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DECISION-MAKING ON STRATEGIES FOR LIFE EXTENSION OF SHIPS IN THE BRAZILIAN NAVY USING A TECHNO-ECONOMIC ANALYSIS APPROACH

by

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LIST OF ACRONYMS AND ABBREVIATIONS

BCR	Benefit-Cost Ratio
BN	Brazilian Navy
CapEx	Capital Investment Expenditures
CBA	Cost-Benefit Analysis
CDF	Cumulative Distribution Function
CO_2	Carbon Dioxide
DGePM	Navy Program Management Directorate
EOL	End-of-Life
FMS	Foreign Military Sales
GDP	Growth Domestic Product
HM&E	Hull, Mechanical, and Electrical
IHM	Inventory of Hazardous Materials
IPEA	Instituto de Pesquisa Econômica Aplicada
LCB	Life Cycle Benefits
LCC	Life Cycle Costs
LE	Life Extension
ManEx	Maintenance Expenditure
NAM	Navio-Aeródromo Multipropósito (Multipurpose Aircraft Carrier)
NPV	Net Present Value
OpEx	Operational Expenditure
RiskEx	Risk Expenditure
SSC	System-Structure-Component
WD	Weibull Distribution

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I. INTRODUCTION

The imperative to extend the service life of naval vessels has become increasingly critical amid budgetary constraints and the essential goal of maintaining fleet readiness. Liu et al. (2021) highlight the economic pressures stemming from the escalating costs of constructing new ships, positing that comprehensive maintenance actions are crucial for existing ships to safely continue service beyond their initially designed life. Similarly, Ramírez and Utne (2015) recognize the challenges posed by aging systems as the systems approach their designed service termination, emphasizing the necessity of strategic decisions to extend their operational lifespan.

As ships reach their designed end-of-life (EOL), important decisions must be made regarding their continued operation. Liu et al. (2020) note that uncertainties in structural functioning due to stressors like corrosion and fatigue can complicate assessments. They further argue that despite these challenges, the extension of a ship's service life beyond its intended duration emerges as a strategically viable option to alleviate the significant expenses involved in fleet renewal. Therefore, it becomes crucial to plan the extension of a ship's service life in a manner that is cost-effective and ensures the fleet's reliability.

Historically, decisions about extending the life or replacing equipment were made subjectively, relying on experts' judgements (Animah et al., 2018). Brown and Willis (2006) explain, though, that life extension (LE) strategies need to be assessed for their economic viability and risk-mitigation, which would depend more on quantitative or empirical data. The proposed framework aims to support decision-making by integrating reliability concepts, probability failure predictions, and cost-benefit analysis (CBA). This techno-economic model combines technical evaluations focused on prioritization and failure forecasting with economic assessments of costs and benefits. Ultimately, the framework intends to enhance operational readiness while observing budget constraints by providing decision-making support to the Brazilian Navy (BN) in evaluating various LE strategies for its ships.

A. BACKGROUND

The BN has been facing challenges related to its aging fleet. For planning purposes, warships are typically projected to have a useful life of 30 years (Brito, 2020). Registers show, in Figure 1, that over half of the BN's vessels, consisting of frigates, corvettes, and patrol boats, have surpassed the designed 30-year service life (Marinha do Brasil [BN], 2023a).

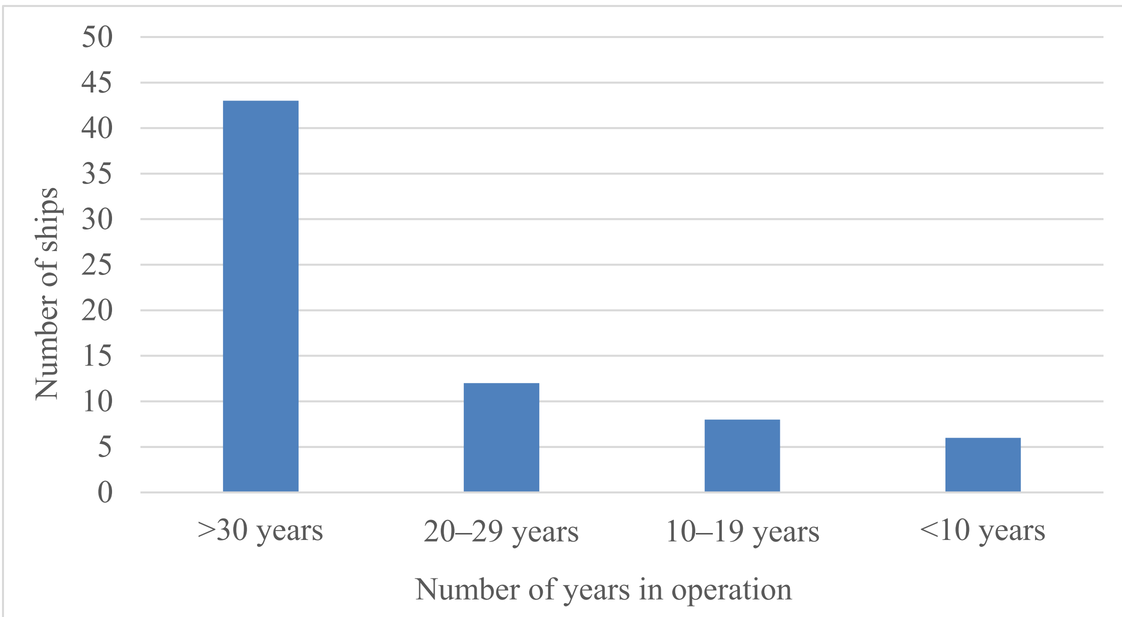

Figure 1. Operational Age of Brazilian Navy Ships.
Source: BN (2023a).

Maintaining a modern and capable naval fleet is essential for nations to ensure maritime sovereignty and security. Yet, budget constraints and rapid technological advancements challenge this goal, potentially compromising the BN's readiness by increasing maintenance issues and failure rates without timely asset upgrades or replacements. This situation is exacerbated as the maintenance and repair costs of aging equipment rise, alongside difficulties in sourcing replacement parts, risking obsolescence and compatibility issues with newer systems, as observed by Brown and Willis (2006). Recognizing these challenges, the BN has undertaken the Tamandaré Frigate Class

Program as part of its broader modernization initiative, aimed at enhancing deterrence capabilities while safeguarding national sovereignty and vital resources (BN, 2023b). However, Melese and Solomon (2015) emphasize that such initiatives require significant long-term investments, underlining that the influence of government deficits and debts on military spending is inescapable.

Acknowledging the substantial costs associated with acquiring new vessels, a pragmatic strategy of blending LE programs with the acquisition of new assets could be a financially sound approach. This practice, far from being innovative, mirrors strategies employed by other navies, underscoring its effectiveness and practicality. The U.S. Navy's decision to approve service LE for four Arleigh Burke–class destroyers exemplifies this approach, demonstrating a balance between enhancing operational capabilities and managing fiscal constraints (U.S. Navy, 2023).

B. RESEARCH QUESTIONS

- What is the current state of research related to LE strategies of aging assets?
- What are the key issues and challenges currently faced in the field of asset LE?
- How can a techno-economic model be effectively applied to assess and inform LE strategies for BN's maritime assets, ensuring operational readiness and economic viability?
- What criteria should be included in a techno-economic framework to effectively balance technical reliability and economic feasibility in the LE of BN's naval ships?
- What directions should future research on asset LE take to address existing gaps and emerging challenges?

To answer these questions, a techno-economic analysis is performed to identify the most suitable strategy for ships reaching their designed EOL to provide decision-making support to the BN. The suggested method not only helps decision-makers identify the most appropriate strategy but also enables those in charge of operations to lower the costs involved in prolonging the service life of assets.

C. SCOPE

Given budget constraints, evolving mission requirements, and the need to maintain fleet readiness, this thesis aims to contribute to this domain by presenting a techno-economic framework designed to support decision-making processes related to service LE for ships, with a particular focus on the BN.

To lay the foundational concepts, this research delineates the current landscape of asset LE across various industries. Identifying the main issues and challenges in asset LE programs becomes the next focal point, especially the inherent complexity of ships, alongside budgetary and operational hurdles. This involves a comprehensive literature review to understand the methodologies, technologies, and strategies employed to prolong the operational life of assets. This review informs the creation of an LE framework that is both theoretically sound and practically applicable.

At the core of this thesis is the development of a techno-economic framework to be applied to a case study within the BN. This framework aims to support decision-making processes by integrating reliability concepts and probability failure predictions for the technical analysis, alongside CBA for the economic assessment. This approach aims to ensure that decisions regarding the LE of ships are made with a balanced view of technical viability and economic rationality. Also, the thesis proposes directions for future research on asset LE to address existing gaps and emerging challenges.

II. LITERATURE REVIEW

The following literature review provides insights into technical and economic aspects related to LE strategies. The studies address the necessity of integrating economic and technical analyses to make informed decisions on extending the service life of naval ships, with a focus on achieving a balance between ensuring technical reliability, economic feasibility, and adherence to sustainability principles. However, the literature reviewed does not address these challenges to the BN's context.

A. LIFE EXTENSION OF SHIPS

1. Technical Challenges

Extending the service life of naval ships involves technical challenges, especially corrosion and fatigue, which significantly affect their structural integrity over time. Liu et al. (2020) emphasize that engineers should understand the degradation mechanisms that compromise ship structures. This deep understanding is crucial for developing effective inspection and maintenance strategies that can impact the cost and feasibility of LE initiatives. However, the unpredictability of structural performance due to these degradation processes introduces a substantial amount of uncertainty into the decision-making process for extending the service life of ships.

In response to these challenges, a shift toward data-driven approaches is observed in the literature. For instance, predictive maintenance models discussed by Begovic et al. (2006) employ statistical techniques, including the Weibull distribution and Monte Carlo simulations, to bolster maintenance reliability and support informed LE decisions. Complementarily, Roy et al. (2023) demonstrate U.S. Navy initiatives into the application of artificial intelligence and artificial neural networks to enhance structural integrity assessments, thereby refining the accuracy of evaluations and optimizing maintenance and repair schedules. This trend toward adopting technology and data-driven methodologies signifies a pivotal advancement in the realm of naval ship LE, blending sophisticated analytics with traditional engineering insights to address the challenges of extending asset service life.

Concurrently, environmental sustainability emerges as a paramount concern, as evidenced by the 2009 Hong Kong Convention, which mandates a comprehensive inventory of hazardous materials (IHM) on ships, as highlighted by Chockalingam et al. (2022). This legislation mandates aligning LE practices with the principles of the circular economy, aimed at sustainability. Effective management of the life cycle of naval assets, in adherence with these environmental standards, enables the optimization of existing resources, restricts the environmental footprint of the fleet, and sustains operational readiness within the economic boundaries of the Brazilian economy.

2. Life Extension Strategies

Although deciding on a strategy can be challenging, there are four main strategies for extending the life of naval assets. As per Morey et al. (2021), the decision-making process for LE is complex, primarily because it involves assets that are not only intricate and have long lifespans but are also capital-intensive and have lengthy replacement lead times. Additionally, these assets are often crucial for achieving an organization's objectives, further complicating the decision-making process. Still, Shafiee and Animah (2017) provide a valuable classification of these strategies, delineating them into four primary categories: replace, reuse, remanufacture, and repair. Each strategy presents a unique set of economic and technical considerations that are pivotal in guiding decision-making processes, as shown in Table 1.

Table 1. Life Extension Strategies.
Adapted from Shafiee and Animah (2017).

Life Extension Strategies	Description
Reuse	Defined as the continued operation of equipment or components until the end of their economic life. This strategy is economically appealing in the short term but demands careful assessment of the risks associated with aging assets, including increased failure rates and maintenance challenges.
Refurbishment	Extends the life of a system by restoring it to nearly new condition. This process may involve partial replacement, reconditioning, and redesigning.
Repair	Focuses on restoring a system to a functional condition, either proactively or reactively, and is typically less costly than replacement or refurbishment. Repair strategies must consider the availability of parts, and the impact on downtime.
Replacement	Involves substituting existing assets with new ones. This strategy, while potentially offering the highest level of reliability, requires significant investment, making the economic implications an important consideration. The decision to replace must weigh the costs against the benefits of extended asset availability and performance.

B. COST-BENEFIT ANALYSIS

CBA is a useful tool in the evaluation and decision-making process for ship LE projects. Boardman et al. (2018) characterize CBA as a technique for evaluating projects or investments weighing monetary impacts against optimal resource allocation. This analysis is critical in navigating the complexities of large-scale LE projects, where financial resources are limited and the potential for significant societal impact is high.

Incorporating CBA into the decision-making process for LE offers a holistic scrutiny of available pathways, considering not just the immediate financial implications but also the long-term environmental, social, and functional ramifications. Liu et al. (2020) emphasize the importance of considering factors such as deterioration rates, life cycle risks, and maintenance costs in this calculus. By enabling the identification of LE methodologies that yield the most beneficial investment returns, CBA ensures that choices uphold not only technical feasibility but also economic prudence and strategic congruence with the organization's broader objectives.

C. TECHNO-ECONOMIC FRAMEWORK

The development of a techno-economic framework for ship LE assessment is essential for bridging the gap between determining technical reliability and economic feasibility. This integrated approach considers the direct and indirect costs associated with maintenance, upgrades, and operational adjustments alongside the technical requirements of extending asset life. By aligning technical assessments with economic analysis, decision-makers can navigate the complexities of LE more effectively.

Within the CBA process, the use of financial indicators such as net present value (NPV) and benefit-cost ratio (BCR) supports the evaluation of the economic viability of LE projects. According to Animah et al. (2018), these indicators guide companies in assessing the financial outcomes of LE strategies, guiding organizations toward more profitable decisions. For the BN, employing a techno-economic framework equipped with financial metrics can facilitate more informed, strategic decisions, enhancing the operational readiness of its fleet.

D. KEY LEARNING POINTS FROM LITERATURE REVIEW

The literature review reveals the importance of adopting an integrated techno-economic approach to address the challenges of LE of naval ships, especially for the naval context amid budget constraints and the pressing need to sustain fleet readiness. In addressing the specific needs of the BN maritime assets, applying a techno-economic model could help balance technical reliability and economic viability. Such a model must incorporate criteria that account for the unique operational contexts of naval ships, including risk management, environmental impacts, and compliance with international maritime regulations. While previous studies have offered economic and technical analyses to inform life-extending decisions for naval ships, no studies have tailored these analyses to the BN context. Therefore, the main focus of this study is developing a techno-economic framework to support the decision-making process in LE strategies applicable to the BN.

III. METHODOLOGY

This chapter outlines a techno-economic model tailored for assessing LE strategies for ships, structured into three phases: preparation, analysis, and decision-making. It employs a dual-module assessment approach: technical (focusing on reliability and failure prediction) and economic (conducting a thorough benefit and cost analysis). This model is set to guide asset managers, particularly within the BN, in making informed decisions for extended maritime asset operations.

A. TECHNO-ECONOMIC MODEL

For the evaluation of LE strategies for naval vessels, this study adapts the model proposed by Animah et al. (2017) to evaluate LE strategies for naval vessels, as depicted in Figure 2. The framework is divided into three phases: 1) preparation for LE strategies; 2) techno-economic analysis of LE strategies, and 3) decision-making and implementation. The main tasks in each of the phases are described in the following sub-sections.

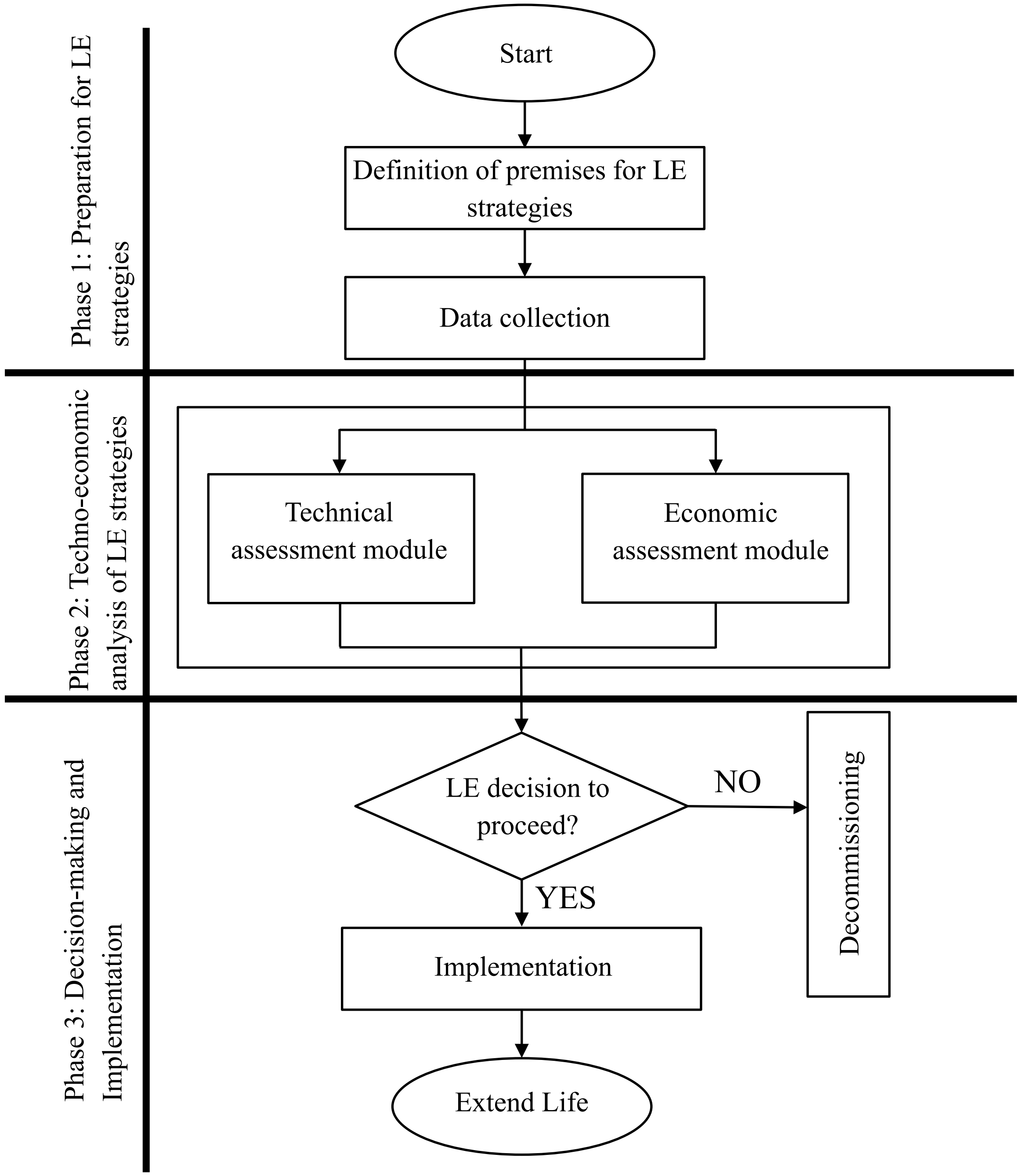

Figure 2. Framework for LE Strategies for Ships.
Adapted from Animah et al. (2017).

1. Phase 1: Preparation for LE Strategies

This stage involves defining the basis for EOL and gathering relevant data of the asset being evaluated.

a. Definition of Premises for EOL Strategies

The initial step in the model is to clearly define the objectives at the outset of an LE process, ensuring these goals align with the expectations of all stakeholders involved in the extended use of the assets. In the context of the BN, the stakeholders include naval command and leadership, responsible for strategic planning and future utility of the asset; government, responsible for approval, policy guidance, and budget; and engineering teams, responsible for the technical assessment of the ship's condition.

b. Data Collection

This research is unclassified and employs various parameters designed to estimate values within the model. To ensure the assessment is applicable to real-world scenarios, data inputs (such as ships' designs), operational records, maintenance history, and other relevant data were obtained from subject matter experts from the Navy Program Management Directorate (DGePM–BN), responsible for the life cycle management of the BN fleet. Supplementary data were obtained from research in the literature. A summary of the main data utilized is presented in the application case.

2. Phase 2: Techno-Economic Analysis of LE Strategies

The second phase is composed of two steps: (i) technical assessment module, which studies prioritization and failure prediction, and (ii) economic assessment module, which examines the monetary added value of LE, as shown in Figure 3.

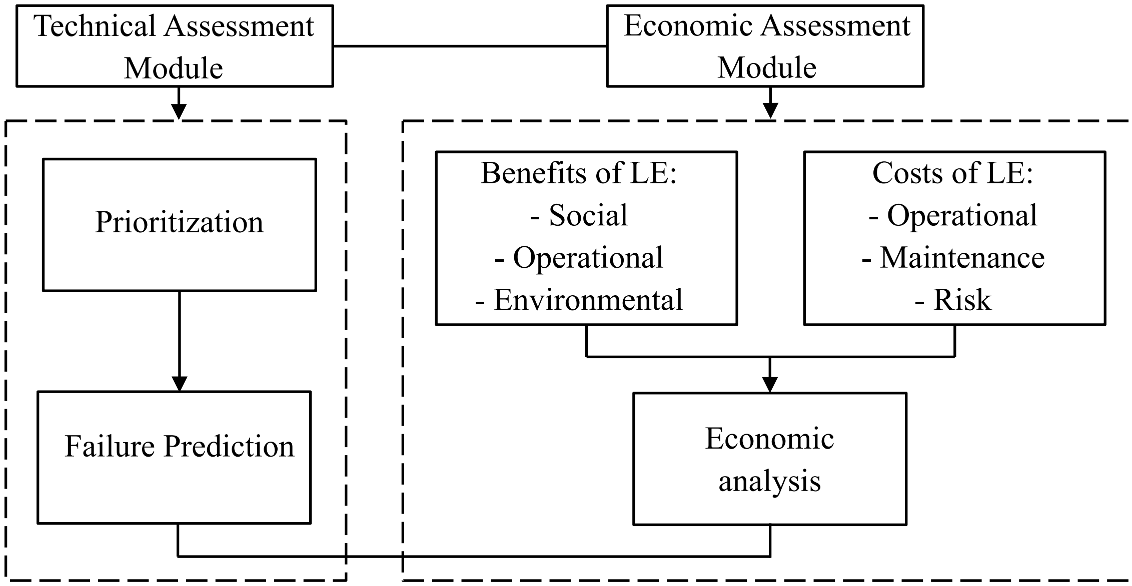

Figure 3. Techno-Economic Analysis of LE Strategies. Adapted from Animah et al. (2017).

a. *Technical Assessment Module*

(1) Prioritization

This process aids in directing resources toward the most vital areas, considering the impracticality of evaluating every system, structure, and component (SSC) in complex assets. Animah et al. (2017) acknowledge this challenge, suggesting that the feasibility of LE often confronts constraints such as high costs or extensive time requirements, making the prioritization essential for the enhancement of reliability. Also, as highlighted by Esa and Muhammad (2023), the categorization of onboard SSC into three key functions—float, move, and fight, in order of importance—should pave the way for evaluations of risk level in the naval environment.

Expanding on the necessity of prioritization, the concept of hierarchical decomposition, as presented by Yang and Jine (2020), offers a structured framework to dissect the complexity of systems, such as ships, into manageable layers. This approach simplifies understanding the ship's complexity by categorizing assets into SSC, highlighting how individual failures affect overall system reliability. A broad diagram of a hierarchical breakdown of the ship's systems is illustrated in Figure 4.

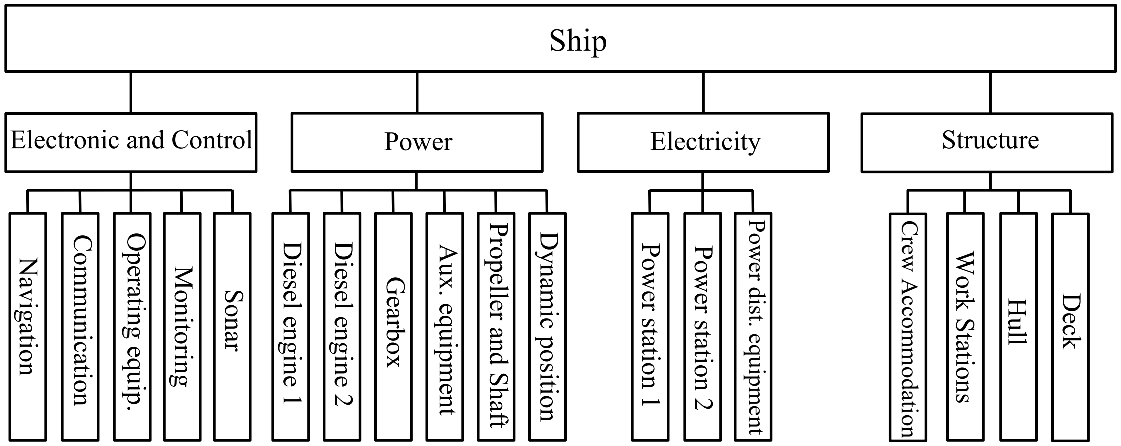

Figure 4. Hierarchical Decomposition Structure of a Ship.
Adapted from Yang and Jine (2020).

At this point, an evaluation should be directed toward those SSC that could significantly degrade the asset's mission. Figure 5 showcases the prioritization process.

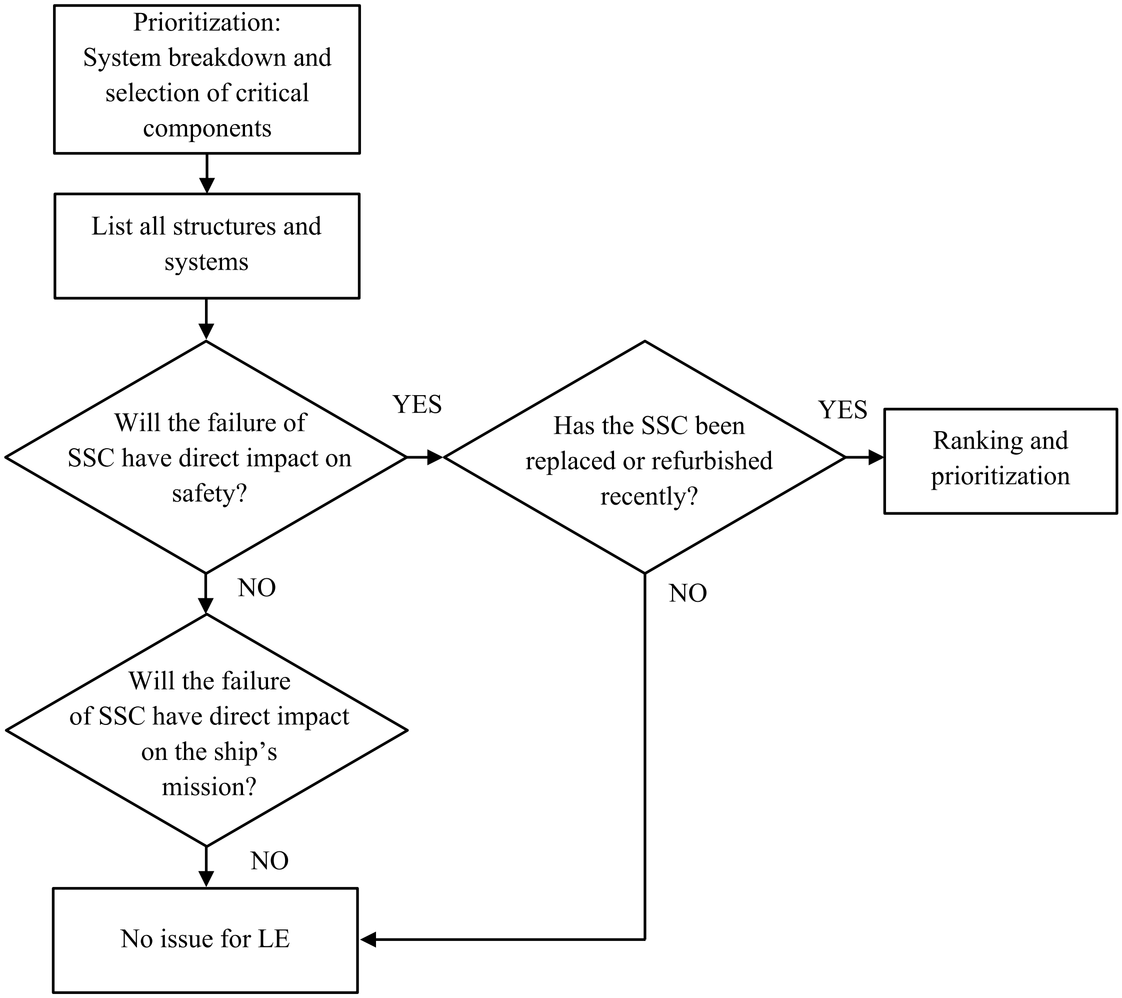

Figure 5. Prioritization Process for LE of Ships.
Adapted from Animah et al. (2017).

(2) Failure Prediction

Concerning future maintenance cost estimations, this study utilizes a failure prediction model. Building on the understanding of structural integrity and failure, Wang and Yin (2019) and Xu et al. (2023) contribute to the field by applying statistical models to predict failures in mechanical systems, specifically utilizing the Weibull distribution (WD). This choice is based on the observation that mechanical components, which constitute a significant portion of maritime equipment, exhibit failure patterns that align well with WD for predictive purposes.

Refining the analysis further, the hazard function, denoted as $\lambda(t)$, is presented in the literature (Modarres & Groth, 2023; Wang & Yin, 2019) as a metric to provide information about the instantaneous rate of failure within a brief time interval. It is typically graphed as a “bathtub curve,” as shown in Figure 6, where β is the shape parameter of WD. When $\beta > 1$, the hazard function increases with time, indicating an increasing failure rate (reliability decreasing over time). When $\beta < 1$, the hazard function decreases with time, suggesting a decreasing failure rate (reliability improving over time). When $\beta = 1$, the hazard function is constant, indicating a constant failure rate (reliability remains constant over time).

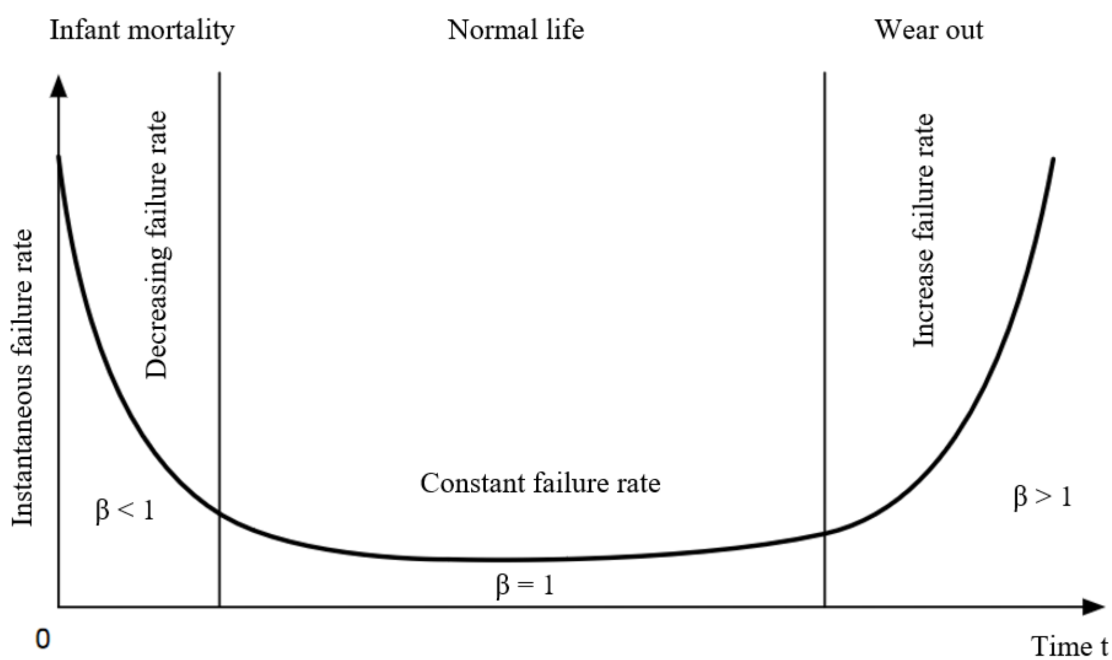

Figure 6. Example of a Bathtub Curve.
Source: Lu et al. (2016).

Let $\lambda(t)$ represent the failure function of the asset in a given time. Then, as proposed by Animah et al. (2018), the expected number of asset failures over the year t to $t+1$ of the extended life phase is given by the following equation:

$$n_f(t) = \int_t^{t+1} \lambda(t)dt \text{ ,} \tag{1}$$

where $n_f(t)$ represents the number of failures in time *t*.

Therefore, as proposed by Animah et al. (2018), the following equation results in the anticipated number of asset failures, given a two-parameter WD with shape and scale parameters *β* and *η*, respectively, at year *t*. An expanded calculation is presented in Appendix A.

$$n_f(t) = \int_t^{t+1} \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} = \frac{\left[(t+1)^{\beta} - t^{\beta}\right]}{\eta^{\beta}}, t = l_o, ..., l_o + l_e - 1. \tag{2}$$

To calculate the expected number of failures, it is necessary to determine the parameters *β* and *η* for insertion into Equation 2. To identify these parameters, we employ the graphical method. The graphic is structured to represent the Weibull cumulative distribution function (CDF), where *β* represents the slope of the best-fit line and *η* represents the characteristic life, or the age at which there is a 63.2% probability that the unit will have failed (Clement & Lasky, 2019). As McCool (2012) observes, a straight line is fitted to the collection of points, serving as an estimation of the population line. This approach entails plotting the transformed ordered sample values on the abscissa, alongside an estimated cumulative distribution function on the ordinate. Specifically, the transformation process involves plotting *ln(Failure Time)* on the vertical axis against *ln(-ln(1-Cumulative Probability))* on the horizontal axis, representing the Weibull CDF (Figure 7). The linear equation that fits this plot presented by McCool (2012) is shown below, with the slope of the line representing the shape parameter *β*:

$$ln(-ln(1 - CumulativeProbability)) = \beta ln(FailureTime) - \beta ln(\eta) \tag{3}$$

Rearranging the equation to solve for the scale parameter (*η*), we get:

$$\text{intercept} = -\beta ln(\eta)$$

$$ln(\eta) = -\left(\frac{\text{intercept}}{\beta}\right)$$

$$\eta = e^{-\left(\frac{\text{intercept}}{\beta}\right)}. \tag{4}$$

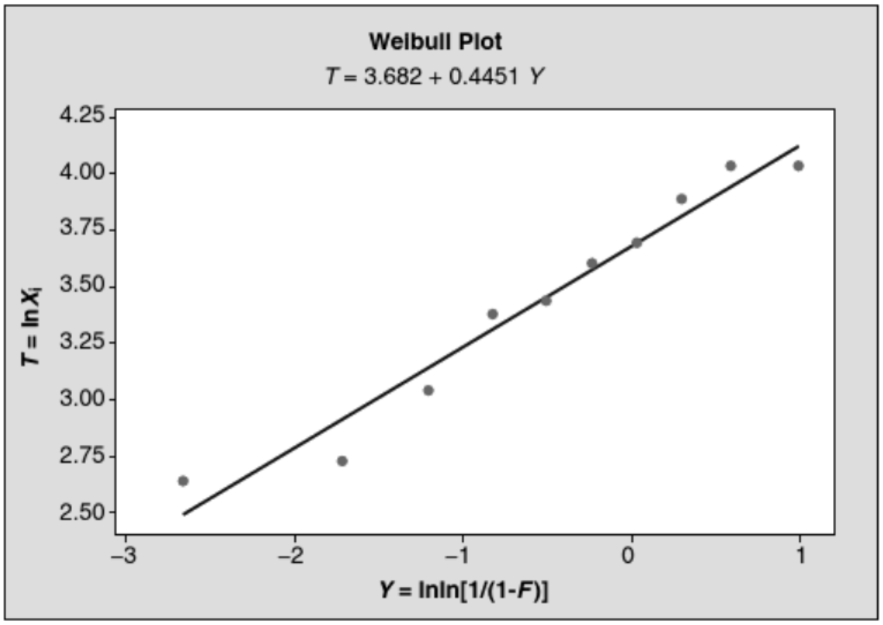

Figure 7. A Weibull CDF Probability Plot.
Source: McCool (2012).

b. Economic Assessment Module

(1) Benefits

According to Animah et al. (2018), the life cycle benefits (LCB) of LE programs (LCB_e), which are tailored to the interests of stakeholders, fall into three primary categories: social, operational, and environmental. These categories can be quantified using the following equation, proposed by Animah et al. (2018):

$$LCB_e = \sum_{t=l_o}^{l_o+l_e} \frac{B_{so}(t) + B_{op}(t) + B_{en}(t)}{(1+r)^t}, \tag{5}$$

where $B_{so}(t)$ represents the social benefits of a LE program in year *t*, $B_{op}(t)$ the operational benefits, $B_{en}(t)$ the environmental benefits, and r (greater than zero) is the discount rate. In this case, we consider the Central Bank's Special Settlement and Custody System (Selic) tax. Selic is considered Brazil's basic interest tax (Banco Central do Brasil, 2023). Additionally, *lo* is the original lifespan and *le* represents the extended life period (Animah et al., 2018).

Social Benefits $(B_{so}(t))$: As per Animah et al. (2017), extending the service life of a vessel in the private sector allows for an additional increased labor productivity. In the military setting, Kavanagh's (2005) research emphasizes the role of on-the-job training in boosting personnel productivity. This effort would bridge the potential operational gap that could arise from decommissioning the ship without an immediate replacement. Although it adds valuable continuity and readiness, it is challenging to measure in economic metrics. Additionally, at the highest level of national strategy, evaluating the benefits of defense spending would involve assessing its effects on long-term economic growth, peace, and prosperity, crucial factors for enhancing social welfare (Melese & Solomon, 2015). Hartley (2012) discusses the economic theory contributions and limitations in the understanding of these benefits. For instance, by ensuring a nation's security and protection, defense expenditure supports conditions that foster beneficial trade and exchange, both domestically and internationally. It also helps in preventing conflicts, with economic advantages manifesting through savings from either avoiding wars or reducing their length. However, the challenge of quantifying specific defense expenditures' contribution to growth domestic product (GDP) growth is rarely addressed (Melese & Solomon, 2015), highlighting the complexity of such measurements.

Operational Benefits $(B_{op}(t))$: The study by Animah et al. (2017) outlines key operational advantages of delaying ship decommissioning. By extending the service life of ships, the BN postpones substantial decommissioning and replacement costs, thereby easing current budget constraints. Also, an increase in asset availability is expected through an enhanced component reliability and shorter maintenance lead times.

Environmental Benefits $(B_{en}(t))$: Environmental benefits comprise the reduction in carbon emissions associated with the manufacturing, operation, and decommissioning processes of naval vessels. For instance, by incorporating environmental considerations into the evaluation of delaying the decommissioning of a navy vessel and drawing insights from the research by Chatzinikolaou and Ventikos (2014) we can refine the assessment with a focus on carbon dioxide (CO_2) emissions, which represent a significant part of a ship's environmental impact over its life cycle. Chatzinikolaou and Ventiko's study of an 80,000 DWT tanker over a 25-year life cycle, encompassing phases from construction through operation to dismantling, revealed that it emitted more than 1 million tons of CO_2, with the operational phase being the predominant source of emissions. It is expected that extending the service life of the vessel would avoid the CO_2 emissions of the dismantling activities and shipbuilding. In this context, Rennert et al. (2022) highlights carbon pricing as a method to address negative externalities associated with carbon emissions, by assigning a cost to the social impacts of carbon emissions. His study estimates a carbon price of $185 per ton.

(2) Costs

According to Animah et al. (2018), the cost drivers for LE decision-making include capital cost, operating cost, maintenance cost and risk expenditure. These factors are reflected in the following equation proposed by the same authors:

$$LCC_e = CAP_e + \sum_{t=l_o}^{l_o+l_e} \frac{C_O(t) + C_M(t) + C_R(t)}{(1+r)^t}, \qquad (6)$$

where LCC_e is the total life cycle cost (LCC) for an LE program, and CAP_e represents the capital investment. Additionally, $C_O(t)$ denotes operating expenses (OpEx), $C_M(t)$ indicates the maintenance expenditure (ManEx), and $C_R(t)$ refers to the risk expenditure (RiskEx), all measured in year t of the extended life (Animah et al., 2018).

Capital Investment for LE (CAP_e): This includes expenses incurred to acquire, improve, or maintain long-term assets. Additionally, as highlighted by Liu et al. (2019), capital repair actions such as crop cracked plate, new plate insertion, and plate thickness enhancement used for deterioration, fatigue, and corrosion are considered. The capital investment required can be calculated using the equation proposed by Khan and Amyotte (2005):

$$CAP_e = \sum_{i=1}^{m} n_i c_i \ , \tag{7}$$

where "*m*" indicates the total number of different types of add-on elements such as systems, components, processes, and capital repair actions incorporated into the asset. For each specific type, "n_i" (I = 1, 2, …, *m*) quantifies the total number of type *i* additions implemented on the asset to extend its life. Meanwhile, "c_i" represents the individual cost associated with each type *i* addition.

Operational Cost during the Extended Life Phase $(C_O(t))$: Operational expenses for ships encompass various categories essential for the day-to-day operations and maintenance of the vessel, shown in Equation 8. Specifically, operational costs include expenditures on fuel and lubricants (C_{Fuel}), a major expense for running the engine and ensuring the ship's mobility. Ammunition expenses (C_{Ammo}) are considered for naval vessels, where defense capability is required. Crew costs (C_{Crew}) encompass wages, training, and other personnel-related expenses. Operational consumables (C_{Cons}) can range from spare parts to cleaning supplies. Lastly, operational costs must account for harbor facility fees $(C_{Harbour})$.

$$C_o(t) = C_{Fuel} + C_{Ammo} + C_{Crew} + C_{Cons} + C_{Harbour} \ . \tag{8}$$

Maintenance Cost during the Extended Life Phase $(C_M(t))$: Maintenance expenses play a crucial role in the total ownership and operational costs of an asset, as detailed by Animah et al. (2018). This encompasses routine maintenance, performed regularly throughout the asset's life; preventive maintenance, aimed at slowing down deterioration and avoiding potential breakdowns during service; and corrective maintenance, for fixing issues and reinstating operation after unexpected failures. However, it should be noted that routine and preventive maintenance costs are included in the OpEx, since they are performed by the ship's crew. The estimated maintenance costs for an LE program in year *t*, denoted as *CM(t)*, are calculated using the following equation, adapted from Animah et al. (2018):

$$C_M(t) = C_{CM} \times n_f(t), \tag{9}$$

where C_{CM} represents the unit cost of carrying out corrective maintenance actions, and $n_f(t)$ is a function of the expected number of asset failures in year t, which was covered in the previous Failure Prediction section.

Risk Expenditure during the Extended Life Phase ($C_R(t)$): Animah et al. (2018) employed the risk-cost model developed in the study by Nam et al. (2011) to analyze the financial impacts of various hazard scenarios using the thresholds provided in Table 2. Regarding the fatality severity, an Instituto de Pesquisa Econômica Aplicada (IPEA; 2022) study offers an estimated value of statistical life in Brazil.

Table 2. Cost Consequences of the Risk Events.
Adapted from Nam et al. (2011).

Severity	Description	Financial loss
Catastrophic	Consequences to the whole installation	100% of OpEx
Major	Consequences to several modules	50% of OpEx
Significant	Consequences to a single module	30% of OpEx
Minor	Consequences limited to the local area	10% of OpEx
Fatality	Personal injury and death	\$2.5 million

According to Animah (2018), to estimate the costs associated with fatalities/injuries and asset damage the following equations can be used:

$$C_F = \sum_{j=1}^{k} n_{Fj} \times C_{Fj}, \tag{10}$$

$$C_{AD} = \sum_{j=1}^{k} n_{ADj} \times C_{ADj}, \tag{11}$$

where k is the number of different risk events, with n_{Fj} quantifying the fatalities/injuries, and n_{ADj} computing asset damages, all related to each risk occurrence j, for j values ranging from 1 to k. Furthermore, the costs related to these events are categorized into C_{Fj}, which covers the costs due to fatalities/injuries, and C_{ADj}, which includes expenses related to asset damages such as repair, replacement, and operational downtime (Animah et al., 2018).

(3) Benefit-Cost Ratio

Boardman et al. (2018) define the BCR as the ratio between the NPV of total benefits and the NPV of costs. For decision support in LE projects, Animah et al. (2018) propose the following equation:

$$BCR = \frac{LCB_e}{LCC_e}. \tag{12}$$

Acceptable LE strategies have a BCR greater than one, with the highest BCR being the most desirable. Those with a BCR less than one are not beneficial.

3. Phase 3: Decision-Making and Implementation

Exploring ship LE decision-making, especially in naval operations, goes beyond technical evaluations. It calls for a multidisciplinary approach, integrating CBA and strategic considerations to guide these complex decisions.

The decision often hinges on a nuanced analysis of upgrade costs, the benefits of more modern ships, and the imperative to maintain a fleet that balances technological sophistication, operational readiness, and budget constraints. This ensures the BN's strategies align with both national defense and global sustainability goals, harmonizing environmental responsibility with fiscal pragmatism and security requirements.

IV. APPLICATION AND RESULTS

This chapter implements the proposed techno-economic model to streamline LE decision-making for the BN's Multipurpose Aircraft Carrier (NAM) Atlântico.

The NAM Atlântico, pictured in Figure 8, is a multipurpose aircraft carrier and the flagship of the BN. Originally commissioned by the Royal Navy as HMS Ocean in 1998, it served until 2018 before being transferred to Brazil. The primary role of the NAM Atlântico in the BN is to provide aircraft lift and assault capability (Janes, 2023). This includes supporting marine forces in amphibious operations, and participating in humanitarian assistance and disaster relief missions. Therefore, the operational readiness of the NAM Atlântico directly influences the BN's overall capability to achieve its strategic objectives, whether in combat scenarios or in humanitarian efforts. The general characteristics of the ship are summarized in Table 3.

Figure 8. NAM Atlântico.
Source: BN (2023c).

Table 3. NAM Atlântico Characteristics.
Source: Naval Technology (2022).

Info	Data
Builder	Vickers Shipbuilding and Engineering
Displacement	21,758 tonnes
Length	203.43 m
Propulsion	Two Crossley Pielstick 16 PC 2.6 V 200 medium-speed diesel engines, rated at 23,904 hp, with two independent shafts and a five-bladed fixed-pitch propeller
Speed	18 knots (Maximum)
Range	8,000 Nautical Miles
Vehicles carried	40 amphibious vehicles
Aircraft carried	18 helicopters

The NAM Atlântico was selected to undergo the proposed model primarily because it is nearing the end of its 30-year designed service life. The BN expects that the ship will serve for an additional 10 years.

A. PHASE 1: PREPARATION FOR LE STRATEGIES

1. Definition of Premises for LE Strategies

The project aims to identify an LE strategy for the NAM Atlântico that ensures both technical integrity and economic viability. The main objective is to prolong the service life of the current ship by 10 years. This extension would ensure that there is no gap in capabilities while the procurement, construction, and commissioning processes for a new ship are completed.

Among the strategies identified in the literature review, three LE strategies were considered for the ship: (i) reuse, (ii) refurbishment, and (iii) replacement, as shown in Table 4.

Table 4. LE Strategies and Description

No.	LE strategy	Description
(i)	Reuse	Use as-is, minimal intervention
(ii)	Refurbishment	Recommended repair on diesel main engine and Hull
(iii)	Replacement	Replace the ship for an analogous ship

2. Data Collection

Input data for the research is summarized in Table 5. The CO_2 emissions for the NAM Atlântico during shipbuilding and dismantling are 2,471 tons and 6,650 tons, respectively. This data is based on the gas emission estimates from Chatzinkolaou and Ventikos's (2014) study, which evaluated a ship weighing 74,296 tons. A proportional calculation was used, considering the NAM Atlântico's weight of 21,578 tons. The carbon pricing of $185 per ton is derived from Rennert et al. (2022), which estimates the social cost of CO_2 emissions through probabilistic socioeconomic projections and climate models. Operation and sustainment costs are $5,180,856.23, which the research from Gavião et al. (2018) estimated based on open sources for the NAM Atlântico. The BN expects that adopting the "refurbished" strategy would enhance the ship's availability compared to the "reuse" strategy, leading to higher operating costs but lower maintenance expenses.

Estimating the cost of new ships presents a notable challenge, primarily due to the classified nature of such information. The BN, with a recent quest for "homemade" weapon systems development (Sanchez, 2024), frequently leverages the Foreign Military Sales (FMS) program to procure assets, addressing immediate capability gaps. This approach involves acquiring existing assets from other countries, as evidenced by the procurement of the NDM Bahia from the French Navy and the NAM Atlântico from the Royal Navy (Janes, 2016, 2023). Given this context, using the depreciated cost of similar class ships, like the Mistral-class amphibious assault ship sold by the French government to Egypt—as documented by Dalton (2015)—offers a rough estimate of the magnitude of expenses involved. Considering the price at which decommissioned ships are currently being bought in the global market, $530 per ton according to Willmington (2024), the decommissioning cost is $11,395,000.00. Interest rates data is collected from the Brazilian Central Bank.

It is important to note that these data may be subject to uncertainties external to this research, such as operation duration, ship type, maintenance costs and resources, and damage profile of the ship being evaluated.

Table 5. Input Data for the Case Study

Input Data	Amount	Calculations Based On
CO_2 dismantling emissions	2,471 tons	Chatzinkolaou and Ventikos (2014)
CO_2 shipbuilding emissions	6,650 tons	Chatzinkolaou and Ventikos (2014)
Carbon pricing	$185.00	Rennert et al. (2022)
Operating and sustainment costs	$5,180,856.23	Gavião et al. (2018)
New ship cost	$221,925,400.00	Dalton, M. (2015)
Decommissioning cost	$11,395,000.00	Willmington, R. (2024)
Main engine repair cost	$4,000,000.00	BN notional data estimation
Hull repair cost	$33,000,000.00	BN notional data estimation
Corrective maintenance Cost	$30,000.00	BN notional data estimation
r	11.25%	Brazilian Central Bank (2023)

B. PHASE 2: TECHNO-ECONOMIC ANALYSIS OF LE STRATEGIES

1. Technical Assessment Module

a. Prioritization

The selection of the diesel main engines and the hull of the NAM Atlântico for LE evaluation is based on an engineering technical assessment, detailed in Table 6. This assessment, using illustrative notional data due to the research being unclassified, identified a high failure rate for the engine and significant corrosion and fatigue on the hull.

Table 6. Selected Systems for LE Assessment

Prioritization: NAM Atlântico		
System	Sub-System	Risk Level with Respect to Aging
Structure	Hull	High
Power	Diesel main engine	High
Electronic and control	Communication	Moderate
Structure	Crew accommodation	Low

The function of the diesel main engine system in the NAM Atlântico is to provide the main propulsion, generating power to navigate through various maritime conditions. This system primarily comprises a vibration absorber, engine cylinders, a flywheel, a transmission shaft, a coupling, and a propeller, as illustrated in Figure 9. The hull integrity faced significant challenges due to corrosion and fatigue, compromising its structural stability and safety.

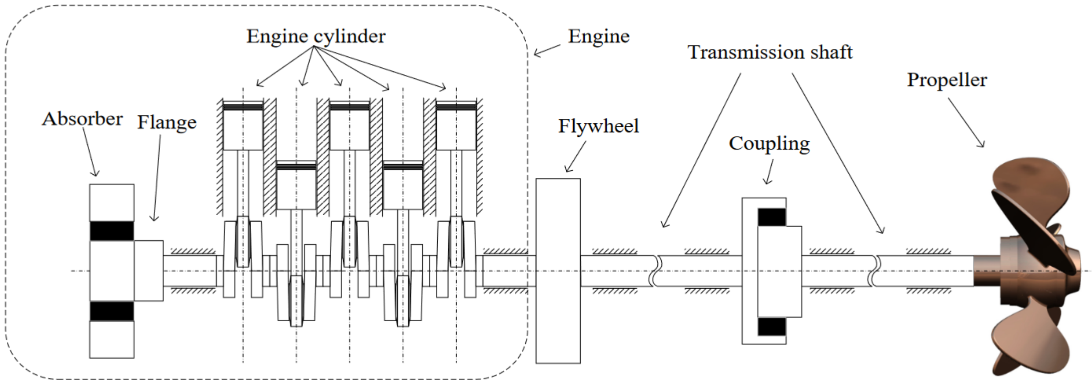

Figure 9. Diagram of a Marine Diesel Engine Propulsion System.
Source: Chen et al. (2020).

b. Failure Prediction

Using the dataset of the diesel main engine failures detailed in Table 7, a graphical estimation was conducted to determine the scale and shape parameters. The Weibull plot (Figure 10) indicated a shape parameter (β) of 1.7946 and a scale parameter (η) of 143.5583. Employing these parameters in Equation 2 enables the calculation of the expected number of asset failures in year *t*, aiding in the anticipation for potential breakdowns and providing improved cost estimations.

Table 7. Failure Prediction Dataset

Failure prediction: Diesel Main Engine				
Failure (days)	Rank	Cumulative probability	Ln(Failure)	Ln(-ln(1-Cumulative probability)
43	1	0.1	3.76	-2.25037
54	2	0.2	3.99	-1.49994
90	3	0.3	4.50	-1.03093
93	4	0.4	4.53	-0.67173
132	5	0.5	4.88	-0.36651
145	6	0.6	4.98	-0.08742
167	7	0.7	5.12	0.18563
183	8	0.8	5,21	0.47588
195	9	0.9	5.27	0.83403

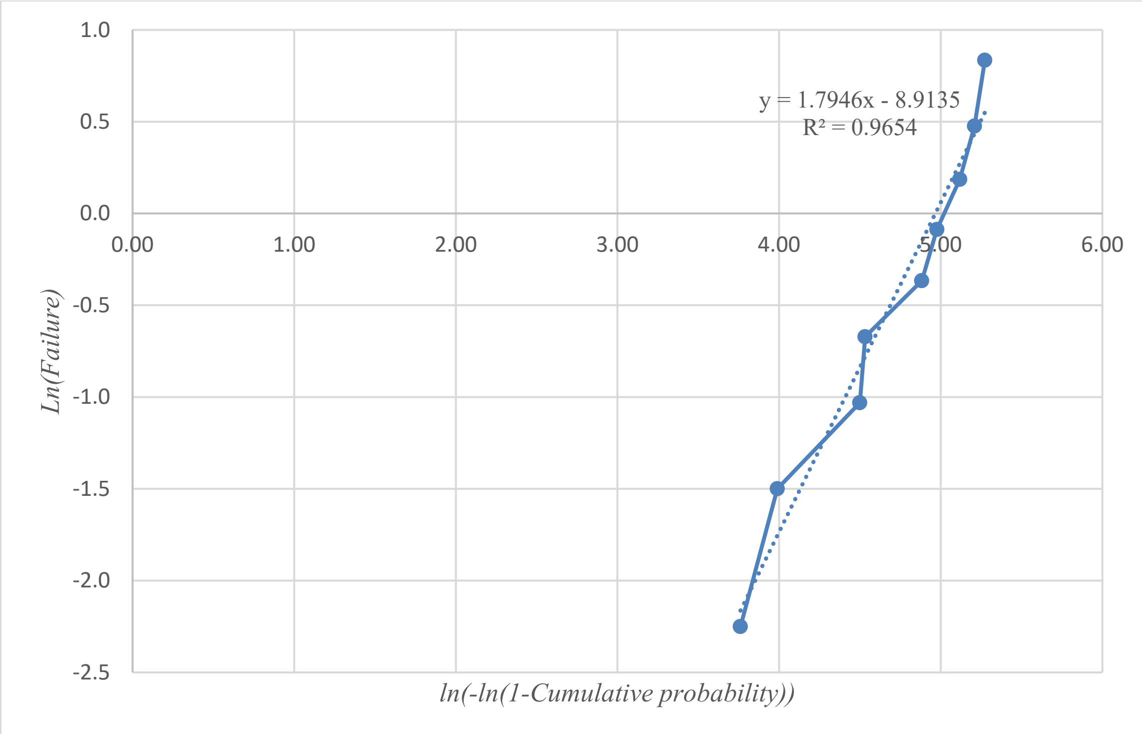

Figure 10. Weibull Plot

2. Economic Assessment Module

In this phase, the outcomes of the LCC analysis are presented in Appendix B. Figure 11 illustrates the contribution of each cost component (capital investment expenditures [CapEx], OpEx, ManEx, and RiskEx) to the total costs associated with different LE strategies. Despite the quantifiable cost components being systematically analyzed, the inability to fully monetize the broader benefits represents a limitation of the study. Reuse and refurbishment strategies offer operational benefits—delaying the costs of purchasing a new ship and decommissioning the existing ship—and environmental advantages by preventing CO_2 emissions associated with constructing a new ship and decommissioning the old one. On the other hand, the replacement strategy does not confer these operational and environmental benefits. Instead, this strategy is associated primarily with social benefits, which, although potentially significant, were difficult to measure and therefore excluded from the calculation. This exclusion notably impacts the BCR, rendering it zero for replacement strategies.

RiskEx emerges as the leading factor driving up total cost throughout the three strategies evaluated. On the one hand, operating aged vessels presents heightened risks due to increased mechanical failure from wear and tear, incurring higher maintenance and repair costs. On the other hand, new vessels incorporate new technologies, ensuring greater operational safety and efficiency. They also generally incur lower maintenance and repair costs, offer higher reliability, and are more fuel-efficient, leading to operational cost savings.

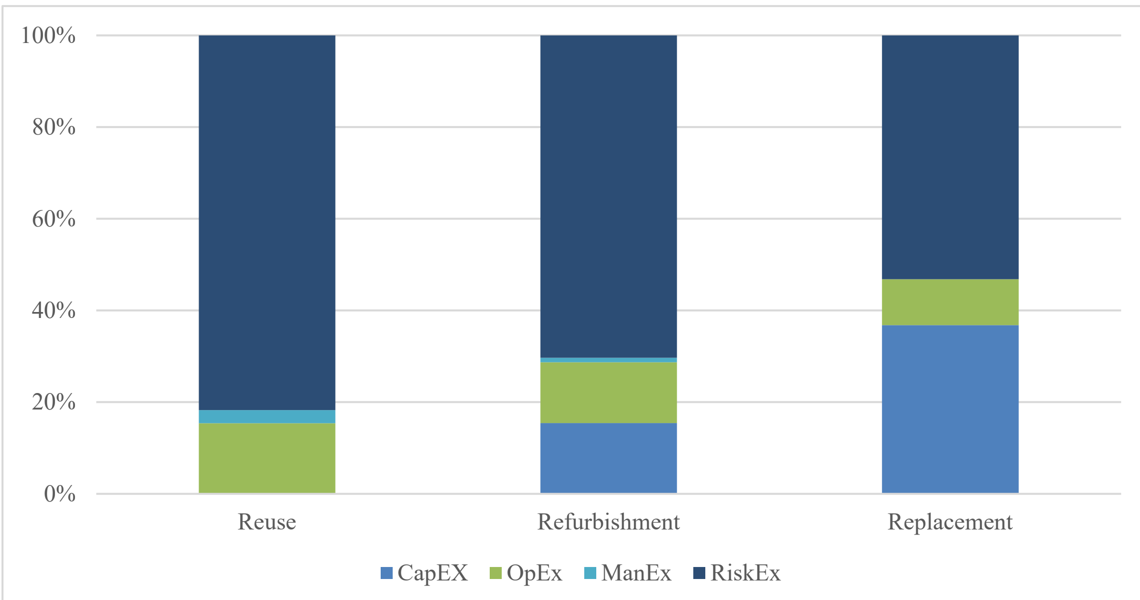

Figure 11. Contribution of Cost Elements to Total Expenditure for Each LE Strategy

Choosing to avoid CapEx by adopting the “reuse” strategy often results in significantly higher ManEx and OpEx. This increase is due to the necessity of frequent repairs, upgrades, and maintenance to ensure the older vessel meets current operational standards and safety regulations. While this approach can mitigate the upfront costs associated with acquiring new assets, it may lead to increased long-term expenses as the ongoing need for maintenance and modernization becomes more demanding over the lifespan of the vessel.

Opting to replace an existing vessel is financially more demanding than LE strategies, as illustrated in Figure 12. It requires a detailed assessment of its long-term impacts, since military budgets can be subject to significant fluctuations due to economic conditions and shifting defense priorities. Additionally, this strategic investment aims to ensure the highest level of operational availability compared to other LE strategies.

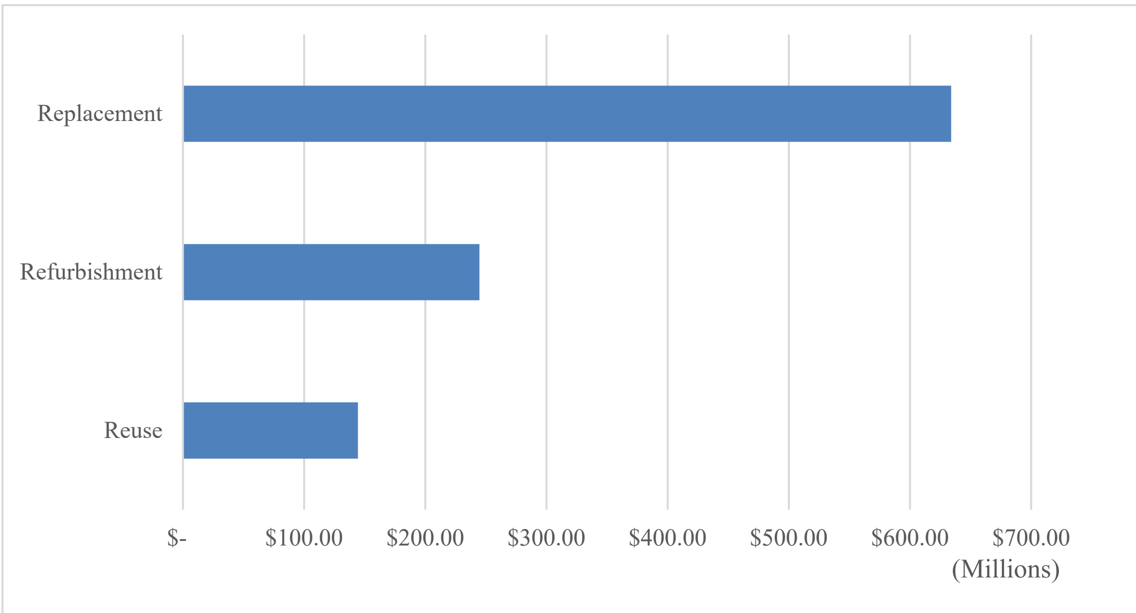

Figure 12. Total NPV for Each Strategy

It should also be noted that the economic environmental benefits considered in the model account for less than 1% of the total economic benefits computed. However, the tangible benefits that come from addressing environmental concerns are significant and should be promoted further.

Table 8 presents the BCR for each of the LE strategies. It is found that the BCR for the "reuse" strategy is greater than 1, standing out as the most favorable choice, mainly because there is no CapEx involved. However, the economic benefits observed are counterbalanced by an elevation in associated risks, as previously discussed.

Table 8. BCR for Selected Strategies for LE Assessment

No.	LE Strategy	BCR
(i)	Reuse	1.517
(ii)	Refurbishment	0.916
(iii)	Replacement	0.000

C. PHASE 3: DECISION-MAKING AND IMPLEMENTATION

Based on the BCR values given in Table 8, the “reuse” is the best suitable strategy for LE. By extending the service life of the NAM Atlântico, the BN will delay significant decommissioning, replacement, and capital maintenance expenses, thereby mitigating immediate budget constraints.

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V. CONCLUSION AND RECOMMENDATIONS

Facing significant budget limitations, the imperative to extend the service life of naval vessels has become increasingly critical for the BN to maintain fleet readiness. This thesis presents a techno-economic methodology for LE decision-making for ships. The framework evaluates technical conditions of assets and conducts CBA for their extended operational phase.

The thesis focused on two main objectives: (a) providing a tool for assessing the most suitable LE strategy from a balanced technical and economic perspective, assisting asset managers in complex decisions involving deteriorating equipment; and (b) demonstrating the practical application of the method through a case study on the BN NAM Atlântico. The analysis considered three LE options based on the available data: reuse, refurbishment, and replacement.

The technical module leveraged the prioritization of SSC to direct resources towards the most vital areas and the WD analysis for failure prediction and estimation of corrective maintenance expenditures during extended operation. The economic quantification revealed reuse as the most cost-effective choice given the substantially lower capital investments.

Ships, like other systems, are getting increasingly complex. Also, combat systems are placing increasing demand on the power generation, ventilation, crew size, and interior space requirements of ships (among other resources). So, SSC analysis may need to move beyond the traditional hull, mechanical, and electrical (HM&E) perspective to a broader systems integration approach. These factors also come into play when refurbishment (or even repair) of HM&E ends up triggering the integration of significantly different combat systems.

Further research can be improved with the inclusion of different deterioration and failure prediction models, as well as other life cycle costs and benefits elements. For instance, techniques such as Weibull analysis could be adapted for a broader perspective that factors in the need for systems integration onboard ships. The inherent difficulties in valuing social and environmental benefits introduces further uncertainties into the economic evaluation and can be further explored in future research. Appropriate tools can be developed to reduce uncertainty involved in the risk-cost model. Also, extending the application of the proposed model across other military branches would provide further evidence of its effectiveness.

APPENDIX A. NUMBER OF FAILURES CALCULATION

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

$$n_f(t) = \int_t^{t+1} \lambda(t)dt \therefore$$

$$n_f(t) = \int_t^{t+1} \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} dt$$

Substitute u-values:

Let u $= \frac{t}{\eta}$, so $du = \frac{1}{\eta}dt$

Adjust limits:

The limits of integration become $u(t) = \frac{t}{\eta}$ to $u(t+1) = \frac{t+1}{\eta}$

Express dt in terms of du:

From the substitution, $du = \frac{1}{\eta}dt \Rightarrow dt = \eta du$

Substituing u and dt into the integral:

$$n_f(t) = \int_{\frac{t}{\eta}}^{\frac{t+1}{\eta}} \frac{\beta}{\eta}(u^{\beta-1})\eta du$$

$$n_f(t) = \beta \int_{\frac{t}{\eta}}^{\frac{t+1}{\eta}} u^{\beta-1}du$$

$$n_f(t) = \beta\left[\frac{u^\beta}{\beta}\right]_{\frac{t}{\eta}}^{\frac{t+1}{\eta}}$$

$$n_f(t) = \left[u^\beta\right]_{\frac{t}{\eta}}^{\frac{t+1}{\eta}}$$

$$n_f(t) = \left(\frac{t+1}{\eta}\right)^\beta - \left(\frac{t}{\eta}\right)^\beta$$

$$\therefore n_f(t) = \frac{\left[(t+1)^\beta - t^\beta\right]}{\eta}$$

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APPENDIX B. LCC ANALYSIS

Non-financial parameters			Based on:
β	1.7946		McCool (2012); Nnaji et al. (2020)
η	143.5583		McCool (2012); Nnaji et al. (2020)
r	11.25%		Brazilian Central Bank (2023)
LE	10 years		This research
Ship tonnage (tons)	21578		Marinha do Brasil (2023c)
Catastrophic (qty/%xOPEX)	1	100%	SME estimation/Nam et al. (2011)
Major (qty/%xOPEX)	5	50%	SME estimation/Nam et al. (2011)
Significant (qty/%xOPEX)	5	30%	SME estimation/Nam et al. (2011)
Minor (qty/%xOPEX)	3	10%	SME estimation/Nam et al. (2011)
Fatality (qty/$)	0	$ 2,500,000.00	SME estimation/IPEA (2022)
(A) CO2 emissions dismantling (tons)	2471.58		Chatzinkolaou, S. & Ventikos, N. (2014)
(B) CO2 emissions shipbuilding (tons)	6650.91		Chatzinkolaou, S. & Ventikos, N. (2014)
(A) + (B) CO2 emissions (tons)	9122.50		This research

Financial parameters		Based on:
New ship cost	$ 221,925,400.00	SME estimation/Dalton, M. (2015)
Main engine repair cost	$ 4,000,000.00	SME estimation
Hull repair cost	$ 33,000,000.00	SME estimation
Corrective maintenance engine cost	$ 30,000.00	SME estimation
Operating and sustainment costs	$ 5,180,856.23	SME estimation/Gaviao et al. (2018)
Decommissioning cost	$ 11,395,000.00	Willmington, R. (2024)
Carbon pricing ($/ton)	$ 185.00	Rennert et al. (2022)
CO2 $$ savings with LE	$ 1,687,661.80	This research

			Reuse	Refurbishment	Replacement	Reuse Ben (t)/LCBe	Refurb Ben (t)/LCBe
BCR reu	1.517715327	*CapEX*	$ -	$ 37,000,000.00	$ 233,320,400.00	*0.7547%*	*0.7547%*
BCR ref	0.916553886	*OpEx*	$22,258,361.98	$31,797,659.98	$63,595,319.95		
BCR rep	0.000000000	*ManEx*	$4,138,037.02	$2,300,957.52	$0.00		
		RiskEx	$ 117,969,318.51	$ 168,527,597.88	$ 337,055,195.75		
			$ 144,365,717.51	$ 239,626,215.37	$ 633,970,915.70		

Reuse	0	1	2	3	4	5	6	7	8	9	10
Bso (t)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Bop (t)	$ 221,925,400.00										
Ben (t)	$ 1,687,661.80	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
NPV	$ 223,613,061.80	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
LCBe(reuse)	$ 223,613,061.80										

Reuse	0	1	2	3	4	5	6	7	8	9	10
Cop (t) Reu	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36	$ 3,626,599.36
Cm (t) Reu	$ 30,000.00	$ 104,075.15	$ 215,455.39	$ 361,053.59	$ 538,873.30	$ 747,456.79	$ 985,666.00	$ 1,252,573.42	$ 1,547,400.05	$ 1,869,476.85	$ 2,218,219.30
Cr (t) Reu	$ 117,969,318.51										
NPV	$ 121,625,917.88	$ 3,353,415.29	$ 3,104,298.75	$ 2,896,124.95	$ 2,719,344.38	$ 2,566,754.05	$ 2,432,843.48	$ 2,313,375.12	$ 2,205,089.48	$ 2,105,487.03	$ 2,012,661.99
LCCe(reuse)	$ 147,335,312.40										

Refurbishment	0	1	2	3	4	5	6	7	8	9	10
Bso (t)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Bop (t)	$ 221,925,400.00										
Ben (t)	$ 1,687,661.80	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
NPV	$ 223,613,061.80	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
LCBe/ref	$ 223,613,061.80										

Refurbishment	0	1	2	3	4	5	6	7	8	9	10
Cop (t) Ref	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23	$ 5,180,856.23
Cm (t) Ref	$ 20,000.00	$ 69,383.43	$ 143,636.92	$ 240,702.39	$ 359,248.87	$ 498,304.53	$ 657,110.67	$ 835,048.95	$ 1,031,600.03	$ 1,246,317.90	$ 1,478,812.86
Cr (t) Ref	$ 168,527,597.88	$ -	$ -	$ -	$ -	$ -					
NPV	$ 173,728,454.11	$ 4,719,316.56	$ 4,302,077.54	$ 3,937,532.03	$ 3,616,745.30	$ 3,332,606.71	$ 3,079,367.42	$ 2,852,337.06	$ 2,647,665.93	$ 2,462,180.51	$ 2,293,255.56
LCCe/ref	$ 243,971,538.72										

Replacement	0	1	2	3	4	5	6	7	8	9	10
Bso (t)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Bop (t)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ben (t)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
NPV	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
LCBe/rep	$ -										

Replacement	0	1	2	3	4	5	6	7	8	9	10
Cop (t) Rep	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47	$ 10,361,712.47
Cm (t) Rep	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Cr (t) Rep	$ 337,055,195.75	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
NPV	$ 347,416,908.22	$ 9,313,898.85	$ 8,372,043.91	$ 7,525,432.72	$ 6,764,433.91	$ 6,080,390.03	$ 5,465,519.13	$ 4,912,826.18	$ 4,416,023.54	$ 3,969,459.36	$ 3,568,053.36
LCCe/rep	$ 641,125,389.20										

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