dfrac{H}{T_{lock}}, \end{cases}$$

where F is fuel consumption, E is CO_2 emissions, γ is the emission factor, C is annual lock capacity, and H is the total annual operating time available. This formulation highlights how operational variability propagates through the system, affecting time, energy use, environmental performance, and infrastructure throughput.

3.2 Scenario definition and sensitivity analysis

A scenario-based approach was adopted to represent different operational conditions. Six scenarios were analyzed:

1. **Scenario A (Baseline):** nominal mean operation times with low dispersion ($CV = 5\ \%$).
2. **Scenario B (High dispersion):** nominal mean operation times with increased variability ($CV = 20\ \%$).

3. **Scenario C (Increased mooring time):** mooring-related operations multiplied by a factor of 1.5, with low dispersion ($CV = 5\ \%$).
4. **Scenario D (Increased mooring time with high dispersion):** mooring-related operations multiplied by 1.5 with high variability ($CV = 20\ \%$).
5. **Scenario E (Hydraulic delay):** baseline parameters with increased lock chamber filling/emptying time.
6. **Scenario F (Reduced navigation speed):** baseline parameters with reduced navigation speed during movement segments.

For each scenario, 10,000 Monte Carlo iterations were performed. In each iteration, the stochastic mooring times were randomly sampled from their respective distributions, while the remaining operations were kept deterministic. The resulting empirical distributions of lock transit time and fuel consumption were characterized through the mean, standard deviation, coefficient of variation, and selected percentiles (P5, P50, and P95) (Campbell *et al.*, 2007; Guan *et al.*, 2021).

The same scenario framework was used as a sensitivity-analysis strategy. Rather than varying each parameter independently across fixed percentage intervals, the analysis evaluates representative operational conditions reflecting different levels of delay and dispersion. This approach makes it possible to identify which operational conditions most strongly affect lock performance and energy consumption.

3.3 Model support and validation strategy

The model parameters were supported by lock operating rules, vessel characteristics, AIS-based speed observations, and nominal operational times derived from procedures and literature. Since this study focuses on methodological development, validation was based on internal consistency and plausibility checks rather than full empirical calibration.

The validation strategy comprised: (i) comparison of deterministic lockage times with reported operational expectations, (ii) verification that stochastic results reproduce plausible operational variability, (iii) consistency with benchmark studies on lock operations, and (iv) confirmation that sensitivity results follow physically and operationally coherent trends (Campbell *et al.*, 2007; Carroll; Bronzini, 1971; Rogers; Hofseth; Adams, 2012).

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3.4 Reliability-based capacity formulation

The stochastic formulation provides not only an estimate of the expected lockage time but also the probability distribution of the total transit time t_t. This distribution can be used to derive operational performance indicators relevant to waterway planning and capacity assessment.

Let $Q_\alpha(t_t)$ denote the α-quantile of the total lock transit time distribution obtained from the Monte Carlo simulation. For example, $Q_{50}(t_t)$ represents the median lock transit time, while $Q_{95}(t_t)$ corresponds to a conservative estimate that incorporates operational variability.

Based on this stochastic description, the annual operational capacity of the lock can be expressed as

$$K_\alpha = \frac{H}{Q_\alpha}(t_t), \tag{4}$$

where H is the total number of operational hours available per year and $Q_\alpha(t_t)$ is the corresponding percentile of the transit-time distribution. Thus, K_α represents the annual lock throughput associated with a reliability level α.

The effect of stochastic variability on capacity can be quantified by the relative capacity loss,

$$\Delta K_\alpha = \frac{K_{50} - K_\alpha}{K_{50}} \times 100\%. \tag{5}$$

This metric measures the reduction in effective annual capacity when a reliability-based planning criterion is adopted instead of a median-based estimate. The proposed formulation therefore links stochastic lock transit modeling directly to infrastructure planning and operational management.

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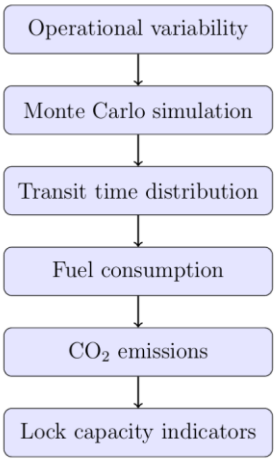
Figure 2 - Conceptual framework of the proposed stochastic model, showing how operational variability propagates through Monte Carlo simulation to transit time, fuel consumption, emissions, and lock capacity indicators



Source: Own elaboration

4 Case Study: Bariri Lock

4.1 Study area and operational relevance

The Bariri lock is one of the navigation locks located on the Tietê River section of the Tietê-Paraná Waterway and constitutes an important operational node in the inland navigation system of southeastern Brazil. Located at approximately kilometer 468 of the waterway, the lock integrates the navigation corridor that connects production areas in the interior of the country to intermodal logistics terminals and downstream export routes.

From an operational perspective, Bariri is particularly relevant because it represents the type of lock infrastructure that conditions the effective throughput of the corridor. Its chamber dimensions, together with the standard convoy configurations adopted on the Tietê-Paraná Waterway, require sequential lockage procedures for wider push-barge formations. As a result, the lock provides a representative case for evaluating how operational variability affects transit time, energy consumption, and effective capacity in Brazilian inland waterways.

4.2 Lock characteristics

The Bariri lock was commissioned in 1969 and is one of the six locks operating

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on the Tietê River. The facility operates continuously, except for scheduled maintenance periods, and serves both loaded and empty convoy movements along the corridor.

The main technical characteristics of the lock are summarized as follows:

1. Chamber length: 142 m.
2. Chamber width: 12 m.
3. Maximum lift: 25.3 m, depending on reservoir conditions.
4. Filling and emptying system: gravity-fed culverts embedded in the lock walls.
5. Typical chamber filling time: 12 -15 minutes.
6. Typical chamber emptying time: 10 -12 minutes.

Among these characteristics, the chamber width is the main operational constraint for convoy traffic. Because the standard BP2x2 convoy has a beam substantially larger than the chamber width, the complete unit cannot be transposed in a single lockage. This makes convoy dismemberment a necessary procedure and increases both the total lockage time and the operational complexity of the process.

4.3 Convoy configuration

The standard convoy formation considered in this study is the BP2x2 configuration, composed of one pusher and four barges arranged in two rows. Each barge has typical dimensions of approximately 60 m in length and 10.67 m in beam, yielding a total convoy length of about 137 m and an overall beam of 21.34 m (Silva, 2015). Under usual operating conditions, this convoy configuration is widely used for bulk cargo transportation on the Tietê-Paraná Waterway.

Since the Bariri lock chamber is only 12 m wide, the BP2x2 convoy must be temporarily divided into two BP1x2 units before lock transit. After the first unit is transposed, the pusher returns to collect the remaining barges, repeating the procedure for the second unit. Once both units have passed through the lock, the convoy is reassembled downstream and resumes navigation. This operational requirement makes Bariri a particularly appropriate case for studying stochastic variability in lock operations, because the sequence of maneuvers, mooring operations, and recoupling stages increases the number of time-dependent processes involved in each transit.

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4.4 Case-study relevance for the proposed framework

The choice of the Bariri lock as case study is justified by three main factors. First, it is representative of the operational constraints observed in the Tietê-Paraná Waterway, particularly those associated with chamber width limitations and convoy dismemberment. Second, the lock plays an important role in the continuity of navigation along the corridor, so local delays may propagate through the broader logistics chain. Third, its operational configuration provides a suitable setting for testing a stochastic modeling framework capable of linking procedural variability to system-level indicators such as fuel consumption, emissions, and annual lock capacity.

For these reasons, the Bariri lock offers a robust empirical context for evaluating the proposed Monte Carlo framework and for discussing how operational improvements may contribute to more reliable and efficient inland waterway transport.

5 Results and discussion

5.1 Lock transit time distribution and operational reliability

Figure 3 presents the probability density functions of total lockage time obtained from the Monte Carlo simulations for the six operational scenarios. The results indicate that lockage time varies approximately between 6 and 7 h, depending on the operational conditions associated mainly with mooring-related activities. Scenarios A, B, and F are centered around 6 h, whereas scenarios C and D are shifted toward approximately 7 h due to longer mooring times. Scenario E occupies an intermediate position, with mean lockage time close to 6.7 h.

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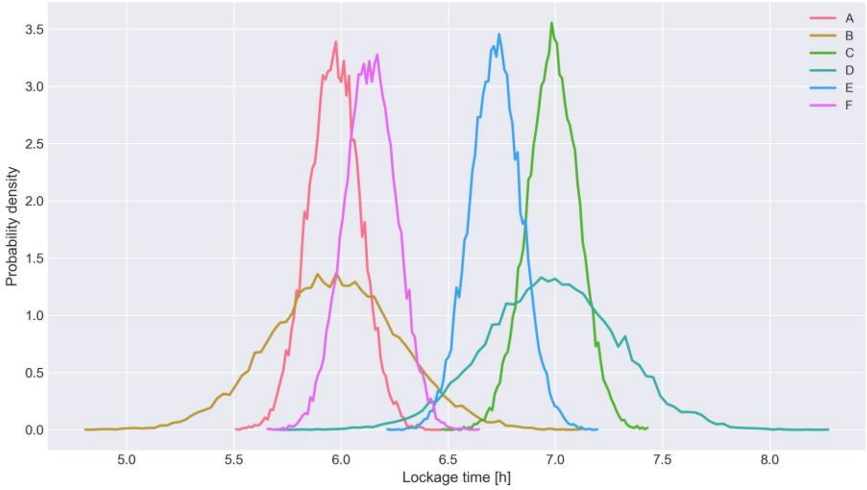
Figure 3 - Probability density functions of total lockage time obtained from Monte Carlo simulations for the six operational scenarios. Differences in location and spread reflect changes in the mean and dispersion of mooring-related operations



Source: Own elaboration

As expected, scenarios with larger dispersion in the stochastic inputs produce wider density functions and lower peak values, indicating higher operational uncertainty. Since mooring time was modeled as the dominant random component, the resulting lockage-time distributions remain approximately Gaussian, with means shifted according to the adopted scenario conditions. This result confirms that the stochastic representation captures not only changes in expected performance but also changes in predictability.

Figure 4 compares the deterministic lockage times with the Monte Carlo mean values and their corresponding P5-P95 intervals. The deterministic solution closely matches the simulated mean in all scenarios, indicating that the deterministic model provides an unbiased estimate of expected lockage time. However, the stochastic model reveals substantial differences in uncertainty across scenarios, particularly in B and D, which exhibit the widest percentile intervals.

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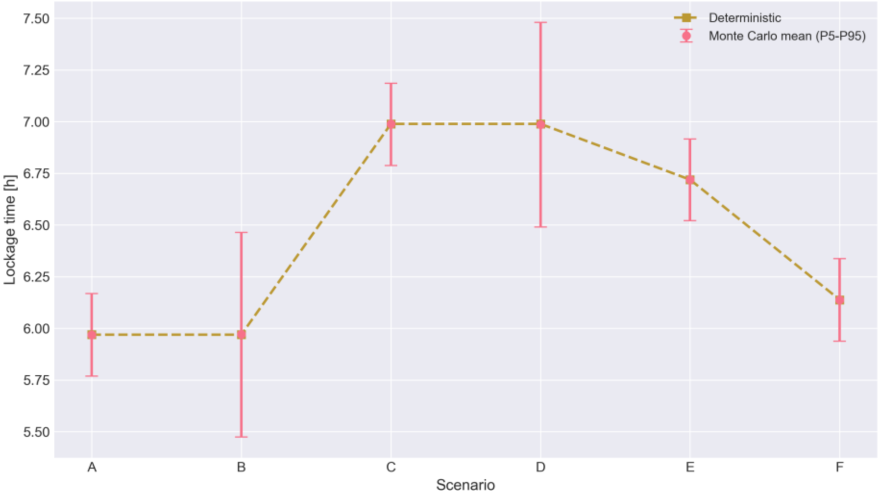
Figure 4 - Comparison between deterministic lockage-time estimates and Monte Carlo results. Error bars represent the P5-P95 interval, illustrating the effect of operational variability on lockage reliability



Source: Own elaboration

This distinction is operationally relevant because scenarios with similar mean lockage times may differ considerably in reliability. In practical terms, lower average transit time does not necessarily imply more reliable operations if dispersion remains high. This result is consistent with earlier studies showing that service-time variability is a critical determinant of effective lock performance and cannot be adequately represented by purely deterministic approaches (Rogers; Hofseth; Adams, 2012; Wilson, 1978).

To quantify reliability, the Lock Reliability Index (LRI) was defined as

$$LRI = \frac{P_{95} - P_5}{P_{50}}, \tag{6}$$

where P_5, P_{50}, and P_{95} denote the 5th percentile, median, and 95th percentile of the lockage-time distribution, respectively. Lower values of (LRI) indicate more stable and predictable operations.

Table 4 shows the estimated values of the reliability index across scenarios. Scenarios C and E present the lowest LRI values, indicating lower normalized dispersion despite their longer average lockage times. By contrast, scenarios B and D show the highest values, confirming that increased variability in mooring time significantly reduces operational reliability.

Table 4 - Estimated lock reliability index across scenarios

Scenario	$P_5[h]$	$P_{50}[h]$	$P_{95}[h]$	LRI
A	5.77	5.97	6.17	0.067
B	5.47	5.97	6.47	0.168
C	6.78	6.99	7.19	0.059
D	6.49	6.99	7.48	0.142
E	6.52	6.72	6.91	0.058
F	5.94	6.14	6.34	0.065

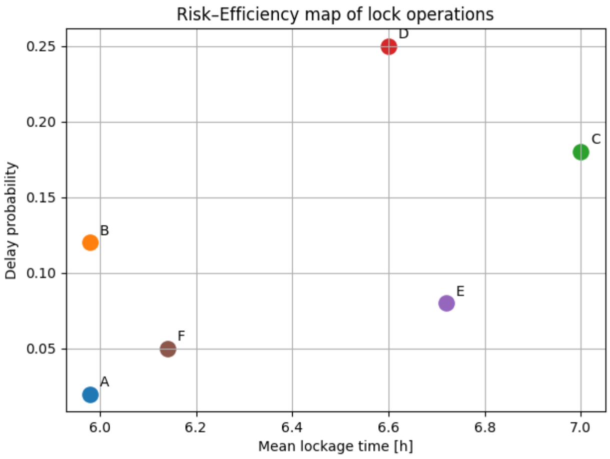
Source: Own elaboration

To complement the percentile-based analysis, Figure 5 presents a risk-efficiency map relating mean lockage time to the probability of delay, defined as

$$P_{delay} = P(T > T_c), \tag{7}$$

where T_c is a critical threshold. In this study, a threshold of 7 h was adopted to represent lockage durations associated with relevant operational delay. The figure shows that scenarios A, B, E, and F maintain low delay probability, whereas scenario D combines high average time with high uncertainty and therefore represents the least favorable operating condition.

Figure 5 - Risk-efficiency map relating mean lockage time to delay probability $P(T > T_c)$ for the six scenarios, with $T_c = 7\ h$ adopted as the critical operational threshold



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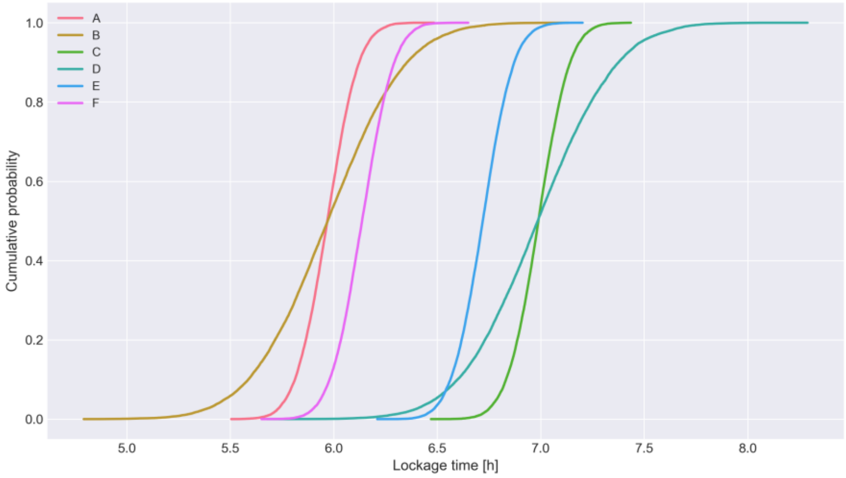
From a management perspective, the risk map suggests different improvement priorities depending on the scenario. In D, efforts should focus on reducing operational variability through standardized mooring routines, crew training, and better coordination between convoy operators and lock personnel. In C, by contrast, the process is relatively stable but slow, indicating that reducing systematic delays may be more effective than focusing on variability alone.

Figure 6 shows the cumulative distribution functions of lockage time. The curves confirm the same three operational regimes already identified in the density plots: faster scenarios (A, B, F), intermediate scenario (E), and slower scenarios (C, D). The steeper slopes of A, C, E, and F indicate lower dispersion, whereas B and D exhibit flatter curves associated with higher operational uncertainty.

Figure 6 - Cumulative distribution functions of total lockage time for the six operational scenarios, showing differences in completion probability and operational reliability



Source: Own elaboration

Using the same threshold $T_c = 7\ h$, service reliability was defined as

$$SR = P(T \leq T_c) = F(T_c). \tag{8}$$

The results indicate that scenarios A, B, and F have very high service reliability, with probabilities close to unity of completing lockage within the specified threshold. Scenario E also shows high reliability, whereas scenarios C and D have substantially lower probabilities, indicating a much higher likelihood of delay. Together, these results reinforce the importance of evaluating the full transit-time distribution rather than relying solely on mean values.

5.2 Comparative scenario performance

Table 5 summarizes the main performance indicators for the six scenarios, including mean lockage time, standard deviation, percentile bounds, reliability index, fuel consumption, fuel rate, and CO_2 emission rate. The table consolidates the main trends observed in the previous figures.

Table 5 - Comparative performance indicators for the simulated lockage scenarios

Scenario	Mean time [h]	Std [h]	P5 [h]	P95 [h]	LRI	Fuel [L]	Fuel rate [L/h]	CO_2 rate [kg/h]
A	5.968	0.122	5.768	6.168	0.067	366.803	61.47	165.41
B	5.971	0.301	5.474	6.464	0.166	366.896	61.47	165.41
C	6.988	0.121	6.787	7.186	0.057	403.526	57.75	155.45
D	6.986	0.304	6.490	7.480	0.142	403.450	57.74	155.45
E	6.719	0.120	6.521	6.916	0.059	393.837	58.60	157.79
F	6.137	0.122	5.937	6.337	0.065	284.026	46.29	124.62

Source: Own elaboration

Two main patterns emerge. First, the effects of variability and the effects of systematic delay are distinct. Scenarios A and B have nearly identical mean lockage times but very different standard deviations and LRI values. Likewise, scenarios C and D have similar means but markedly different uncertainty levels. Second, scenario F stands out as the most energy-efficient operating condition, with both low dispersion and substantially lower fuel use.

These results show that lock performance should be assessed through multiple indicators rather than by average transit time alone. In this respect, the present findings align with the broader literature on lock-service modeling, which emphasizes that effective operational performance depends on both expected cycle time and its variability (Caljouw, 2015; Daggett; Ankeny, 1975).

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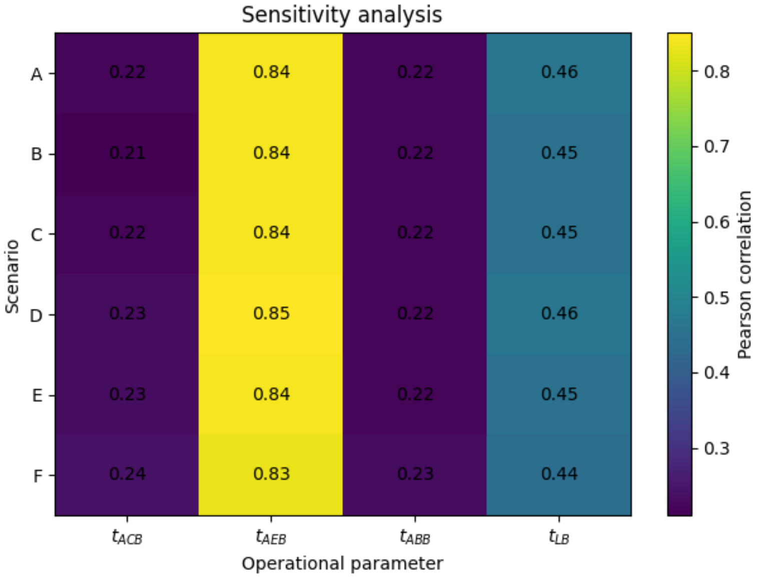
5.3 Sensitivity analysis

The sensitivity analysis indicates that t_{AEB} is the dominant operational parameter controlling total lockage time, with Pearson correlation coefficients close to 0.84 in all scenarios. As shown in Figure 7, the uncertainty associated with this mooring-related parameter is the main source of variability in the lockage process.

Figure 7 - Sensitivity heatmap for total lockage time, showing the relative influence of the main stochastic parameters across the simulated scenarios



Source: Own elaboration

The release-time parameter t_{LB} exhibits a secondary influence, with average correlation values around 0.45. By contrast, t_{ACB} and t_{ABB} present substantially lower correlations, approximately 0.22-0.23, indicating a more limited contribution to total lockage-time dispersion. This ranking remains stable across all scenarios, suggesting that the dominant sensitivity pattern is robust under different assumptions of delay and variability.

Figure 8 complements this result by showing the sensitivity of mean lockage time to the main operational parameters. Together, these findings indicate that the most effective performance-improvement strategies should focus on reducing both the mean value and the variability of t_{AEB}, while secondary gains may be obtained through optimization of t_{LB}.

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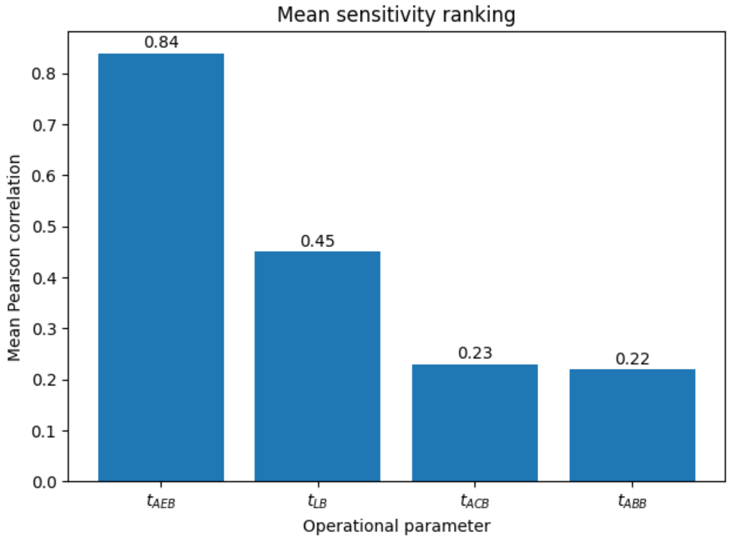
Figure 8 - Sensitivity of mean lockage time to the main operational parameters, highlighting the dominant contribution of mooring-related stages



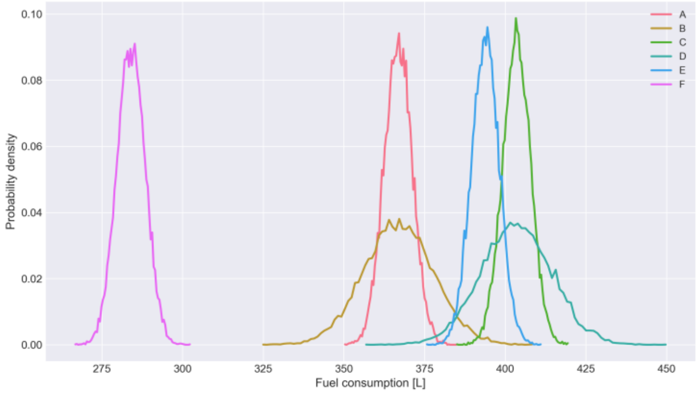
Source: Own elaboration

From an operational perspective, this result is particularly relevant because it isolates the mooring stage as the key bottleneck in the convoy-dismemberment context of Bariri. Unlike broader network models, which often emphasize traffic interactions or vessel sequencing, the present case highlights the dominant role of local operational procedures in determining effective lock performance.

5.4 Fuel consumption, emissions, and capacity implications

Figure 9 presents the probability density functions of total fuel consumption for the six scenarios. Three energy regimes can be identified. Scenario F is clearly the most efficient, with a distribution centered around $284\ L$. Scenarios A and B form an intermediate group near $367\ L$, while scenarios C, D, and E represent the highest-consumption regime, centered between approximately 390 and $410\ L$.

Figure 9 - Probability density functions of fuel consumption during lockage operations for the six operational scenarios, illustrating the impact of operational variability on energy demand



Source: Own elaboration

The width of the fuel-consumption distributions reflects the same pattern observed for lockage time. Scenarios B and D exhibit broader distributions and therefore greater operational uncertainty, whereas A, C, E, and F show narrower curves and more stable behavior. Since propulsion remains active during maneuvering and waiting stages, longer and more uncertain operations directly translate into higher energy demand. The contrast between the most and least efficient operating regimes is substantial. The difference between scenario F and scenarios C-D is approximately

$$\Delta F \approx 403 - 284 \approx 119\,L$$

per lockage. Assuming 3000 lockage operations per year, the corresponding annual fuel savings would be approximately

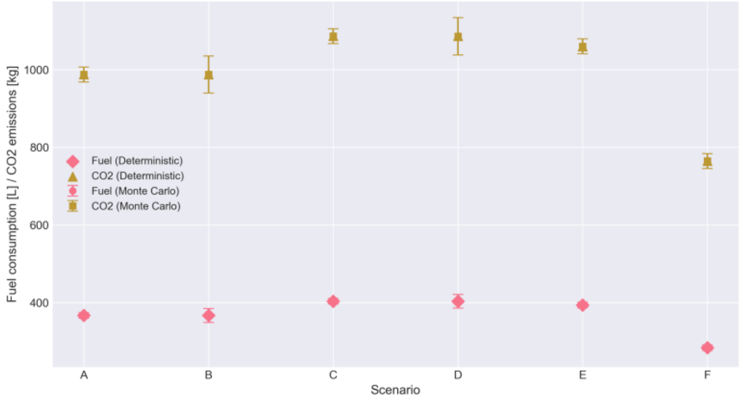
$$\Delta F_{annual} \approx 3000 \times 119 \approx 3.6 \times 10^5\,L.$$

Using an emission factor of $2.68\,kgCO_2/L$, this corresponds to a potential annual reduction of approximately

$$\Delta CO_2 \approx 9.6 \times 10^5\,kgCO_2,$$

or about 960 tonnes of CO_2. These values highlight that operational improvements in lockage procedures may generate not only logistical gains but also relevant energy and environmental benefits. Figure 10 compares deterministic and Monte Carlo results for fuel consumption and corresponding CO_2 emissions. In all scenarios, deterministic values are very close to the simulated means, but the stochastic approach reveals the uncertainty bands associated with operational variability. Again, scenarios B and D show the largest P5-P95 intervals, indicating greater sensitivity to uncertain operating conditions.

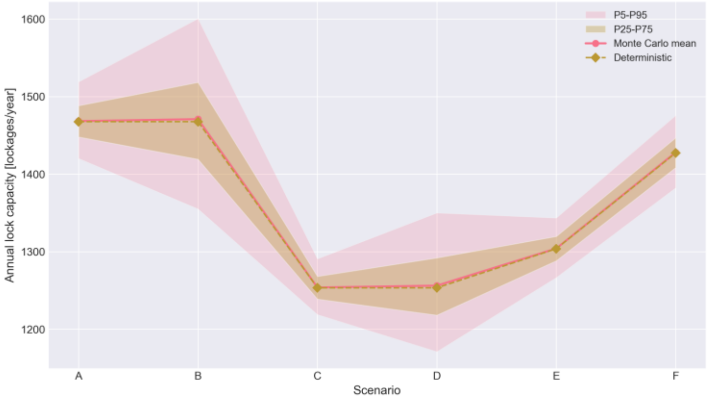
Figure 10 - Comparison between deterministic estimates and Monte Carlo simulation results for fuel consumption and associated CO_2 emissions. Error bars represent the P5-P95 range



Source: Own elaboration

Figure 11 shows the annual lock capacity obtained for the different scenarios. The deterministic values closely match the Monte Carlo means, but the stochastic results reveal significant differences in uncertainty. Scenarios A and B produce the highest annual capacities, close to 1465 lockages per year, whereas scenarios C and D yield the lowest values, around 1250 lockages per year. The total variation between the highest and lowest capacity regimes is approximately 215 lockages per year, corresponding to nearly 17 % of annual throughput.

Figure 11 - Annual lock-capacity fan chart for the simulated scenarios. Shaded regions indicate the interquartile range (P25-P75) and the broader uncertainty interval (P5-P95)

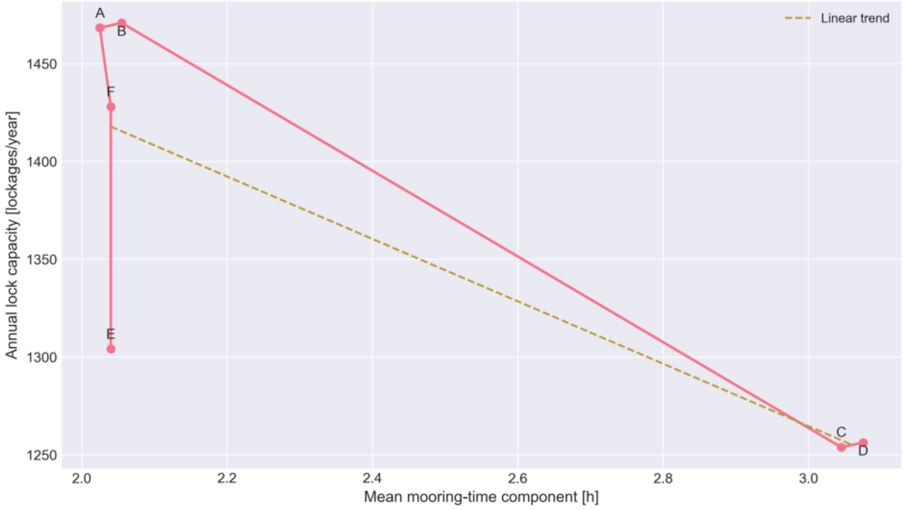


Source: Own elaboration

These results show that effective lock capacity is not determined solely by chamber dimensions or annual operating hours, but also by the efficiency and predictability of operational procedures. This interpretation is consistent with the distinction between nominal and effective capacity emphasized in the lock-operations literature (Daggett; Ankeny, 1975).

Finally, Figure 12 illustrates the relationship between annual lock capacity and the mean mooring-time component. A clear negative relationship is observed: as mean mooring time increases, the number of lockages that can be performed per year decreases. The approximately linear trend indicates that, within the analyzed operational range, lock capacity responds elastically to changes in mooring duration.

Figure 12 - Relationship between annual lock capacity and mean mooring time across the simulated scenarios, indicating the sensitivity of throughput to changes in mooring duration



Source: Own elaboration

Scenarios A and B, with mean mooring times near $2.0\ h$, achieve the highest capacities, whereas scenarios C and D, with mean mooring times slightly above $3.0\ h$, exhibit the lowest throughput. The total difference is approximately $\Delta C \approx 1470 - 1250 \approx 220$ lockages per year, corresponding to a reduction of roughly 15 % in annual capacity. From an operational standpoint, this confirms that mooring is not merely one stage of the process, but a critical control variable governing infrastructure throughput.

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Overall, the results show that operational variability propagates through multiple layers of the system. Variations in mooring time affect the distribution of lock transit time, which in turn influences fuel consumption, CO_2 emissions, and annual lock capacity. This chain of propagation demonstrates that relatively small uncertainties in local operational procedures can produce measurable impacts on both logistics performance and environmental outcomes in inland waterway systems.

6 Conclusions and future work

Efficient management of inland navigation locks is essential for ensuring the reliability and sustainability of waterway transport systems. This study developed a stochastic modeling framework to analyze push–barge convoy lockage operations at the Bariri lock on the Tietê-Paraná Waterway, combining deterministic operational modeling with Monte Carlo simulation in order to quantify the impact of operational variability on lock transit time, fuel consumption, CO_2 emissions, and annual lock capacity.

Deterministic formulations alone cannot represent the uncertainty associated with real operational conditions. The Monte Carlo approach allows the full probability distribution of lockage time to be obtained, enabling the estimation of risk percentiles and reliability indicators that are relevant for operational planning and infrastructure management.

This approach is aligned with established practices in fields such as transportation engineering and logistics, where conceptual models and simulation-based methods (e.g., stochastic modeling and scenario analysis) are widely used to explore the solution space prior to the availability of robust observational datasets.

The analysis demonstrates that operational variability plays a central role in determining the performance of lock operations. In particular, the sensitivity analysis indicates that the mooring stage is the contributor to lockage time variability. Variations in this parameter significantly affect the dispersion of transit times and therefore the predictability of lock operations. As a result, scenarios with similar mean lockage times may present substantially different reliability levels, highlighting the importance of evaluating the entire distribution of operational outcomes rather than relying solely on average values.

The stochastic simulations also reveal the strong relationship between operational efficiency and energy consumption. Longer maneuvering and waiting times increase the duration during which propulsion systems remain active, leading to higher fuel consumption and CO_2 emissions. The comparison between operational scenarios shows that differences in operational conditions may produce variations of approximately $120\,L$ of fuel per lockage operation. Assuming approximately 3000 lockages per year, this difference corresponds to potential annual savings of about $3.6 \times 10^5\ L$ of fuel and a reduction of nearly 960 tonnes of CO_2. These results highlight that improvements in operational efficiency can simultaneously enhance logistical performance and environmental sustainability in inland waterway transport systems.

Another important contribution of this study is the translation of operational variability into annual lock capacity estimates. The results show that the effective throughput of the lock may vary by approximately 15-17 % depending on operational conditions. This finding indicates that lock capacity is not determined solely by physical infrastructure characteristics, but also by the efficiency and variability of operational procedures. In particular, the elasticity analysis reveals a clear negative relationship between mean mooring time and annual lock capacity, identifying the mooring stage as one of the main operational bottlenecks in the lockage process.

From a scientific perspective, this work contributes to the literature on inland waterway transport by proposing a stochastic modeling framework capable of linking operational variability to energy consumption, environmental emissions, and infrastructure capacity. The methodology demonstrates how Monte Carlo simulation can be used to derive percentile-based performance indicators, providing a more comprehensive representation of lock operations than deterministic approaches alone. In addition, the results highlight the importance of integrating operational efficiency, environmental performance, and infrastructure capacity within a unified analytical framework.

Despite these contributions, some limitations should be acknowledged. The operational parameters adopted in the simulations are based on typical procedures observed in the Tietê-Paraná Waterway, but the model has not yet been calibrated using detailed empirical datasets.

An additional limitation of the proposed framework concerns the interpretation of the sensitivity results. Although the analysis identifies mooring time as the dominant factor controlling lockage-time variability, this dominance is partially influenced by the uncertainty structure imposed in the model formulation. In particular, stochastic variability was explicitly assigned only to mooring-related operations, while other operational stages were treated as deterministic.

As a consequence, the relative importance of mooring time may be amplified by the modeling assumptions, rather than reflecting exclusively the intrinsic physical or operational behavior of the system. Therefore, the sensitivity results should be interpreted as conditional on the adopted stochastic structure, representing a scenario-based assessment rather than a fully data-driven attribution of variability sources.

Additional extensions of the proposed framework may include the incorporation of vessel arrival processes and queueing effects, if it is necessary, as well as network-level analyses involving multiple locks along inland waterway corridors. Integrating optimization techniques with the stochastic simulation framework may also enable the development of decision-support tools for lock scheduling and convoy dispatching. Finally, future studies could extend the model to evaluate broader economic and environmental impacts associated with operational improvements in inland waterway systems.

Overall, the results demonstrate that operational variability is a key determinant of lock performance, influencing transit time reliability, energy consumption, emissions, and effective infrastructure capacity. By incorporating stochastic analysis into lock operation modeling, the proposed framework provides a more realistic representation of inland waterway systems and offers valuable insights for infrastructure management, operational planning, and sustainable logistics strategies.

As a result, the model outcomes should be interpreted as conditional on the adopted structural assumptions, rather than as a complete representation of all sources of uncertainty present in real operations. This implies that part of the

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observed variability—and the dominance of specific parameters—may reflect the modeling structure itself.

Future research should address the current limitations by extending the stochastic representation to additional operational components and calibrating the uncertainty structure using empirical data, thereby enabling a more comprehensive assessment of the relative contribution of different processes to lockage-time variability. In this context, validation of the proposed framework using real operational data—such as time-motion measurements of lock operations, AIS vessel tracking records, and operational logs from lock management authorities—will be essential to refine probabilistic parameters and enhance the predictive capability of the model. Furthermore, future developments should explore alternative model structures, incorporate additional stochastic elements, and compare different formulations in order to assess the robustness of the results and improve the overall representativeness of the system.

Finally, it is emphasized that the present model represents an initial stage in the scientific process and may be further refined through calibration and validation using real data, thereby enhancing its predictive capability without compromising its conceptual structure.

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