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Clóvis Candido de Oliveira Neto

OPTIMIZING AIRCRAFT MAINTENANCE OUTSOURCING DECISIONS: A COST-BENEFIT ANALYSIS

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OPTIMIZING AIRCRAFT MAINTENANCE OUTSOURCING DECISIONS: A COST-BENEFIT ANALYSIS

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To the Brazilian Navy for the opportunity to enhance my knowledge, to the professors at ITA and Embraer for their invaluable insights throughout this master's program, with special thanks to Professor Dr. Marques, my advisor, for his invaluable guidance and support. To my wife, for her unwavering love and dedication.

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"Mathematics is the alphabet with which God has written the universe".

(Galileo Galilei)

Resumo

A decisão de internalizar ou terceirizar os serviços de manutenção de uma frota de aeronaves é um dilema que causa impactos diretos nos custos, na disponibilidade das aeronaves, bem como na capacidade de cumprir as missões a que são designadas. Essa escolha exige uma análise cuidadosa de diversos fatores, e a ausência de um modelo que simule diferentes cenários de manutenção dificulta a tomada de decisão.

A ausência de um modelo capaz de simular cenários reais impede os gestores de frota de avaliarem de forma precisa o impacto de diferentes opções de manutenção no custo total do ciclo de vida das aeronaves, bem como na sua disponibilidade operacional ou os desdobramentos administrativos e logísticos das diferentes opções. Essa falta de clareza pode levar a decisões equivocadas, resultado em custos excessivos, indisponibilidades de aeronaves e consequentemente afetar a capacidade de cumprir as missões que são designadas.

Esta pesquisa propõe um modelo que simula diversas configurações de manutenção, desde a manutenção totalmente interna (*in-house*) até a manutenção totalmente terceirizada. O modelo leva em consideração informações sobre a frota, os componentes embarcados nas aeronaves, contratos de manutenção em vigor, estrutura de manutenção interna e dados de disponibilidade das aeronaves. Além disso, o modelo permite analisar o impacto de diferentes cenários, como o impacto do tamanho da frota nas decisões, custos de recursos, tamanho da estrutura de manutenção, reparos mal sucedidos, contratos específicos para componentes de alta complexidade e variações cambiais.

Este trabalho oferece um guia prático para auxiliar gestores de frota e profissionais da aviação na tomada de decisão sobre a manutenção de aeronaves. Ao simular diferentes cenários e analisar o impacto de diversos fatores, o modelo permite identificar a opção de manutenção mais eficiente em termos de custo-efetividade, maximizando a relação disponibilidade operacional x custo do ciclo de vida, bem como indicando fatores relevantes na tomada de decisão.

Abstract

The decision to internalize or outsource maintenance services for a fleet of aircraft is a dilemma that has a direct impact on costs, aircraft availability and the capability to perform the missions that they are assigned. This decision demands a careful analysis of several factors, and the lack of a model that simulates different maintenance scenarios turn the decision-making process more difficult.

The absence of a model capable of simulating real scenarios lead fleet managers to not accurately assess the impact of different maintenance options on the total life cycle cost of aircraft, as well as their operational availability or the administrative and logistical implications of the different options. This lack of clarity can lead to wrong decisions, resulting in excessive costs, unavailability of aircraft and consequently affecting the ability to fulfill assigned missions.

This research proposes a model that simulates various maintenance configurations, from totally in-house maintenance to complete outsourcing. The model takes into account information about the fleet, the components on board the aircraft, current maintenance contracts, the in-house maintenance structure and aircraft availability data. In addition, the model makes it possible to analyze the impact of different scenarios, such as the impact of fleet size on decisions, resource costs, the size of the maintenance structure, unsuccessful repairs, specific contracts for highly complex components and also exchange rate variations.

This work offers a practical guide to help fleet managers and aviation professionals make decisions about aircraft maintenance. By simulating different scenarios and analyzing the impact of various factors, the model makes it possible to identify the most efficient maintenance option in terms of cost-effectiveness, maximizing the operational availability x life cycle cost ratio, as well as indicating the weight of real cases variations.

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List of Acronyms

A/C	Aircraft
ADT	Administrative Delay Time
BCR	Benefit Cost Ratio
BITE	Built In Test Equipment
CONOPS	Concept of Operation
DI	Due In
EBO	Expected Back Order
EIS	Entry Into Service
FMECA	Failure Mode, Effects, and Criticality Analysis
FR	Fill Rate
FTA	Fault-Tree Analysis
GAO	General Accounting Office
IPL	Initial Provisioning List
IPS	Integrated Product Support
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LDT	Logistic Delay Time
LORA	Level of Repair Analysis
LRU	Line Replaceable Unit
LSC	Life Support Cost
METRIC	Multi-Echelon Technique for Recoverable Item Control
MDT	Maintenance Downtime
MMT	Mean Maintenance Time

MPMT	Mean Preventive Maintenance Time
MRO	Maintenance, Repair and Overhaul
MTA	Maintenance Task Analysis
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
O&S	Operating & Support
OEM	Original Equipment Manufacturer
OH	On Hand
QPA	Quantity of the item per aircraft
RCM	Reliability Centered Maintenance
SI	Significance Index

List of Symbols

A_a	Achieved Availability
A_i	Inherent Availability
A_{op}	Operational Availability
f_{PM}	Preventive maintenance frequency
m_{io}	Average demand of each item at the depot
λ_{ij}	Average number of item “i” in repair at base “j”

Contents

1 Introduction

This research presents an approach on the supportability of aerospace defense systems. First of all, a system consists of a nucleous of elements combined in such a manner to accomplish a function in response to an identified need (BLANCHARD, 1998).

According to Leveson, N. G. (1995), modern aircraft are classic examples of complex systems, which are an intricate network of interconnected components that interact in a non-linear manner. These systems are composed of subsystems, which have their own functions, which interact in order to achieve the expected function for that system. Additionally, in complex aerospace Defense systems (aircraft), the operation and support phase accounts for 60% to 75% of the total costs of their life cycle (BLANCHARD; VERMA; PETERSON, 1995).

According to Blanchard (2014), a system must first be designed to be supportable, produced, distributed to the user, and maintained effectively and efficiently throughout its planned life cycle. In recent years, systems have been increasing in complexity with the on-going introduction of new technologies, the industrial base has been changing, the availability of resources has been dwindling, the costs of acquiring new systems and maintaining and supporting existing systems have been increasing and competition has been increasing worldwide. Additionally, the author states that given the current economic dilemma of decreasing budgets with upward inflationary trends, there will be even less resources available for doing business in the future, and one of the greatest challenges facing businesses, industries, government agencies, and the general consumer of products and services today is the growing need for a more effective and efficient method for the managing of our valuable resources.

Due to that, the need to address system Life Cycle Cost (LCC) is evident. Furthermore, it has been indicated that much of the projected LCC for a given system can be greatly impacted by decisions made during the early phases of advanced planning and conceptual design (BLANCHARD, 1998), as can be seen in Figure 1. The same is valid for an entity planning to acquire a fleet of systems, where the impact on the LCC will be greater the earlier supportability analyses begin.

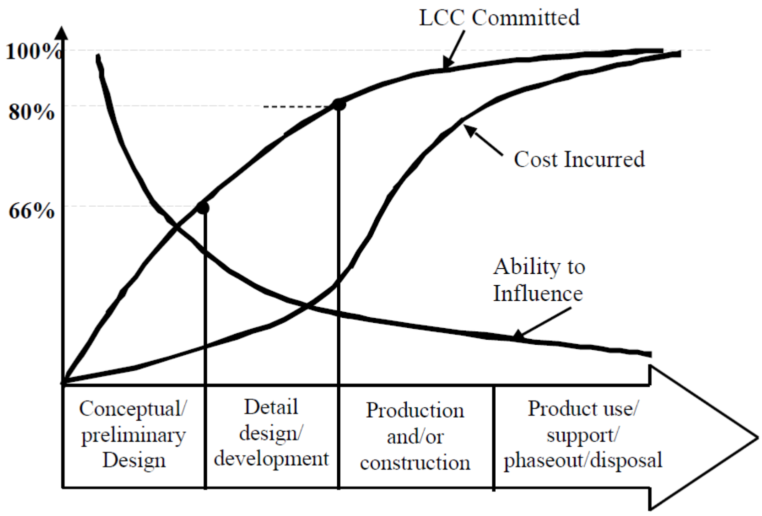

Figure 1: Life Cycle Cost commitment (FABRYCKY, 1994)

As can be seem in Figure 1, the “Ability to influence curve” begins high and decrease rapidly. It means that in the first project phases, when there are few decisions made, it is easier to influence and propose suggestions, and as the project progresses to later stages, where most of the decisions have already been made, the ability to influence the project becomes less. On the other hand, the “LCC commit” has the opposite behavior. In the early phases, with few decisions made, the life cycle cost commitment is small, and increase as the decisions are made.

So, the early a project analysis begins, better results could be achieved. Meanwhile, in the early stages there is a lack of information and knowledge about some details needed to perform the analysis. Due to that, the dilemma of lack of information in the early phases and the need to perform project analysis as early as possible must be managed in order to achieve satisfactory results.

According to Blanchard (2014), there are some gaps in the supportability of the current system, and some of his quotes on this issue are: “experience in recent years has indicated that the complexity and the costs of systems, in general, have been increasing. A combination of introducing new technologies in response to a constantly changing set of performance requirements, the increased external social and political pressures associated with environmental issues”, “many of the system currently in use today are not adequately responding to the needs of the user”, and “that there is a lack of total cost visibility”.

Although the aircraft have a considerably high acquisition cost, it still represents a small fraction of the total cost, where the operation and supportability (O&S) represents a large part of the whole costs. According to O’Hanlon et at (2018), the General Accounting Office (GAO) of United States consider the 70:30 ratio, where 70% of the total cost is for Operation and

Supportability, and 30% is for the acquisition cost. A typical illustration of the order of magnitude of the main costs is shown in Figure 2.

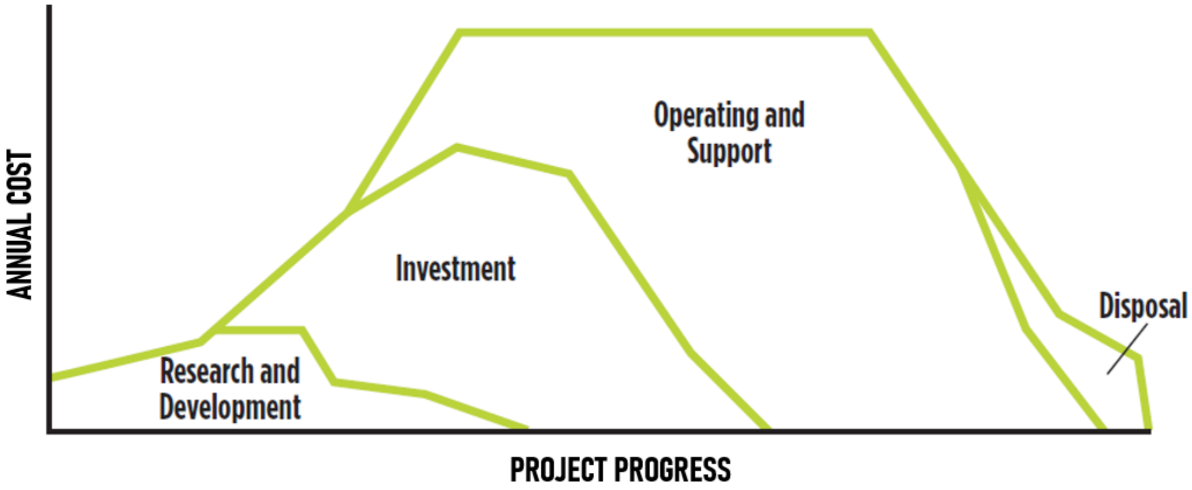

Figure 2: Illustrative Defense system life cycle cost (JONES et al, 2014)

Considering the most expensive phase (Operating and Support), one of the important decisions to be made is about the support structure to be used to perform the required maintenance services. In this way, the decision to outsource or perform aircraft maintenance in-house is a critical strategic choice. While outsourcing can offer potential benefits such as cost savings and access to specialized expertise, it also introduces risks related to quality control, data security, and potential disruptions in service. Conversely, in-house maintenance provides greater control over operations but may require significant investments in infrastructure, personnel, and equipment. To make a well-founded decision, it is essential to carefully evaluate the organization's specific needs, capabilities, and long-term objectives. Factors to consider include the complexity of the aircraft fleet, the availability of skilled personnel, the cost of maintaining in-house capabilities, and the potential risks associated with outsourcing.

The deregulation of the airline industry (which began in the late 1970s in the USA) marked a significant milestone for the outsourcing of aircraft maintenance, repair, and overhaul (MRO) services. By freeing airlines from government restrictions on routes, fares, and market entry, deregulation created a more competitive environment that encouraged the emergence of specialized MRO providers. These new companies could focus on delivering high-quality maintenance services at competitive prices, benefiting airlines by reducing costs and improving operational efficiency.

As a result of deregulation, airline operators were able to concentrate on their core business of transporting passengers and cargo while outsourcing non-core functions such as maintenance. This strategic decision allowed airlines to optimize their resource allocation, reduce overhead costs, and potentially improve their financial performance. By contracting with specialized MRO providers, airlines could access expertise and infrastructure that they might not have been able to develop or maintain in-house. Furthermore, projections indicate that spending on outsourcing is likely to increase over time, indicating the relevance of this issue, as can be seen in Figure 3.

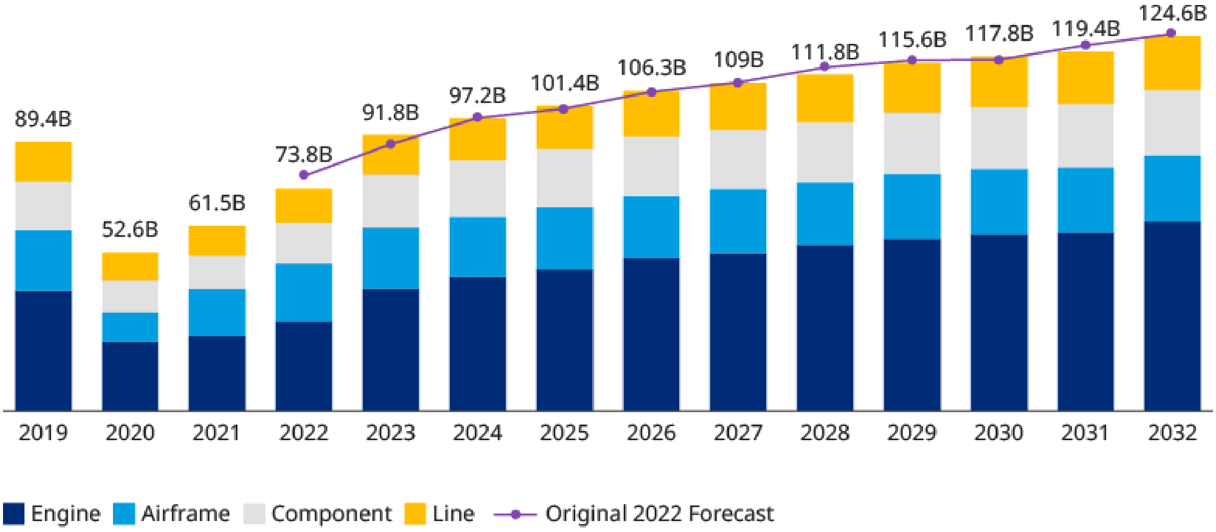

Figure 3: Global MRO spend by segment

Source: Oliver Wyman report. Available in: https://www.oliverwyman.com/our-expertise/insights/2022/oct/global-fleet-and-mro-market-forecast-update-2022.html. Accessed in: 10/03/2024

1.1 Motivation

Due to the LCC commitment trend (Figure 1) and the magnitude of supportability costs (Figure 2), a comprehensive supportability analysis becomes an indispensable approach to be made by the operators. Supportability analysis constitutes an iterative and continuous analytical process to ensure that supportability requirements are considered in both the development of new systems and in the reengineering of existing systems currently in operational use (BLANCHARD, 1998).

According to Figueiredo Pinto and Abrahão (2018), “methods for optimizing logistics processes are constantly being researched, proposed and tested in the constant pursuit of ensuring the supportability and financial viability of complex defense systems, which are equipped with increasingly advanced technologies and high added value”.

Figueiredo Pinto and Abrahão (2018) also said that “an essential and recurring theme in much of the research efforts is the prediction of LCC. In the specific case of military aircraft, the stochastic challenge brought about by the natural uncertainty that logistics processes have to face is aggravated by the need to project cost estimates for distant horizons, which may exceed the three-decade mark and include incremental updates or improvements (upgrades) or mid-life modernizations”. Therefore, it becomes evident the need and importance, as well as the complexity of supportability and LCC analysis.

There are several tools and methods for analyzing the supportability of systems, and some of the traditional and commonly used methods are: Maintenance Task Analysis (MTA); Reliability Centered Maintenance (RCM); Level of Repair Analysis (LORA**);** Failure Mode, Effects, and Criticality Analysis (FMECA); Fault-Tree Analysis (FTA) (BLANCHARD, 1998)**.**

Although these tasks have their purposes, applying them alone addresses niches of the supportability problem, but does not indicate in a simple and direct way a ranking of the factors with the greatest and least impacts on the cost of the system's supportability. The lack of a comprehensive analysis results in possible local optimal solutions, but these would not necessarily be the best solution for the problem as a whole.

Additionally, the issue of life cycle costs of defense systems is constantly highlighted by the U.S. Government Accountability Office (GAO). There is a concern about the balance between defense spending and the maintenance of defense capabilities. In their reports, GAO highlights the need to develop strategies to increase efficiency in aspects related to the supportability of systems in order to preserve combat capability and keep life cycle costs within budget (U.S. Government Accountability Office – GAO, 2022).

Although the importance of supportability analysis is evident, there is low maturity in the supportability management of complex systems, possibly due to difficulties in identifying the main vectors (IRIGON, 2020). In a military scenario, Gang Ding et al (2021) said that Commanders at all levels lack of scientific control methods and index requirements in the process of organizing support activities, and lack of mature modern intelligent system to support the dispatch of support resources. It was stated that, in order to improve the benefit of aviation maintenance support, it is necessary to improve the ability of comprehensive evaluation and optimization the main vectors. Martins (2023) also understands that it is essential that defense aircraft fleet managers have a strategy to identify, whenever necessary during the service phase, the most efficient line of action to improve supportability.

Therefore, it is important that fleet managers have a model that helps identify the best supportability strategy during the fleet operation and support phase, always seeking the most efficient alternative in terms of cost/effect.

1.2 Research Problem

The need to address the supportability and identify the best support strategies since the early project phases is unanimous when considering complex systems engineering. The sooner supportability issues are addressed, the greater the impact on operation and support cost and the ability to influence project decisions. Nonetheless, one of the most important decisions to be made is with regard to the supportability strategy to be used, more specifically with regard to whether maintenance services should be performed in-house or outsourced. This decision must be made years before the system entry into service (EIS), since it will result in planning and it will require a lot of investment to set the support structure ready to serve the fleet demands.

According to Al-Kaabi et al (2007), there are 4 main supportability strategies adopted by fleet managers: Fully integrated MRO (in-house); Partially outsourced MRO; Mostly outsourced MRO; and Fully outsourced MRO. The method to be used depends on various factors. Since if the demand is justifiable, or if the operators have the capacity to perform the tasks, the criticality of the tasks, the company core business, the initial and recurrent investments needed, or even strategic decisions by organization’s leaders.

When deciding which maintenance strategy to use, there are several factors to be considered, and some researches have approached these factors. Bazargan (2016) created a model to minimize the total cost of preventive maintenance programs over a planning period subject to some constraints. Hsu and Liou (2013) created a model to consider various parameters (e.g. cost, risk, flexibility, etc.) to choose the best outsourcing alternative throughout a questionnaire with experts. McFadden and Worrells (2013) provide a qualitative approach offering a list of factors that may impact outsourcing decisions, from partially to whole outsourced.

Liu and Tyagi (2017) addressed the outsource decision to convert fixed into variable costs. Commine (2023) explores the impact of outsourcing aircraft maintenance on flight safety.

Al-Kaabi et al, (2007) propose a qualitative approach through a flowchart process where the airline directors are asked questions in terms of their core businesses, capacity, demand and fleet.

Although all the mentioned works addressed the outsource issue in some way, the vast majority of the articles obtained qualitative analyses, such as interview with professionals, human factors, and safety. In addition, as mentioned by Massoud Bazargan (2016), there is a research gap regarding quantitative studies of the outsourcing of aeronautical maintenance services, since the vast majority of studies approach the theme qualitatively. As an example, there is a widespread concept that airlines with larger fleets have lower outsourcing level, since they are more able to support the cost associated with establishing a maintenance structure. However, no model was seen aiming to validate this premise, and if it is validated, what would be the breakeven number of aircraft for that. Additionally, virtually no attention has been given to the quality of outsourced maintenance services and its impact on logistical performance.

Due to that, the research problem consists of how to structure a model that cover the research gaps identified, aiming to model the support structure that analyze and quantify the different options for supportability, considering real data from a fleet already in operation, and that covers factors usually seem in practice, like resource constraints, unfulfilled contracts, subcontracting, and wide geographical distance of operations and suppliers. Additionally, this model will also optimize the inventory composition, as well as present metrics provisions for logistical performance and the cost of support, which helps to increase the situational awareness in the decision-making process during a project development.

1.3 Research questions

Considering a real fleet of aircraft and the way it is currently supported, what would be the impact on logistical metrics of considering different support structures? In addition, how does the fleet size and the cost of resources influence this decision? Also, how large should the maintenance structure to be in order to attend the fleet demands? What would be the impacts on cost and availability in cases of unsuccessful repair, as well as the impacts of contracting services that require longer time and the cost of transportation for special components, and finally the impact of exchange rate variations?

1.4 Objective

In order to solve the research problem and answer the research questions that summarizes it, the objective of this work is to develop a quantitative model for the supportability of a defense aircraft fleet that analyzes and quantifies the impact on operational availability and Life Support Cost of different outsource x in house decisions. Moreover, the model considers the impact of fleet size and resources costs to its decision, as well as evaluate the impact of unsuccessful repair when hiring a company without adequate capacity and skills. It also evaluates the impact of specific contracts for complex items and exchange rate variations. Finally, this research aims to become a guide for fleet managers and other professionals involved in aircraft maintenance.

1.4.1 Specific Objectives

To achieve the general objective, the following specific objectives (SO) were defined:

- SO #1. To establish the standard support structure (Default Model) based on field observations.
- SO #2. Analyze the support option considering fully outsourced maintenance based on data from the current contract.
- SO #3. Analyze the support option considering fully internalized maintenance, considering the fleet size, and the cost of the resources needed to acquire repair.
- SO #4. Evaluate how large the maintenance structure should be to handle the fleet demand, and its impact on availability, repair waiting list, and the fleet's ability to accomplish its missions.
- SO #5. Evaluate whether the Default Model is the most cost-effective solution based on the proposed model.
- SO #6. Analyze the support option considering the occurrence of unsuccessful repair, due to hiring a company without adequate capacity.
- SO #7. Analyze the impact of specific contracts for complex items that require longer transport times and costs.
- SO #8. Analyze the impact of exchange rate variations on fleet supportability.

1.5 Research Relevancy

By combining real data of technical, logistical, and commercial aspects of a fleet management into a single model, this research aims to create a model that helps fleet managers to gain situational awareness of their fleet supportability, and providing them with an estimation of the impact of different decisions to outsource or internalize support services, as well as evaluating the impact of variations that may occur during the in-service phase. Additionally, the academic relevancy is the development of the model evaluation.

1.6 Thesis Organization

The outline of the thesis is as follows.

Section 1, that ends at this section, presents the introduction, addressing the context of aircraft supportability, passing through the motivation, pointing out the concerns of cost of maintaining operational systems, followed by the research problem, defined the general and specific objects, presented the relevance of the research as well as its organizational structure.

Section 2 presents the consolidated theoretical knowledge needed to understand the following chapters, as well as a comparison between this work and previous research on the supportability of aerospace systems and complex Defense systems.

Section 3 covers the methodology used in this work, as well as the software used and a Demonstrative Model, aiming to validate the methodology.

Section 4 is the application of the methodology considering a real case scenario, with real data acquired in field. This was used to build the Default Model, and all the variations presented earlier were made based on this model.

Section 5 presents the result discussions and the conclusion of the work, as well as some suggestions of future work.

2 Theory review

2.1 Life Cycle of Complex Systems

This sub-section is separated into life cycle phases and life cycle costs of complex systems.

2.1.1 Life Cycle Phases of Complex Systems

Life cycle includes the entire spectrum of activity for a given system, commencing with the identification of need and extending through system design and development, production and/or construction, operational use and sustaining maintenance and support, and system retirement and material disposal (BLANCHARD and BLYLER, 2016).

In the military context, one of the main references is SX000i. This document is an international specification for the aerospace sector, specifically in the field of integrated product support (IPS), with the aim of promoting standardization, efficiency and quality in product support processes. They state the product life cycle of a product from beginning to end using a functional model with distinct sequential phases.

Although the definitions are quite similar, there are occasional differences in the divisions of the phases between different sources. For this reason, a schematic table has been drawn up as follows, with the main sources and their life cycle phases divisions.

Table 1: Life Cycle Phases

ASD/AIA SX000i 2021	Preparation		Development	Production	In service		Disposal
NATO AAP-20	Pre-concept	Concept	Development	Production	Utilization	Support	Retirement
US DoD Instruction 500.02	Material solution	Technology development	Engineering and Manufacturing Development	Production and deployment	Operations and support phase		
BLANCHARD, 1998	Conceptual design	Preliminary design	Detail Design and Development	Production and/or Construction	Utilization and Support		Retirement and Disposal
UK MoD Source: AOF	Conceptual	Assessment	Demonstration	Manufacture	In service		Disposal
Ministry of Defense MD40-M-01	Conception		Development	Production	Operation and Support		Disposal

Because of the different definitions, this work used the approach presented by SX000i, and the phases with their main activities are presented below.

Preparation:

- Identify user needs.
- Develop product requirements.
- Assess potential material solutions.
- Identify and reduce technology risks.
- Establish a business case including analysis of alternatives, cost estimate, for the launch of the Development phase.

Development:

- Develop a product that meets user requirements and can be produced, tested, evaluated, operated, supported and retired.
- Develop an affordable and executable manufacturing process.
- Ensure operational supportability with particular attention to minimizing the logistics footprint.

Production

- Produce of manufacture the product.
- Teste the product.
- Conduct product acceptance to confirm that the product satisfies the requirements.

In service:

- Operate the product.
- Deliver the required services with continued operational and cost effectiveness.
- Assess, decide on modification and upgrade.
- Evaluate continuously the effectiveness and efficiency of the product.
- Product support: Provide support that enables continued product operation and sustainable service.
- Implement modifications and upgrades.

Disposal:

- Demilitarize (if necessary).

- Dispose of the product in accordance with all legal and regulatory requirements and policy relating to safety. Security and environment.

Finally, it should be noted that this work focuses on the “in service” phase, that covers the supportability activities required to restore the fleet to adequate operational condition.

2.1.2 Life Cycle Costs of Complex Systems

Each of the phases described above has its own inherent costs. According to Jones et al (2014), for a defense acquisition program, life-cycle cost consists of Research & Development costs, Investment costs, Operating and Support costs, and Disposal costs over the entire life cycle. These costs include not only the direct costs of the acquisition program, but also indirect costs that would be logically attributed to the program. In this way, all costs that are logically attributed to the program are included.

An illustration is presented showing the order of magnitude of the life cycle costs of a defense system in Figure 2. As can be seen, besides the acquisition cost normally is the most addressed value, the cost of operation and support (O&S) accounts for the majority of the system's expenses.

Additionally, Blanchard and Blyler (2016) states that when addressing economic aspects, there is usually a lack of total cost visibility, as illustrated in Figure 4. For many systems, there is a well-known idea of the design, development and production costs. However, the costs associated with sustain management are somewhat hidden.

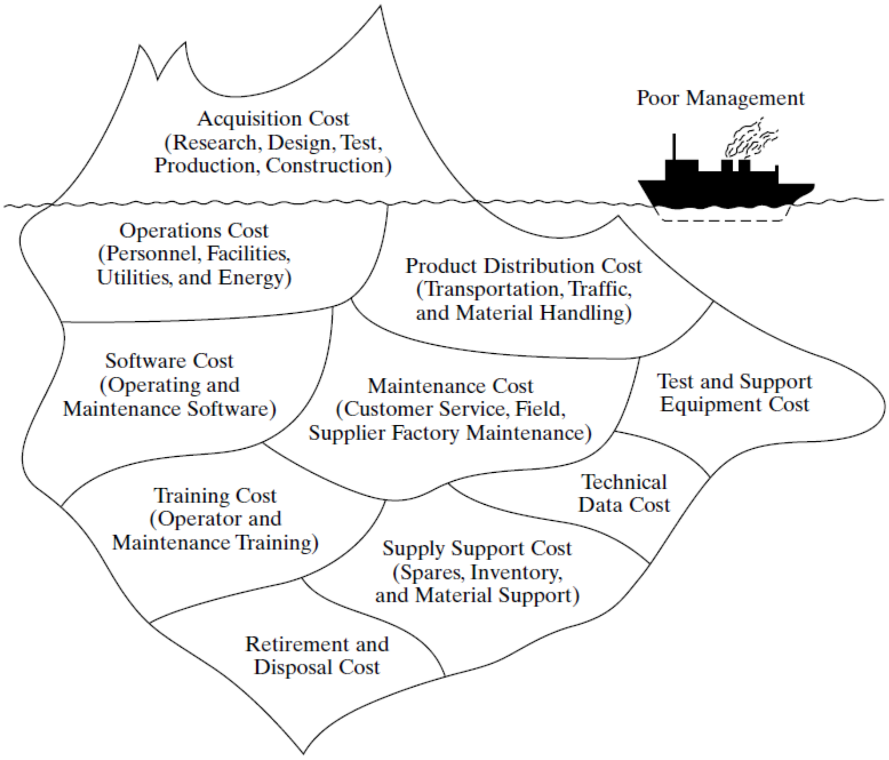

Figure 4: Total cost visibility (BLANCHARD, 2014)

According to Blanchard and Blyler (2014), the main supportability costs can be divided in:

- Maintenance facilities
- Test, measurement, handling, and support equipment / resources
- Maintenance and support personnel
- Training and training support
- Technical data information systems/Databases
- Computer resources (hardware / software)
- Supply support: Spare parts and inventories
- Distribution: Packaging, handling, storage and transportation

2.2 The Supportability Problem

According to Blanchard (2014), “design for supportability” is the degree to which a system can be effectively supported, both in terms of the built-in design characteristics of the prime mission-related elements of the system and the characteristics of the overall maintenance and support infrastructure (e.g., personnel, supply support and related inventories, test equipment, maintenance facilities).

However, designing a system with an emphasis on supportability becomes an even greater challenge because of the current environment in which we are inserted, and some of the challenges ahead is certainly a prerequisite to the successful implementation of system design for supportability. Although individual perceptions may differ, depending on what various individuals observe, there are a few trends that appear to be significant. These trends are summarized in Figure 5 (BLANCHARD and BLYLER, 2016).

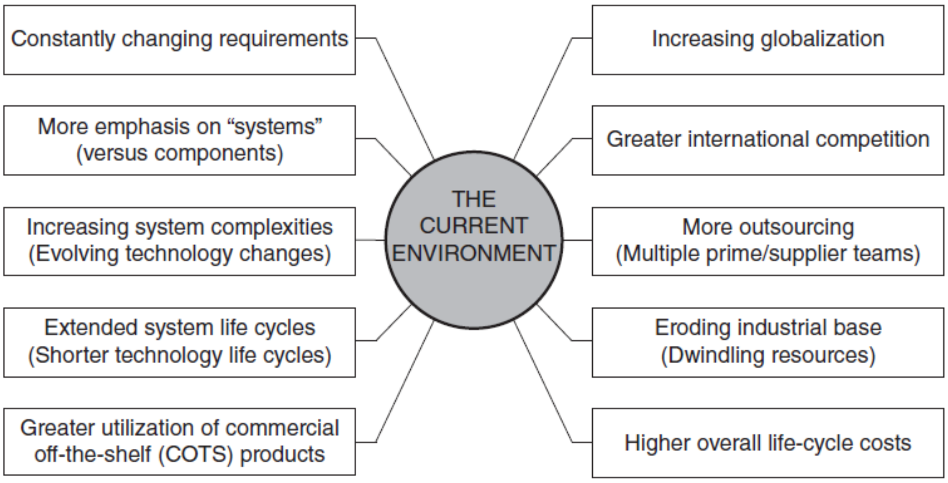

Figure 5: The current environment (BLANCHARD and BLYLER, 2016)

Additionally, supportability has been considered after the fact, and its associated activities have been implemented downstream in the system life cycle, and have not received the appropriate level of management attention. These practices have been detrimental in many instances, and the results have been costly. Figure 6 provides a rough comparison showing the effects of early life-cycle planning (solid line) versus addressing supportability issues later on (dashed line).

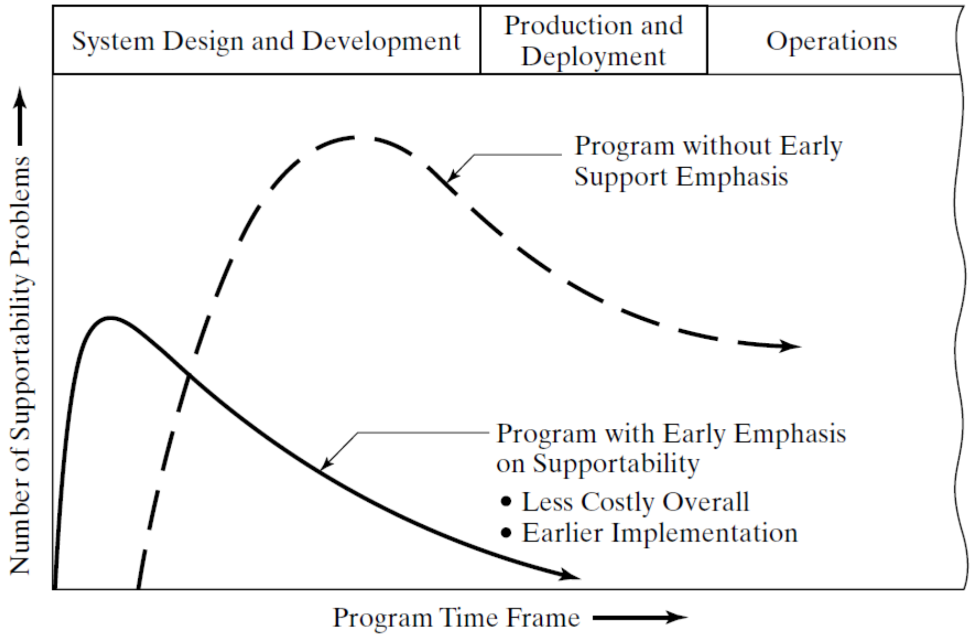

Figure 6: The consequences of not addressing supportability from the beginning (BLANCHARD, 2014)

The solid line represents a system with early emphasis on supportability, where the majority of the bugs are fixed and adjusted on the beginning of the program, leading to a mature system when it is launched to customers. On the other hand, the dashed line represents a system without early emphasis on supportability, which leads to an immature system that will have higher supportability problems, causing increase in costs and reduce in overall efficiency.

2.3 Supportability measures

In this sub-section it was covered the main indicators related to the understanding of this research.

2.3.1 Failure rate

The failure rate measures how frequently an item/system fails. According to Blanchard (2014), the rate at which failures occur in a specified time interval is called the failure rate during that interval. The failure rate (λ) is expressed as equation (1).

$$\lambda = \frac{number\ of\ failures}{total\ operating\ hours} \tag{1}$$

Assuming that the probability density function (pdf) of a failure, denoted by f(t), can be expressed by an exponential density function, the failure rate can be correlated to mean time between failure (MTBF) according to equation (2)

$$\lambda = \frac{1}{MTBF} \tag{2}$$

The equation for the probability density function assuming an exponential distribution can be expressed by equation (3).

$$f(t) = \frac{1}{MTBF} \times \mathrm{e}^{(-t/MTBF)} = \lambda \times \mathrm{e}^{(-\lambda \times \mathrm{t})} \tag{3}$$

The probability density function is a continuous representation of a histogram that shows how the number of component failures is distributed in time. In practical terms, it indicates the pattern of the failures. The exponential density function is an important distribution in reliability work, since it is a memoryless distribution, and represents, with good approximation, failures of a random and sudden nature (BIROLINI, 1999). Assuming this distribution, an illustrative probability density function, f(t), is illustrated in Figure 7.

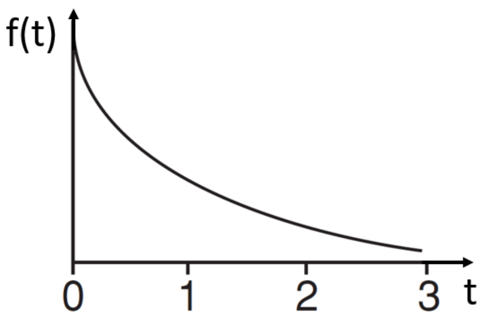

Figure 7: Illustrative probability density function considering exponential failure distribution (adapted from O’CONNOR; KLEYNER, 2012)

Additionally, the model considers constant failure rate (λ). This assumption is represented by the intermediate region of the bathtub curve, which illustratively represents the useful region of a given component/item. An illustrative bathtub curve is represented in Figure 8.

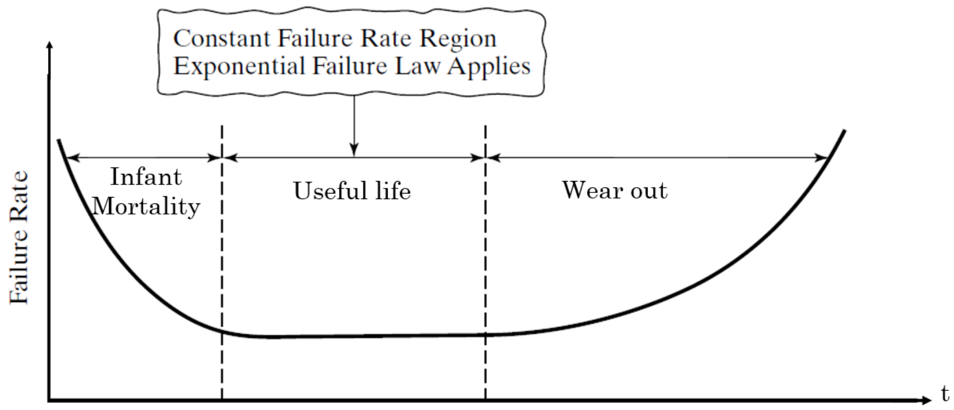

Figure 8: Illustrative Bathtub Curve (adapted from BLANCHARD, 2014)

2.3.2 Reliability

According to Blanchard (2014), reliability can be defined as the probability that a system (or product) will perform in a satisfactory manner for a given period of time, or in the accomplishment of a mission, when used under specified operating conditions. The reliability function, R(t), can be defined as equation (4).

$$R(t) = 1 - F(t) = \int_{t}^{\infty} f(t)dt \tag{4}$$

Where F(t) is the probability that the system will fail until the time “t”.

Considering the probability density function described by an exponential function, the reliability function can be simplified by the equation (5).

$$R(t) = \mathrm{e}^{(-\lambda \times t)} \tag{5}$$

Another important aspect is that if an item has a constant failure rate and an exponential probability density function of failure, the reliability of that item at its MTBF is approximately 0.37. In other words, there is a 37% probability that a system will survive its MTBF without failure (Blanchard, 2014).

2.3.3 Maintainability

Maintainability is an inherent design characteristic dealing with the ease, accuracy, safety, and economy in the performance of maintenance functions, and can be measured in terms of a combination of elapsed times, personnel labor-hour rates, maintenance frequencies, maintenance cost, and related logistic support factors (Blanchard, 2014). Despite other classifications, maintenance can be classified into two groups:

- Corrective maintenance: the unscheduled actions, initiated as a result of failure (or a perceived failure), that are necessary to restore a system to its required level of performance. Such activities may include troubleshooting, disassembly, repair, removal and replacement, reassembly, alignment and adjustment, checkout, and so on (Blanchard, 2014).
- Preventive maintenance: the scheduled actions necessary to *retain* a system at a specified level of performance. This category may include periodic inspections, servicing, calibration, condition monitoring, and/or the replacement of designated critical items (Blanchard, 2014).

Moreover, the probability distribution function for repair times (related to corrective maintenance) can usually be expected to take one of three common forms:

- Normal distribution: Applied to straightforward maintenance actions, which usually has little variation, such as remove and replace tasks.
- Exponential distribution: Applied to equipment with excellent built in test capability and remove and replace repair tasks. The maintenance rate is constant.
- Log-normal: Applied to systems where tasks time and frequency vary. Experience has indicated maintenance times for complex systems is approximately log-normal (Blanchard, 2014).

In addition to the concepts described above, there are other metrics that affect how efficient the company deals with its maintenance actions. They are described below.

- Logistic delay time (LDT): It is the maintenance downtime that is expended as a result of waiting for a spare part to become available, waiting for necessary test equipment to perform maintenance, waiting for transportation, or waiting to use a facility required for maintenance. It is a result of the capabilities required to perform the tasks.
- Administrative delay time (ADT): It is the delayed for administrative reasons: personnel assignment priority, labor strike, organizational constraint, and etc. It is a result of the administrative efficiency.
- Maintenance downtime (MDT): It constitutes the total elapsed time required to repair and restore a system to full operating status (in case of corrective actions) and/or to retain a system to full operating status (in case of preventive actions). It includes the active maintenance time (for corrective or preventive), the logistic and the administrative delay times.

The composition of a typical uptime/downtime diagram can be expressed in Figure 9.

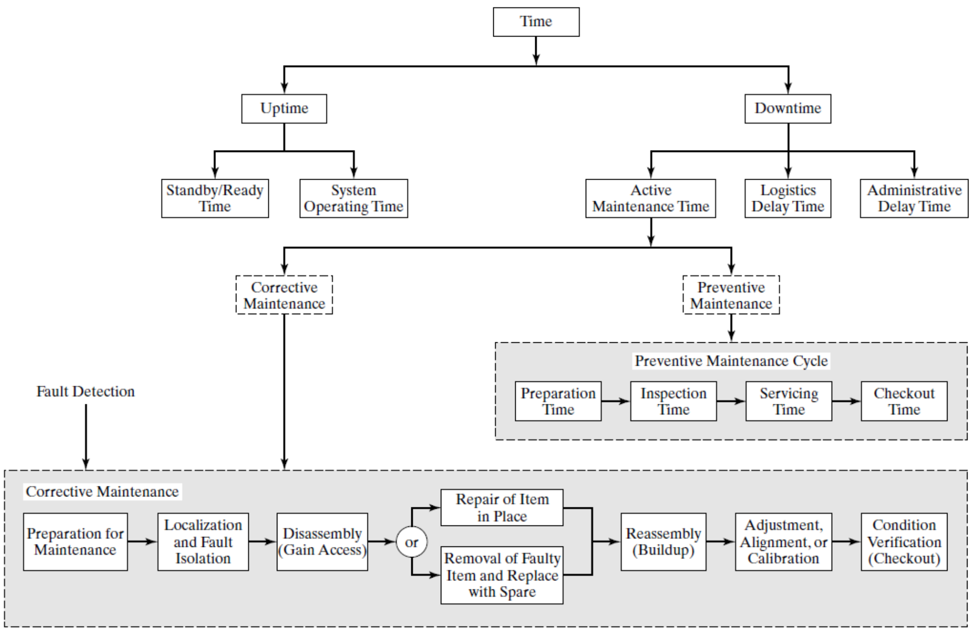

Figure 9: Uptime/downtime intervals (Blanchard, 2014)

2.3.4 Availability

A system availability can be expressed in different ways, depending on the data available and the entity purpose. But the main idea is the same, that is compute the ratio in which the numerator considers uptime, while the denominator considers the total elapsed time (the sum of uptime and downtime). Some of the availability measures are expressed below:

Inherent Availability (A_i)

It is the steady state availability which considers only the corrective maintenance (CM) (O'CONNOR; KLEYNER, 2012). The uptime is the MTBF, while the downtime is the MTTR. The formula becomes the equation (6).

$$A_i = \frac{MTBF}{MTBF + MTTR} \tag{6}$$

Achieved Availability (A_a)

It is similar to inherent availability, with the exception that considers also the preventive maintenance downtime (O'CONNOR; KLEYNER, 2012). Once it considers the preventive maintenance, the uptime becomes the MTBM (mean time between maintenance), and the downtime becomes MMT (mean maintenance time). The formula becomes as equation (7).

$$A_a = \frac{MTBM}{MTBM + MMT} \tag{7}$$

And MTBM can be calculated as:

$$MTBM = \frac{1}{\lambda + f_{PM}} \tag{8}$$

Where: λ = failure rate (considering all failures are repaired)

f_{PM} = preventive maintenance frequency (inverse of PM cycle)

And MMT, considering both corrective and preventive maintenance, can be computed as:

$$MMT = \frac{\lambda \times MTTR + f_{PM} \times MPMT}{\lambda + f_{PM}} \quad (9)$$

Where: MPMT = mean preventive maintenance time

Operational Availability (A_{op})

It is the measure of the “real” availability in an actual operational environment. It includes all typical downtime sources, corrective and preventive maintenance, as well as administrative and logistic delays (O’CONNOR; KLEYNER, 2012). The computation can be performed according to equation (10).

$$A_{OP} = \frac{MTBM}{MTBM + MDT} \quad (10)$$

Where: MDT = mean downtime

Additionally, MDT can be expressed as (11).

$$MDT = MMT + LDT + ADT \quad (11)$$

Where: LDT = Logistic delay time
ADT = Administrative delay time

2.4 Integrated Product Support (IPS) in the development of complex systems

2.4.1 IPS elements

The International Specification for Integrated Product Support (IPS), outlines a comprehensive framework for managing all aspects of aircraft's life cycle, from its initial design and development to its eventual retirement. It covers various aspects with relevant impact on aircraft’s life cycle. The last version (released in 2021) considers 12 elements to be addressed, and considering these elements has the possibility to improve operation consistency and reduce risks associated with aircraft operations, which can lead to higher overall fleet efficiency. The 12 elements are described in Figure 10.

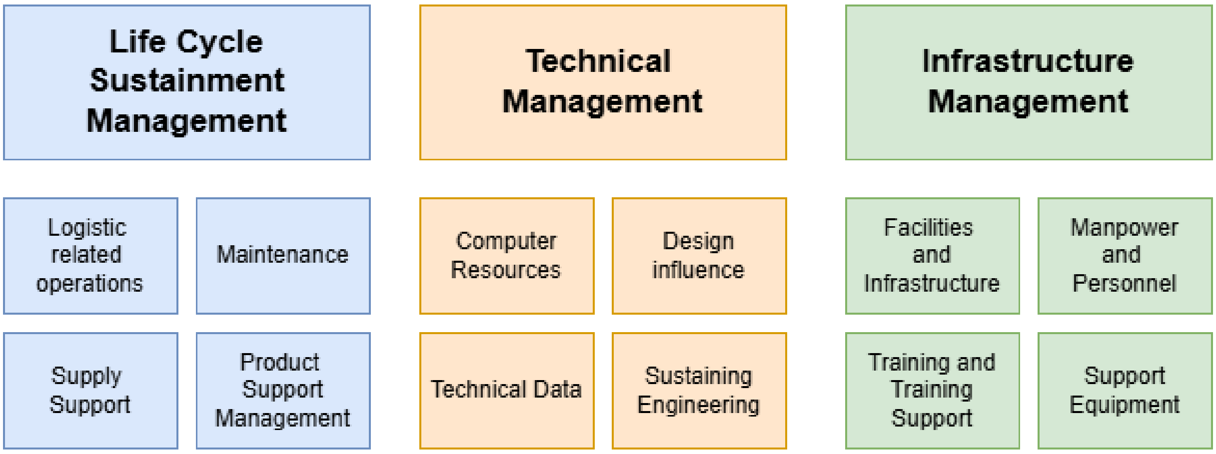

Figure 10: IPS elements

A brief description of the elements is described below.

- **Logistic related operations**: This IPS element covers tasks, which cannot be assigned to an area of the direct operation and maintenance of a Product. However, these tasks can be important for the proper use of a Product. This analysis includes the identification of related tasks and requirements concerning personnel, support equipment, consumables, spare parts, facilities, technical documentation and training. The outcomes are documented in the support-related operations report. Some of the tasks require early consideration in the life cycle, while others can be considered later (ASD/AIA, 2021). For the present research this element covers aspects such as transportation (its metrics, such as time, cost, and different options), storage (where to store, how many of each item and how much it will cost), and items expedition (such as packing and handling).
- **Maintenance**: It establishes maintenance concepts and requirements for the life cycle of the Product. This element has a major impact on the planning, development and acquisition of other product support elements. The objective of maintenance is to identify, plan, resource, and implement maintenance concepts and requirements as well as to execute the maintenance to ensure the best possible equipment/capability is

available at an affordable cost (ASD/AIA, 2021). In this element it is developed the maintenance concept, that considers the contract available, develop a Level Of Repair Analysis (LORA), that ends up serving as a guideline of how the fleet is going to be supported (which tasks will be made, where and when they will be made).

- **Product Support Management**: It consists of elaborating the support concept, the IPS plan and providing obsolescence report. To achieve that, the following activities are performed: Analyze product alternatives; Develop the integrated product support plan; Document lessons learned; Manage configuration; Manage contract; Manage fleet; Manage in service IPS activities; and Perform obsolescence management. Some of the outputs of this elements are: The support concept chose; Support contract; As-is configuration; and fleet performance report (ASD/AIA, 2021). This element works together with the "Maintenance" in order to choose the most suitable support concept.
- **Supply support**: This IPS element aims to identify, plan for, resource, and implement management actions to acquire repair parts, spares, and all classes of supply to ensure the best capability is available to support at the lowest possible life cycle cost. This means having the right spares, repair parts and supplies available, in the right quantities and quality, at the right place, at the right time, at the right price. To achieve this goals, 4 main activities are performed: Manage stocks/stores; Manage warranty; Perform material supply; and provide provisioning data. Some of the outputs of this element are: Inventory reports; Warranty reports; Initial provisioning list; and spare parts list (ASD/AIA, 2021). This element is intrinsically linked to the model developed in this research, since it considers data on the fleet and the operation and generates an initial provisioning list, as well as considering the demand for consumables.
- **Computer resources**: This element aims to identify, plan and resource facilities, hardware, software, documentation, manpower and personnel necessary for planning and management of mission critical computer hardware and/or software systems. The main activities of this item are: Manage computer resources; Perform computer resources analysis; and provide computer resources (ASD/AIA, 2021). This element was not directly addressed in this research.
- **Design influence**: It is the process to influence the design from its inception through the product life cycle to facilitate supportability and to optimize the design for availability, effectiveness, and ownership costs. Design influence is the integration of the quantitative design characteristics of systems engineering (e.g., RAMCT,

supportability, affordability) with the functional IPS elements. The main objective is to ensure that the product meets its availability goals and design costs, with an affordable support cost. To achieve that, 3 activities are performed: Life cycle cost (LCC) analysis; Product support analysis; and support engineering analysis. The main outputs from this element are: Logistic Support Analysis database; Support engineering reports; and LCC report. LCC considers all the costs associated to development, production, procurement, operation, support and disposal of the product (ASD/AIA, 2021). This is the most important element for this research, since it aims to develop a quantitative model for analyzing supportability structure options.

- **Sustaining engineering**: This activity includes the technical tasks (e.g., engineering and support investigations and analyses) that ensure continued operation and maintenance of a Product until its disposal. It also involves the identification, review, assessment, and resolution of deficiencies throughout a Product's life cycle. It returns a Product to its baseline configuration and capability, while identifying opportunities for performance and capability enhancement. The main activities performed at this element are: Evaluate operational suitability; Manage disposal; and perform engineering technical analysis. The main outputs expected are: Engineering change request; Operational suitability report; and feedback information (ASD/AIA, 2021). This element was addressed secondarily in this research, while the operational indicators for the different aircraft operating bases were monitored.
- **Technical data**: Technical data is the information recorded, and it does not include computer software or contract administration data such as financial or management information. The objective is to identify, plan, validate, resource and implement actions to develop, acquire and maintain information, as well as to plan, develop, produce and maintain technical publications (ASD/AIA, 2021). This element was not directly addressed in this research.
- **Facilities and infrastructure**: It consists of the real property assets or mobile facilities required to integrate, support and operate a product. It includes studies to define types of facilities, facility improvements, location, space needs, environmental and security requirements and equipment. Since there is a long period since the facility definition until it is ready to be used (it is necessary to raise investments, planning, construction and acquisition,), it is necessary that this element must be considered to be performed in the early phases of the product/program development (ASD/AIA, 2021). This element was addressed mainly in the fully internalized maintenance option, that

considers the costs needed to acquire the maintenance capability, which includes cost of Ground Support Equipment (GSE), facilities and others.

- **Manpower and personnel**: The objective is to identify, plan and resource personnel, which have the necessary qualifications and skills (ASD/AIA, 2021). This element was addressed evenly when considering the work force needed (e.g. nº of people and expected time) to perform the maintenance tasks, such as corrective, scheduled and removal and installations tasks, and its impact on costs.
- **Support equipment**: The objective is to identify, plan, resource and implement management actions to acquire and support the equipment required to sustain the operation, maintenance and supply of the product to ensure that the product is available to the user when it is needed at the lowest life cycle cost (ASD/AIA, 2021). This element was addressed when considering costs of GSE needed to acquire the capability to execute the corrective maintenance tasks in house.
- **Training and training support**: The objective for this is to identify, plan and resource training support and implement a training strategy and to train personnel to operate, maintain and support the product throughout its life cycle to assure optimum performance and readiness of the product (ASD/AIA, 2021). This element was addressed when considering the costs with training (initial and recurrent) needed to qualify the mechanics to perform the tasks.

At the end, the SX000i summarizes the main activities to be performed of each element and when they are supposed to happen. Some of these activities, with the tasks related to this study was addressed again later on this research.

2.5 Fleet supportability modeling

2.5.1 System approach versus item approach

According to Sherbrook (2004), traditional inventory theory uses the item approach, where the spares for an item are determined by formulas that balance the costs of holding inventory, ordering, and stockout. It is simpler because decisions on the number of spare units of stock to buy on an item are made without considering other items.

On the other hand, the system approach is able to identify the best support solutions and can estimate the system availability and its related impact on cost. The system approach can answer questions like: How much money should we spend to achieve a 90% availability? How much money would we save if the availability requirements was reduced from 90% to 80%? Is it economic to have more repair capability at the operating sites? What does the optimal system cost-effectiveness curve look like? In that way, the fleet manager can have a holistic view of his assets (Sherbrook, 2004).

In summary, the system approach has the advantage to estimate the system cost-effectiveness relation, and this relation is outputted as a curve of inventory alternatives (Marques, 2017). Due to that, the system approach was used to carry out the analysis on this research.

2.5.2 Single site inventory model

First, the one-echelon model was modeled. The one-echelon model simplifies the analysis to the point that it disregards the transportation time of the items. The starting point is the occurrence of a failure in an aircraft. In order to prevent the aircraft from becoming unavailable, the failed component will be removed and a properly functioning component will be installed. The failed component will be sent to a station for repair, and once it has been repaired it will be available for use. As a result, it is clear that additional components will have to be purchased in addition to those installed in the aircraft, in order to allow the stock rotation works properly. If a component fails and there is no substitute in good condition in stock, the aircraft will be unavailable waiting for a component to be repaired and installed. The spare part flowchart of a single item (tail rotor) in a single site can be illustrated as Figure 11.

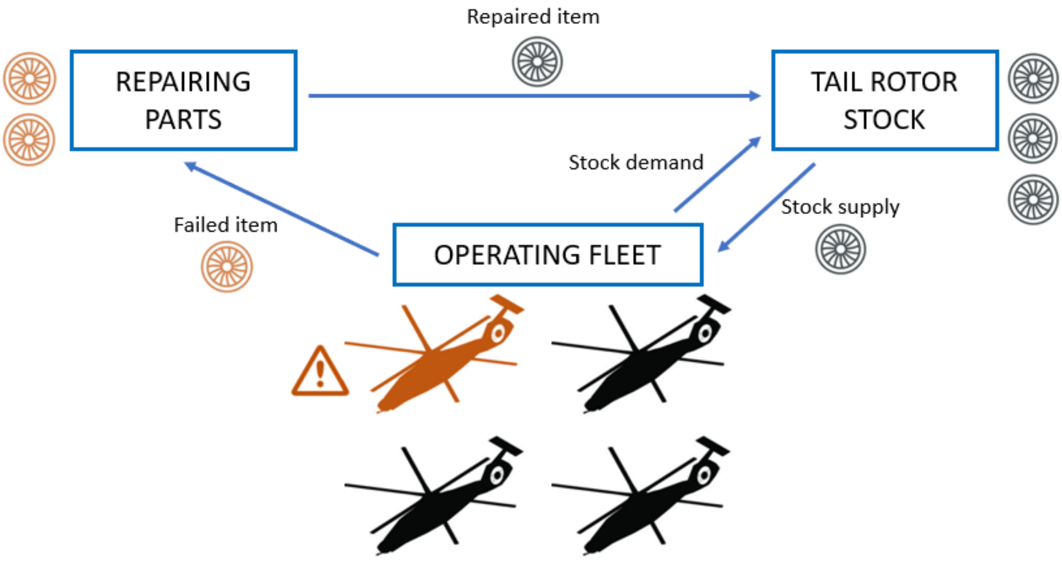

Figure 11: Spare part flowchart

In Figure 11, the Operating Fleet is being used normally until a failure happens on the tail rotor (the orange aircraft). Given that, the item is removed and send to repair, and at the same time the warehouse is asked if there is a tail rotor in good condition to be installed. In case of affirmative answer, the item in good condition will be send to the operating site to be installed. In case of negative answer, the orange aircraft (the faulty one) will wait until the component be repaired.

Considering that the variable being analyzed is stock items, which acquire integer and non-negative values, where X is a random variable and Pr{X=x} is the probability of the random variable "X" having the specific value of "x", the average of X can be given by:

$$E[X] = \sum_{x=1}^{\infty} x \Pr\{X = x\} \tag{12}$$

And to measure the spread of X around the mean it was be used the variance, which can be computed as equation (13):

$$Var[X] = E[X - E[X]]^2 = E[X^2] - (E[X])^2 \tag{13}$$

Another important definition is the Poisson distribution, p(x), which can be given by equation (14):

$$p(x) = (mt)^x.\mathrm{e}^{-mt}/x! \qquad x = 0, 1, 2, 3 \ldots \tag{14}$$

Where m is the average annual demand and t is the average time period measured in years.

According to Sherbrook (2004), when the time between demands is given by an exponential distribution (also called a *Poisson process*), the number of demands in a time period of any fixed length is given by the Poisson distribution. The exponential distribution is the "memoryless" distribution in which the time of the last demand has no influence on the time of the next demand. Since random failures are the primary type for which our models are designed, the Poisson distribution was used to model the item's demand.

And, according to Palm's theorem, if an item demand is a Poisson process with annual mean "m" and the repair time for each failed is independently and identically distributed according to any distribution with mean "t" years, then the steady-state probability distribution for the number of units in repair has a Poisson distribution with mean "m x t" (Sherbrook, 2004).

2.5.3 Stock Level

To model the stock level, it was assumed that the failed items can always be repaired, and the average time to repair assume a probability distribution with mean "t". The stock level, "s", is the number of spare items to allow the replacement of failed aircraft items, in order to put the aircraft available again. The stock level can be computed according to equation (15).

$$s = OH + DI - BO \tag{15}$$

Where OH means "on hand" (when item is available), DI means "due in" (the item is not available, it is in process to be repaired), and BO means "back order" (when there is a failure but there is no item available to replace). All these variables assume integer and non-negative values.

According to equation (15) the OH is the spares on shelf in good condition. If all the items are available, DI = 0 and s = OH. Meanwhile, if there are some items in process to be repaired (DI ≠ 0), then the amount available items are smaller than the stock level (OH < s). There also may be times when there is nothing on the shelf and a failure happens, it happens when the number of items being repaired (DI) will be equal or even greater than “s”. This is the situation when back order ≠ 0. The pattern of the stock on hand can be expressed by Figure 12.

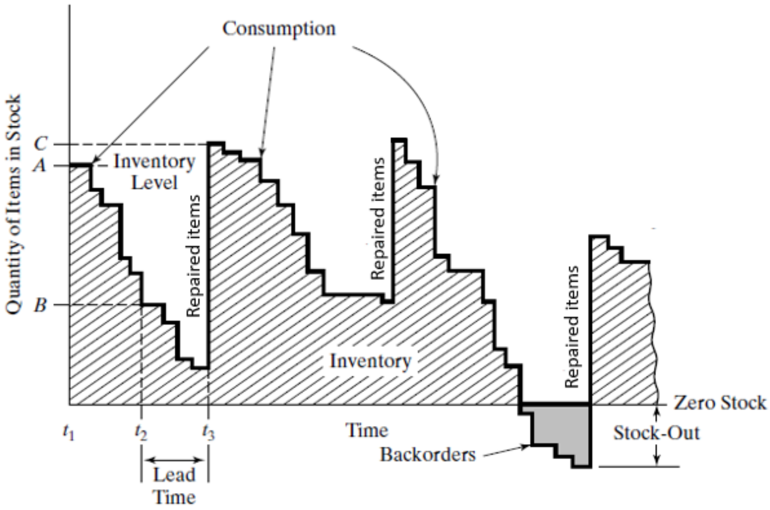

Figure 12: Stock cycle representation (adapted from BLANCHARD, 2014)

2.5.4 Item demand

The average demand (m) of an item per hour is proportional to failure rate (FRT), utilization rate (UTIL), quantity of items per aircraft (QPA) and the quantity of aircraft being operated (QTYACFT). The item demand can be expressed by equation (16).

$$m = FRT \times UTIL \times QPA \times QTYACFT \tag{16}$$

Additionally, the average quantity of items being repaired can be expressed. Considering the item demand as a Poisson process with mean “m” and the average repair time with mean “t”, the average quantity of items being repaired can be expressed as a Poisson process, within Palm theorem, with average:

$$\lambda = m \times t \tag{17}$$

Where “λ” is the average quantity of items being repaired.

2.5.5 Fill Rate (FR) and Expected Backorder (EBO)

There are two principal measures of item performance, “fill rate” and “backorders”. They are intrinsically related to the equations (15), (16), and (17).

Fill rate is the percentage of demands that can be met at the time they are placed. It will happen if DI = s - 1 or less, because it implies that there is stock on hand (OH). Whenever the number due in is s or more, there is no stock on hand. Thus, we can designate the expected fill rate EFR(s) according to equation (18).

$$\begin{gathered} EFR(s) = \Pr\{DI = 0\} + \Pr\{DI = 1\} + \cdots \Pr\{DI = s - 1\} \\ EFR(s) = \Pr\{DI \leq s - 1\} \end{gathered} \tag{18}$$

Backorder is the number of unfilled demands that exist at a point in time. Whenever we are unable to fill a demand, a backorder is established. The backorder lasts until there is a resupply or a failed item is repaired. It is important to note that a backorder happens only when all the stock level “s” are in repair “DI”, which means that OH = 0 and there is(are) demand that can not be satisfied. The computation of the expected backorder (EBO(s)) can be made according to equation (19).

$$EBO(s) = \sum_{x=s+1}^{\infty} (x - s). \Pr\{DI = x\} \tag{19}$$

The expected number of backorders is a non-negative quantity. Note that when s = 0, equation (19) becomes identical to equation (12) for the mean of a distribution. Thus, EBO (0) = $E[X]$ (Sherbrook, 2004).

In order to avoid summation to infinity, equation (19) can be rewrite according to equation (20).

$$EBO(m.t, S) = \lambda - S + \sum_{x=0}^{S} (S - x). \Pr\{X = x\} \tag{20}$$

2.5.6 Marginal Analysis

As previously said, when a backorder happens a system becomes unavailable waiting until an item in repair is finished and it turn in good condition to be used. Due to that, the number of backorder and availability has an inverse relation, and minimizing the expected backorder (EBO) increases availability. The trial-and-error procedure is not an efficient way to develop an optimal backorder-versus-cost curve. Instead, it was used a technique called marginal analysis. The technique is called marginal analysis because at each step in the algorithm look only at one number for each item to determine the next item that should be bought (Sherbrook, 2004).

In order to carry out the marginal analysis, it is necessary to state the benefit-cost-ratio (BCR) equation.

$$BCR = \frac{[\,EBO(S-1) - EBO(S)\,]}{item\ cost} \tag{21}$$

This equation is the increase in system effectiveness per dollar obtained when an additional unit of an item is selected for stockage. To begin the analysis the BCR is computed for all the items. As it is in the beginning, there is no item stocked, so S = 0 for all of them. So, the item with the higher BCR will be the first to be bought, and the BCR of that item should be updated to S=1 for it. After this update, the algorithm will choose again the item with the higher BCR, and so on. After performing this step several times, it will be achieved several optimum points of level of stock that reduces the number of backorders with the least cost, as can be seen an example in Figure 13.

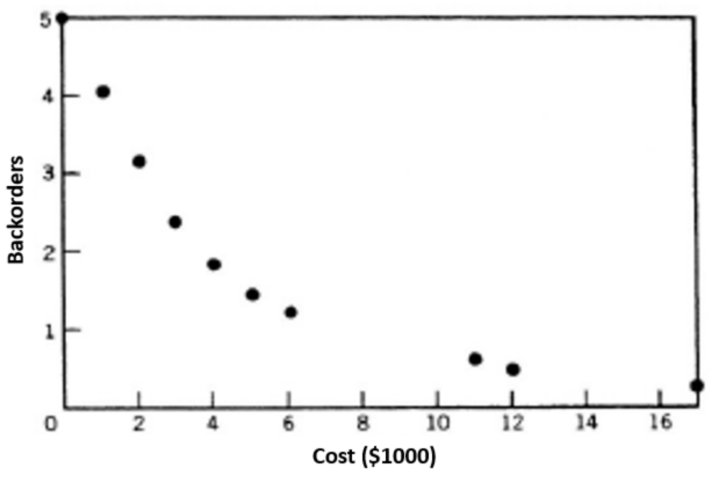

Figure 13: Backorder x Cost curve (Sherbrook, 2004)

2.5.7 Availability and EBO Relationship

As stated in previous stages, there are different availability measures. At this research we are focused on the operational availability, that is stated as equation (10), in subsection "2.3.4 Availability", and it is rewriten below.

$$A_{OP} = \frac{MTBM}{MTBM + MDT} \tag{22}$$

The MDT is the mean downtime, which can be computed as a sum of corrective maintenance time, preventive maintenance time, logistic delay time and administrative delay time. The operational availability is the one that was computed on this research, meanwhile, for didactic explanation purposes the maintenance times will be ignored (maintenance times will be ignored just in the equation below), since we are focusing on the impact of awaiting items, and so we get a relation between availability and only one variable, the backorder.

$$A = \frac{MTBF}{MTBF + \frac{EBO}{m} \times UTIL} \tag{23}$$

Where UTIL is the utilization rate of the aircraft over a year.

With this relation we can use the same marginal analysis to reduce the number of backorders to estimate the availability x costs, as can be seem in Figure 14.

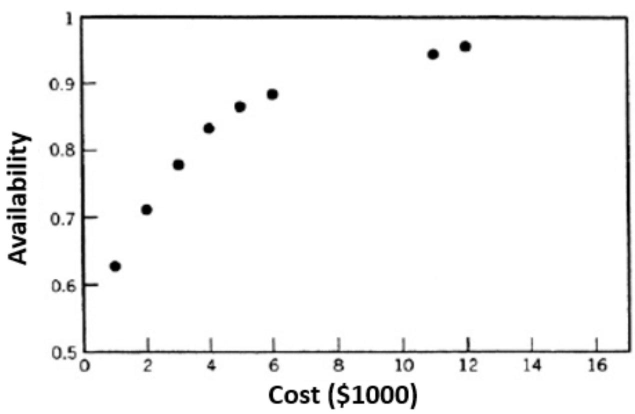

Figure 14: Availability x Cost curve

As can be seen, the availability value asymptotically approaches 100% as the number of parts in stock increases. This estimate occurred because the only downtime being computed is the waiting time for parts to be repaired, and since we have a lot of spare parts (the last points on the “curve”) there will be no waiting time. However, the analysis in this research considered maintenance time into account, so availability values tend to be lower, and buying more spare parts will not lead to 100% availability, due to the inherent reliability and maintainability characteristics of the system under analysis.

Sherbrook (2004) states that operational availability can be computed from maintenance availability and supply availability. Maintenance availability is a single number that depends on the maintenance resources, but it is independent of the supply policy. Supply availability is independent of maintenance resources, but it is not a single number. It is a function of the supply policy, and it is this optimal availability vs. cost relationship that we focus.

Additionally, it is important to remember that each discrete point on the optimal availability vs. cost curve in Figure 14 is the maximum availability for the specified cost, and equivalently the minimum cost to achieve that availability.

2.5.8 METRIC Model

The METRIC (Multi-Echelon Technique for Recoverable Item Control) theory is considered in case there is not only one stock base. This theory calculates the optimal stock level at each of several bases for every item on the system. The objective function is the sum of backorders across all bases, since the minimization of base backorders is equivalent to maximization of availability. This model is typically used when there is one big central stock base, that is called depot, and there are some local stock bases, that is called bases anyway.

According to Sherbrook (2004), there are some assumptions regarding the METRIC model. As stated by him, some of them may not be fully observed in practice, but they should be true most of the time. These assumptions are:

- The decision as to whether a base repairs an item does not depend on stock levels or workload. This premise states that if a particular base has the capability to perform a specific task, this task will be performed there. In other words, there is no restrictions such as personnel or lack of the item, that will be shipped from depot if it is not available at depot.
- There is no lateral supply between bases. The bases will be resupplied from the depot.

- The (s - 1, s) inventory policy is appropriate for every item at every echelon. This is typical for items that demands rate are low and the costs are sufficiently high. This means that there is no batched for repair, in other words, it will be applied the first in first out (FIFO) rule, as well as an item without repair will be replaced by a new one within the one-by-one basis.
- Optimal steady-state stock levels are determined. This means that the factors that contribute to demand will remains fairly constant over a period of time. And if there is any change on that factors the stock level should be recomputed.

In the METRIC model, first it is computed the average demand of each item at the depot, that is the fraction of the demand that is not repairable at each base, summed over all the bases.

$$m_{i0} = \sum_{j=1}^{J} m_{ij}(1 - r_{ij}) \tag{24}$$

Where "i" is the item index, "0" refers to depot, "j" refers to each base, m_{ij} is the demand of item "i" at base "j", and r_{ij} is the probability of repair the item "i" at base "j".

If the base "j" always has the capability to repair the item "i", so the average number of items in repair, λ_{ij}, is given by $m_{ij}T_{ij}$, where T_{ij} is the average time to repair the item "i" in base "j". However, once there is limitation in bases repair process, the average number of item "i" in repair at base "j" is given by:

$$\lambda_{ij} = m_{ij}\left(r_{ij}.T_{ij} + (1 - r_{ij})\left(O_j + \frac{EBO[s_{io}|m_{io}T_{io}]}{m_{io}}\right)\right) \tag{25}$$

Where "i" and "j" assume positive integer numbers, O_j is the order and ship time from depot to base "j", and $EBO[s_{io}|m_{io}T_{io}]$ can be expressed by:

$$EBO(s_{i0}|m_{i0}T_{i0}) = m_{i0}T_{i0} - s_{i0} + \sum_{x=0}^{s_{i0}} (s_{i0} - x)\, P(DI = x) \tag{26}$$

Where DI is the "due in", or the number of items in repair.

2.6 ABC Analysis

ABC analysis is a technique for classifying stocks according to their relevance, which can include the price of the item, the frequency of use, among other criteria. The technique is based on the Pareto principle (80/20 rule), which states that approximately 80% of the effects within any system originate from 20% of the causes, meaning that there is an unequal relationship between the items in a stock (KUUSE, 2024).

Based on this, the aircraft's components were chosen based on an ABC analysis, following a ranking of the most significant components according to the significance index according to equation (27).

$$SI = FR \times PRICE \times QPA \times MTTR \tag{27}$$

Where:
SI: Significance index
FR: Failure rate
PRICE: Acquisition price of the item
QPA: Quantity of the item per aircraft
MTTR: Mean time to repair the item

2.7 LORA

A LORA (Level Of Repair Analysis) is a analytical process to determine where, when and how the maintenance tasks will be performed in a support structure. The decision factors taken into account in a LORA process include economic and non-economic factors, such as political, social and environmental issues (BLANCHARD, 2014).

The economic LORA usually take into consideration a mathematical formulation with one objective function related to a system metric (normally aiming to minimize the costs), respecting some constraints (e.g. set a minimal availability allowable). The LORA process aims to answer some questions, such as: for each event (failure or scheduled maintenance) what maintenance action should be taken and where; for each component, should it be repaired or discarded and where it should happen; and also where to install the resources needed, such as facilities, bench test and warehouse, in order to execute the maintenance tasks. In other words, an economic LORA take into consideration several constrains based on the support structure available and perform an optimization process in order to find the best choice in terms cost saving.

On the other hand, a non-economic LORA, according to Buch (2023), considers factors not directly related to costs, such as: political restrictions and interests; restrictions imposed by component manufacturers; limitations on repair facilities or inappropriate environmental conditions; mobility/transport restrictions and others. Additionally, given that the present research modeled a defense aircraft fleet, a non-economic LORA should consider questions such as: desire to have more control over the operation; avoid/minimize the risk of discontinuity; and guarantee continuity of services during geopolitical instability periods. In this way, non-economic LORA are conditions and/or restrictions that must be satisfied regardless of the financial impact on the cost of fleet supportability.

Since this research focused on cost-benefit analysis, it did not cover aspects related to a non-economic LORA. However, it did cover some aspects related to an economic LORA, since it was analyzed different outsourcing options, which aimed to identify where the maintenance actions should be performed, it was analyzed the costs to acquire the resources, and also analyzed the level and location of inventory.

2.8 Literature Review x Present Research

In order to reach a wide range of works on this topic, the platform LENS.ORG (https://www.lens.org/) was used to search for related works. Afterwards the Google Scholar platform was used too. The keywords used on LENS.ORG for the search were:

- Aircraft OR Airplane OR Airline; AND
- Outsource OR Outsourcing; AND
- Maintenance; AND
- Militar OR Military OR Defense OR Airforce OR Air Force

As a consequence, it was able to check the latest relevant publications (written in English) and related to the research, as well as making sure this present research is being conducted guaranteeing up-to-date literature coverage.

These keywords were chosen in order to make the selection filter as wider as possible (in order to obtain a large number of papers), while at the same time ensuring that they were related to the subject of this research (outsourcing of maintenance services on military aircraft). The result of this search was 168 papers found.

Despite the fact that the search found a reasonable number of papers, and in addition to the fact that the search filter tried to restrict the search to papers on outsourcing maintenance services on military aircraft, most of the papers found did not have good correlation to the research filter. Therefore, it was analyzed the relevance of the researches one by one, and it was observed very few papers left related to the topic proposed for this research.

In view of that, a new search was carried out, removing the last restriction from the search filter (Military OR Defense OR Airforce OR Air Force). In this way, the new search still looks for topics related to outsourcing of aeronautical maintenance services, the only difference being that it was not be restricted to the defense sector. This search returned 444 papers, and the distribution by year is according to Figure 15. As can be seen, there is a constant interest in research related to outsourcing of aeronautical maintenance services since the early 2000s.

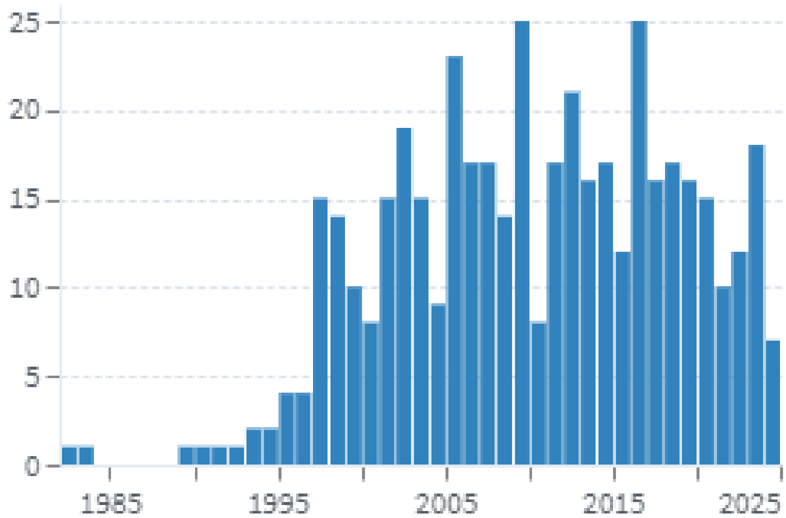

Figure 15: Literature research results (LENS.ORG, 2024)

Again, most of these papers did not actually meet all the search restrictions. In this way, the papers were analyzed one by one again, covering the first 100 papers indicated. It was observed that after the first 100 titles the vast majority no longer had a good relationship with the research topic and could be discarded. After that, the filter was narrowed down to the most relevant researches and a manual selection based on the abstracts was performed aiming to choose the more correlated to the development of a quantitative model considering outsourcing issues. After that, the papers with the best correlation are described below:

Bazargan (2016) work was the most relevant research founded. He developed a mathematical model to minimize the total cost of heavy maintenance programs over a planning period subject to performing all maintenance programs on time and other side constraints. Despite he did not aim to build a cost-effective-correlation, some of the conclusions achieved were:

- A combination of in-house and outsourced maintenance checks is recommended.
- More expensive maintenance checks (heavy D checks) are recommended to be outsourced while less expensive ones to be performed in-house.
- Fixed costs to set-up hangars for in-house maintenance facilities represent a small percentage in the overall cost structure.
- In contrast to other buy/make strategies, this study, encourage more outsourcing for longer planning periods due to increased maintenance cost of aircraft as they age.

Hsu and Liou (2013) created a model to consider various parameters (e.g. cost, risk, flexibility, etc.) to choose the best outsourcing alternative. Through a questionnaire with experts, the author weighted the relevance of these factors in a matrix, and then it was possible to determine the best alternative according to the main needs of the organization. So, if a contractor's priority is cost, the model would deliver a solution. If the priority was other factors, the model could indicate another solution for that contractor. Their main results are:

- Employees with good knowledge skills contribute to better service quality;
- A good relationship between airlines and their partners is the foundation of a successful outsourcing activity; and
- Risk plays a major role in the outsourcing evaluation system, and has the greatest effect on the other dimensions (greater even than cost).

McFadden and Worrels (2012) provides a qualitative approach offering a list of factors that may impact outsourcing decisions. They indicate that airlines see aircraft maintenance as a necessary evil and not their business cores and therefore outsourcing has become more attractive to them. They provide definitions to different modes of outsourcing from partial to whole and offer a list of factors to select MRO providers. The authors defend that each individual airline must determine the point at which there is a positive return on the investment in maintenance capability. Large air carriers with hundreds of aircraft can justify the investment for a multi-level maintenance capability. However, an airline with a relatively small fleet may not have the capital, desire, or need to establish a multi-level maintenance program.

Additionally, it is stated the idea that the airlines should focus on their core business. From JetBlue's Director, for example, line maintenance is part of their core business, due to proximity to clients and the power to influence company's revenue positively or negatively.

Gonçalves and Kokkolaras (2018) proposes a new collaborative approach to airframe maintenance, repair, and overhaul. A quantitative model was introduced to represent the business relationships between original equipment manufacturers (OEMs) and MRO enterprises. The model proposed assumed that reduction of MTTR means value added to operators, so reducing the risk of MTTR is a value-added objective when dealing with outsourcing. In their model, the increase/reduce of MTTR would happen due to unavailability of a specific resource when required, leading to a balance between the risk of MTTR increase at one end and the increase in investment at the other end.

Liu and Tyagi (2017) discussed about to outsource to convert fixed costs into variable costs. The main fixed costs are: facilities; equipment, information technology, rents, personnel salary, insurance, logistics and overhead expenses. The main reason to outsource is to allow the companies to save costs and to focus on its core competencies, but also have access to specialized knowledge. Despite this article does not talk about aircraft maintenance, its main idea has relevance to the present research.

Commine (2022) explores the impact of outsourcing aircraft maintenance on flight safety. Despite this topic is not strongly related to the theme of the present research, there is a great number of papers concerning outsourcing and safety, so this one was taken into considerations in order to cover this common concern. The evidence gathered from expert interviews and case studies indicates that outsourcing does not inherently lead to less safety. When selected and managed diligently, maintenance providers can even uphold high safety standards.

Al-Kaabi et al. (2007) proposes a qualitative approach through a flowchart process where the airlines were asked questions in terms of their core businesses, capacity, demand and fleet. The answers to these questions determine the maintenance strategy ranging from fully in-house to fully outsourced.

Patra and Kumar (2023) developed a numerical example aiming to find optimal availability contract duration under different scenarios, such as stochastic and non-stochastic contract durations, parts level, system level, minimizing total maintenance costs, and other constrains, like minimum operational availability. The conclusion was that the optimal contract duration is a non-decreasing function of spares on hand and the inherent availability of system part.

Since the present research aims to develop a numerical model, the reading was conducted aiming at finding papers that developed models (preferably quantitative models) to analyze in-house vs. outsource strategies and papers that developed models that addressed the outsourcing of aircraft maintenance services possible issues. In view of that, the research from Bazargan (2016), Hsu and Liou (2013), Gonçalves and Kokkolaras (2018), and Al-Kaabi et al. (2007) were the works with greater similarity to the theme proposed in this present research. Even so, as Bazargan (2016) has mentioned and I have observed, “there is a research gap with regard to quantitative studies, since the vast majority of studies approach the subject qualitatively”. Thus, this work aims to fill this gap and be a guide for the efficient management of resources by the operators of an aircraft fleet.

Table 2: Comparable table

	I	II	III	IV	V	VI
Massoud Bazargan, 2016	x	x	x	x		
Al-Kaabi et al. (2007).	x	x		x		
McFadden and Worrells (2012)	x	x		x		
Liu and Tyagi, 2017				x		
Quentin Commine, 2022	x	x		x		
Jukka Holkeri, 2022	x	x		x		
Hsu and Liou, 2013	x	x	x	x		
Patra and Kumar, 2023	x	x	x			
Machado et al., 2016	x	x				
Gonçalves and Kokkolaras, 2018	x	x				
Present research	x	x	x	x	x	x

I- Aviation industry

II- Maintenance services

III- Quantitative analysis

IV- Support policy (in house x outsourced)

V- Inventory level

VI- Cost benefit analysis (operation availability x life support cost)

3 Methodology

3.1 Method

According to Wazlawick (2009), the scientific method or research method describes the way to achieve the research objective. The author states that the research method itself can only be established after defining the objective, which follows the flowchart defined in the Figure 16.

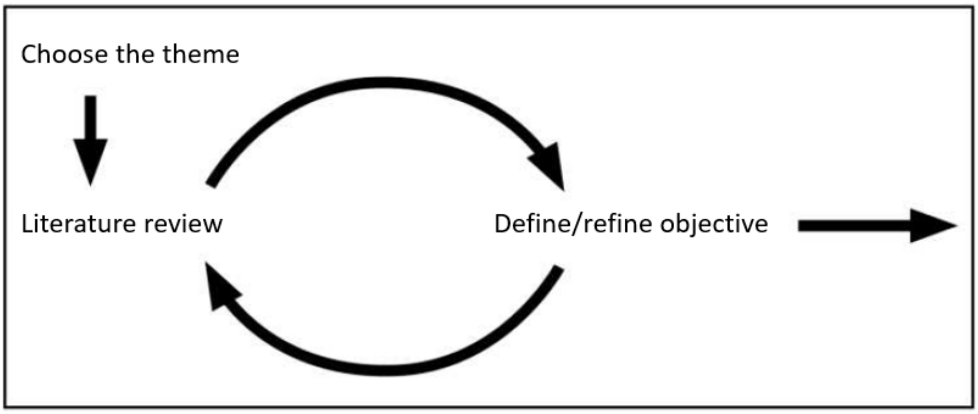

Figure 16: Logical path to defining a research objective (WAZLAWICK, 2009)

Starting with the choice of theme, according to Wazlawick (2009), it should be a theme of interest to both the student and the advisor, and under no circumstances the research theme should not be compatible with the advisor's knowledge. In view of that, it was chosen the theme of analyzing the impact on LSC of a defense aeronautical system related to different support options.

Moving on to the literature review, it was studied other researches already published about outsource of aeronautical maintenance services, with the aim of understanding what is being done and what still needs to be addressed related to cost benefit analysis of aircraft maintenance outsource policy.

Moving on to defining the objective, Wazlawick (2009) states that the objective must be strongly related to the problem identified in the previous step. Thus, the main objective of this work is to execute a quantitative analysis developing a model that consider the a cost-effective analysis of different decision of outsource x internalize the maintenance of a fleet of aircraft, as well as consider some variations related.

With the theme, literature review and research objective outlined, it is necessary to link the research to the theoretical references. Firstly, it is explained its positioning within the IPS life cycle phases. Based on the map of activities available in Chapter 3 of SX000i (IPS activities during the product life cycle), which defines the main activities to be performed for each element of the IPS, as well as defining the interval in the life cycle in which these activities should be carried out. An extract of these activities was made with the main activities to be carried out in the preparation and development phases, according to Table 3.

As previously explained, the proposed method is an approach that belongs to "Perform Life Cycle Cost analysis", that belongs to "Design Influence" element.

Table 3: IPS activities in preparation and development phases

IPS Element	Activity	Preparation Phase	Development Phase
Product Support Management	Manage contract		
	Capture product support requirement		
	Develop ILS plan		
Design Influence	Perform RAM analysis		
	Perform LSA		
	Perform LCC analysis		
Facilities & Infrastruct.	Perform F&I analysis		
Maintenance	Develop maintenance concept		
Support Equipment	Analyze support equipment requirements		

Table 3 presents the main activities and when they should be initialized (the gray bars on the right). The activity in red is the main activity of this research. Although the aim of this research is to "Perform LCC analysis" , the elements of the IPS are integrated, and they are not applied individually, but integrated with other elements. As an example, it can be mentioned that the proposed method is interrelated with practically all the activities and IPS elements in the Table 3, like it is briefly described below.

With regard to "Product Support Management" activities, starting with the "Manage contract" activity, the proposed method analyzed different options for outsourcing maintenance services. In relation to the "Develop ILS plan" activity, the proposed method developed a logistics support architecture compatible with a defense aircraft fleet application used in real case scenarios.

With regard to the Design Influence activities, in addition to the “Perform LCC analysis”, the “Perform RAM analysis and Perform LSA” activities were naturally covered and carried out exhaustively by the method throughout its application.

With regard to the last 3 IPS elements, “Facilities & Infrastructure”, “Maintenance” and “Support Equipment”, the method also covered analysis of them. For “Perform F&I analysis”, the method checked the quantity and location of spare parts stock, as well as analyzing the feasibility of installing organic maintenance hangars and the resources cost related to that. As for “Develop maintenance concept”, the method addressed a maintenance concept that is consistent with a defense aircraft fleet. For “Analyze support equipment requirements”, the acquisition of Ground Support Equipment (GSE) is one of the alternatives that was analyzed and it was tested for its cost benefit ratio.

The proposed method analyzed various decisions regarding the outsourcing of aircraft maintenance services, which take into account the aircraft’s technical factors, current maintenance contracts, the aircraft's usage profile, needs for setting up maintenance bases, options for outsourcing repair services, as well as analyzed the implications of an unsuccessful outsourcing contract. In view of the above, the proposed model can help for a more efficient management of resources, as well as keeping fleet managers aware of the results to be expected for each scenario.

3.2 Filling data gaps

One of the most important processes during the execution of this research was the acquisition of field data. For this process, several steps were carried out, such as interviews with operators and maintainers, contact with the aircraft and engine manufacturer's engineers, access to the current support contract, and even questionnaires about the fleet's supportability. Therefore, the vast majority of the data needed to carry out this modeling was directly obtained and inserted into the model.

However, despite the effort that was made to acquire the data, not all of them could be obtained directly. Some data had to be processed in order to run the simulation properly. The most relevant of these data was in relation to the failure rate of the components.

Failure rates could not be obtained directly. Meanwhile, after several interactions with personnel involved in the operation of the modeled aircraft, a qualitative list of components with high/medium/low failure rates was obtained. Additionally, it was obtained the mean time to repair of the components. Furthermore, it was obtained the total time the fleet is unavailable due to corrective maintenance. In this way, combining all these data, the failure rate was estimated so that the total downtime due to corrective maintenance in the model was proportional to the same downtime observed in reality.

3.3 Modeling Structure

This work had 3 distinct phases, as illustrated in Figure 17: Research flowchart. Each phase was divided into sub-phases, depending on the type of work to be carried out.

The first was the initial phase, divided into three sub-phases. The first sub-phase, which gave rise to the research, is the pre-research. This included a literature review in order to find the research gaps, then it was developed the research problem, the development of the hypothesis and, finally, the definition of the objectives. The main output of this sub-phase was the need to evaluate different in house x outsource maintenance solutions for an aircraft fleet. Then it was defined the analysis and scenarios that would be considered in the research. The last initial sub-phase was the study of the theory considered in the software used to perform the simulations.

Then the development phase followed. At first, it was performed a Demonstrative Model, when a model using generic data was built. Next it was conducted a Sensitivity Analysis, when it was made some variations on the Demonstrative Model and the outputs were analyzed. After that, considering all the variations and checking that the results were within expectations, the methodology was validated and the real case study was ready to be built. Afterwards it was made the field data acquisition, when it was conducted interview with several operators from the Brazilian Air Force, Brazilian Navy and Brazilian Army, as well as meeting with the Original Equipment Manufacturer (OEM) of the aircraft (Helibras) and the engine OEM (Safran). These meeting and interviews permitted to acquire all the data necessary to run the simulation and elaborate the Default Model, like the current maintenance contract information, the main characteristics of the chosen aircraft, as well as the fleet's expected performance requirements (such as minimum/expected operational availability), which can be obtained from aircraft Concept of Operation (CONOPS) document. The next step was the calibration of the model, where the inputs were analyzed and adjusted in order to make the model looks like the data from reality. After that it was elaborated all the alternative scenarios that would be evaluated and compared to the Default Scenario. At this stage it was obtained the curve with several points of availability x life support cost. Afterwards it was chosen the points that meet the requirement (e.g. the expected operational availability indicated in the CONOPS) and it was ran the operational simulation and the cost analysis. After that, if all the requirement was attended, the research went to result analysis, if any requirements were not reached, then another point on the Opus curve was chosen to check if the requirements were meet.

The last phase was the Conclusion, were at first it was conducted the result analysis, where all the alternative scenarios were confronted to the Default Model (that is how the supportability is being realized in real case). This is followed by the final considerations of this research, explaining the limitations and assumptions used to develop the models. Then the results are recorded and stored, and finally the work is successfully concluded, having found the best support solutions for in house x outsource decisions, as well as consider critical factors related to this problem.

The Figure 17 shows the pathway of this research.

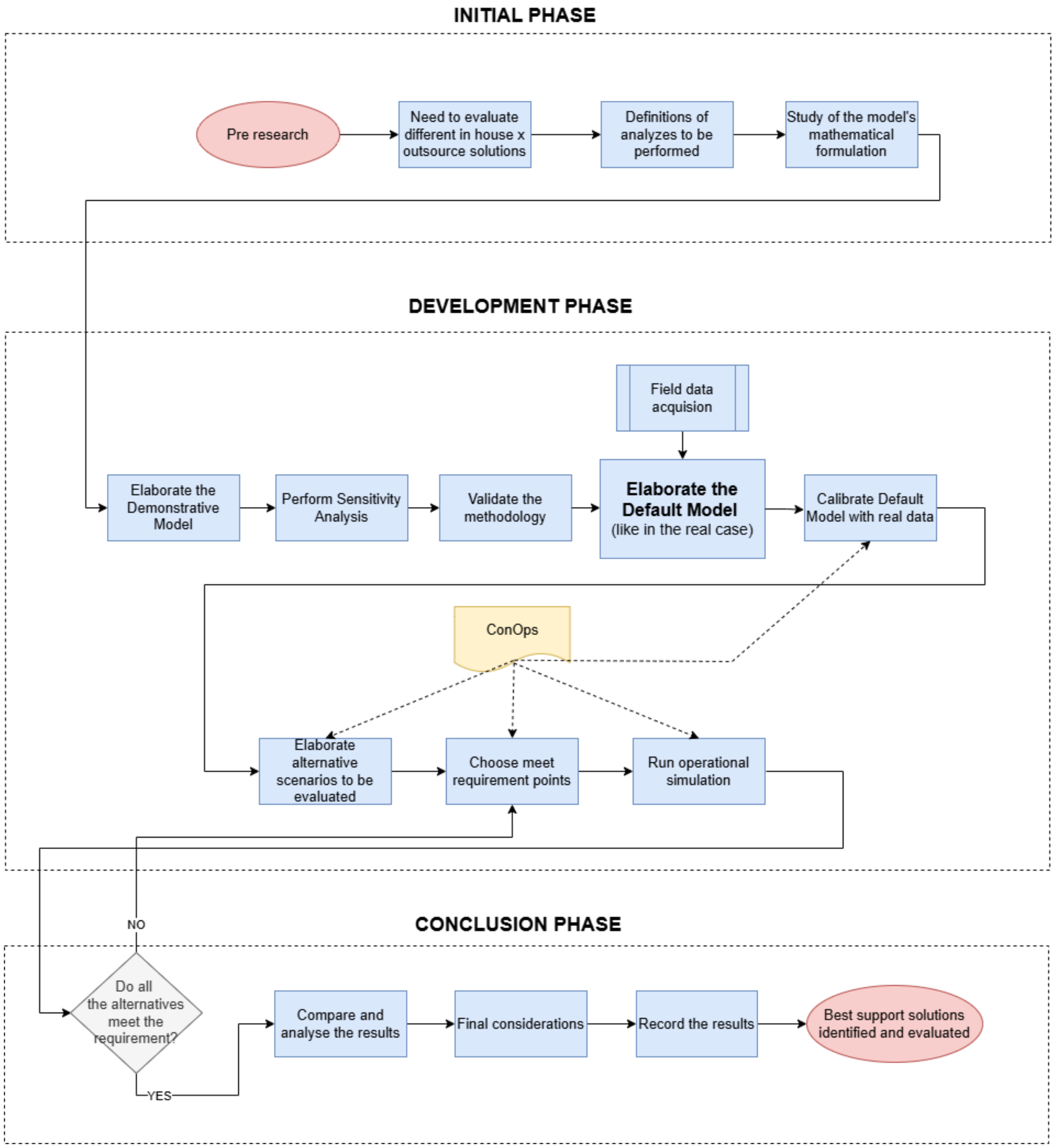

Figure 17: Research flowchart

3.4 Analyzis Performed

This research employed a comparative analysis to evaluate the cost-effectiveness implications of various maintenance strategies considering the decision to internalize or outsource the maintenance tasks of an aircraft fleet. For that, it was first considered the baseline scenario, or “Default Model”, assuming that preventive maintenance tasks are performed in-house, while corrective maintenance is outsourced to the original equipment manufacturer (OEM). That's the policy considered in the baseline model because that is how it is being executed in the real case modeled. Afterwards, the five alternative scenarios were be compared against this baseline.

In the first scenario, the OEM was also responsible for preventive maintenance tasks. So, this is the fully outsourced option. This analysis considered the current contractual data, which provided a realistic assessment of the associated costs and downtime to perform the required tasks. By utilizing current contractual terms, this simulation aligned with real-world operational conditions, which increases the credibility of the results.

The second scenario the corrective maintenance tasks are internalized. So, this is the fully internalized option. This requires a significant investment in resources to acquire the corrective maintenance capability, due to that, it was considered the investments in ground support equipment (GSE), technical publications, facilities, and training. A cost-effectiveness analysis was conducted to compare this scenario with the Default Model, considering factors such as the fleet size, resource costs and how large should the in-house repair structure to be. For the fleet size, it was considered the relationship between fleet size and the optimal maintenance strategy. According to some authors (e.g. McFadden and Worrells, 2012) state, larger fleets may justify a more extensive in-house maintenance capability, while smaller fleets may be better to outsource. Although the previous research did not aim to found a specific breakeven number of aircraft, this research aims to first validate this premise, and then analyzing the breakeven number of aircraft for that. Moreover, the resource cost was also evaluated and the relationship with the fleet size was tested. Additionally, it was analyzed the in-house repair capability by making a trade-off, that in one side there is a big and costly repair capability, which can handle various simultaneous repair that could easily support the fleet and would not compromise the fleet availability, and on the other hand there is a smaller repair capability, that instead of being cheaper than the first one have limited capability to perform simultaneous repair, which tends to impact on fleet availability and mission assigned.

The third scenario considered unsuccessful repairs and its impact on life support cost. This scenario accounts for instances where the outsourced company maintenance provider (in this case is the manufacturer) lacks the necessary expertise or capabilities to perform the repair satisfactory. Due to that, this scenario assumed that in most cases the manufacturer will carry out the repairs themselves, but occasionally the repair will be outsourced to another provider, resulting in increased costs and extended repair times. The impact of unsuccessful third-party repairs on overall maintenance costs and aircraft availability were quantified.

The fourth scenario considered contracts for special components. In many cases, aircraft have components/subsystems or systems with high levels of complexity that require specialized maintenance providers. These components/subsystems may be subject to separate maintenance contracts with the original component manufacturer. This scenario explored the impact of such specialized contracts, particularly when the component manufacturer is located in a different continent. It was considered increased transportation costs and time, keeping the other parameters like Default Model (e.g. time to repair, repair costs, and repair tasks), in order to isolate the effect of a long-distance contract.

The final scenario examined the impact of fluctuations in dollar exchange rates on maintenance costs. This scenario explored the fact some costs are dealt in foreign currencies, while others are dealt with local currency. Due to that, this scenario evaluated the impact of dollar exchange rate fluctuation on the total Life Support Cost.

3.4.1 Model Premisses

In order to perform the analyses desired it is needed to state some premises to build the model. They are listed below:

- Spare parts are a closed cycle. Additionally, the spare parts can always be repaired.
- It is applied FIFO (fist in first out) rule.
- It is considered extensive repair capacity. Therefore, the repair time does not depend on the number of items already being repaired.
- Demand is Poisson with a constant average, regardless of the number of parts being repaired.
- Under no circumstances a repair will be left undone. In addition, they will be carried out only where there is capacity to perform the task.
- Failure rate is constant.
- There is no cannibalization.
- There is no lateral supply.

3.5 Life Support Cost Calculation Method

The LSC method adopted by the OPUS Suite software package is known as VARI-METRIC. This theory has been used by several NATO aircraft manufacturers, several US companies and even NASA (SHERBROOK, 2004). This technique uses what is known as marginal analysis (or marginal allocation), which optimally adds stock items following a cost-benefit ratio (CBR) between all the items embedded that considerer the relation between EBO and item cost. In this way, the “curve” of operational availability x LSC are discrete points, which represent an increase of the item(s) that has the greatest CBR at that level. Additionally, according to Figueiredo-Pinto and Abrahão (2018), this is a maximum cost-effectiveness curve, where all the points represent optimum stock composition solutions for each budget level. A certain percentage availability is adopted as a requirement for the system under analysis and this point corresponds to a specific material list, which must be purchased in order to achieve the desired service level.

The VARI-METRIC is a development of METRIC theory. The use of this theory is known that underestimate the number of back orders, while that theory achieves better results. The way it achieved is using not only the mean pipeline values, but also the variance, this is carried out using a Poisson distribution to demand rates and binomial distribution to estimate orders at each operational base. Using VARI-METRIC is possible to achieve a list points with their availability x LSC. These results were achieved using the OPUS© program.

After the results from OPUS© (the availability x LSC curve), the model is submitted to simulation in the SIMLOX©, bringing dynamism to the analysis by inserting time-dependent variables, such as operational profiles. According to Figueiredo-Pinto and Abrahão (2018), this tool provides a better understanding of the system's behavior over the course of time, identifying bottlenecks and any specific problems that may arise at specific moments in the life cycle, which are not evident in the OPUS© static models.

At the end, the model and the results obtained are input in the third Suite package software, CATLOC©. This software is responsible for compute the costs, where all the simulated period events are computed considering their categories, the time, the stations, the missions and the components embedded.

3.6 Computational resources

The way the proposed method performed the analysis was using OPUS10©, SIMLOX© and CATLOC© tools, all of them are components of OPUS Suite software package, version 2024.0. These are tools intended to perform spare parts optimization and logistic support analysis for complex technical systems, with several uses in both industry and academia. These tools were used in academic works such as Souza (2021), Martins (2023), Buch (2023), in published works such as Marques et al. (2017) and Figueiredo-Pinto and Abrahão (2018), as well as by the FAB to plan support for the KC-390 and F-39 Gripen aircraft. The computer used was a Vaio, with an Intel(R) Core(TM) i5-6200U @ 2.30 GHz processor, 8.00 GB RAM, 256 GB SSD memory, Windows 10, 64-bits.

In Figure 18 there is an illustrative example of how the analysis can be compared.

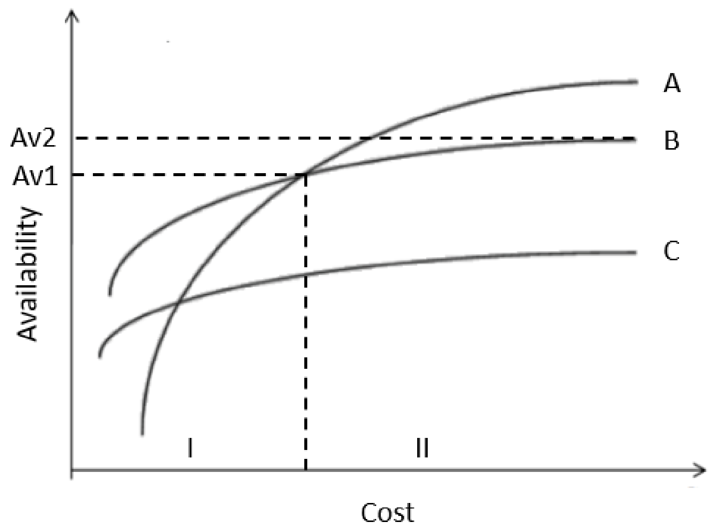

Figure 18: Availability x cost curve for 3 scenarios (adapted from Suite Opus, 2024)

From Figure 18, 3 scenarios (A, B and C) where illustrated in terms of expected availability and cost. These 3 curves are actually several points that indicates the level of inventory and their related availability. The method to achieve these points are the iteration process described in the subsection “2.5.6 Marginal Analysis”. Given the example in Figure 18, is any curve better than the others over the entire availability range? If so, that alternative can immediately be selected. Otherwise, it is necessary to make a decision about the required performance level, and then compare the LSC of the different alternatives for the chosen availability value (OPUS, 2024). As can be seen from Figure 18 there is no alternative better than the others over the entire availability range. If the availability requirement is below “Av1”, represented region “I” in the chart, then alternative B would be the one chosen. Otherwise, if availability requirement increases between “Av1” and “Av2”, then alternative A becomes the best one. If availability requirement is over “Av2” then alternative A would be the only one that reach the target. In this example, alternative C would not be chosen in any case, since there is always one solution that delivers the same or higher availability at a reduced cost.

In view of that, the OPUS Suite has the advantage to easily compute all the variations desirable and the output is an availability x cost curve. Due to that, several analyses can be performed confronted in the same diagram. On the other hand, it has the disadvantage of working with constant failure rates, which can be a limiting factor depending on the analyses to be performed.

3.7 Demonstrative Model

In order to validate the method, a demonstrative model were developed at this stage. The aim of this model was to validate the supportability metrics, to model the supportability and operational profile, to obtain the operational availability x life support cost curves and the level of inventory required.

Then, a sensitivity analysis were carried out, in which variations were made in the model parameters in order to check that the outputs are consistent with the variations implemented. In other words, it was analyzed if the model responds properly to the changes undergone. The demonstrative model, unlike the case study, used fictitious data for the analysis. Therefore, for the aircraft it was considered 7 on-board subsystems (Line Replaceable Units - LRU), with their respective prices, failure rates and quantity per aircraft described in the table below.

Table 4: Demonstrative aircraft items

Item	**Price (US$)**	**Failure Rate (1/10^6 Hrs)**	**Repair Cost (US$)**	**Quantity per A/C**
LRU1	5.000.000,00	1.200	750.000	2
LRU2	4.500.000,00	1.440	675.000	1
LRU3	4.000.000,00	1.728	600.000	2
LRU4	3.500.000,00	2.073	525.000	2
LRU5	3.000.000,00	2.488	450.000	1
LRU6	2.500.000,00	2.985	375.000	1
LRU7	2.000.000,00	3.583	300.000	3

To model the operation, a fleet of 50 aircraft were assumed over a 10 years period, with an average utilization rate of 200 flight hours / year / aircraft. In view of implementing variability in the simulation, the utilization profile shown in the table below were used.

Table 5: Demonstrative operational scenario

Mission Name	**Nominal nº of A/C**	**Minimum nº of A/C**	**Total FH / year**
Special mission	4	2	4.590
Regular patrol	3	1	4.752
Authority transport	2	1	840

The missions were distributed over time as follows: Special missions are characterized by concentrated usage rates, usually with a larger number of aircraft, on a sporadic occasion, so it was simulated 3 special missions with 4 aircraft, with each mission taking 45 days, beginning in January, July and November. Each mission day will have 3 hours of flying in the morning, 3 hours in the afternoon and 2.5 hours in the evening.

Regular patrol missions, on the other hand, are better distributed throughout the year. The regular patrol will take place over 11 months of the year, from January to November, starting on Mondays and running until Saturday, with 3 aircraft flying each day for 3 hours in the morning, 4 hours in the afternoon and 2 hours in the evening.

Finally, authority transport missions, despite their inherent unpredictability, were modeled in weekly blocks, so that each week that authority transport is requested it will have 2 aircraft available, flying from Monday to Friday, flying 3 hours in the morning, 1 hour in the afternoon and 2 hours in the evening. The authority transport demand was modeled for 2 weeks in January, and all weeks in October, November and December.

A graphic demonstration of the number of aircraft being used in this operational profile over a one-year period can be seen in Figure 19.

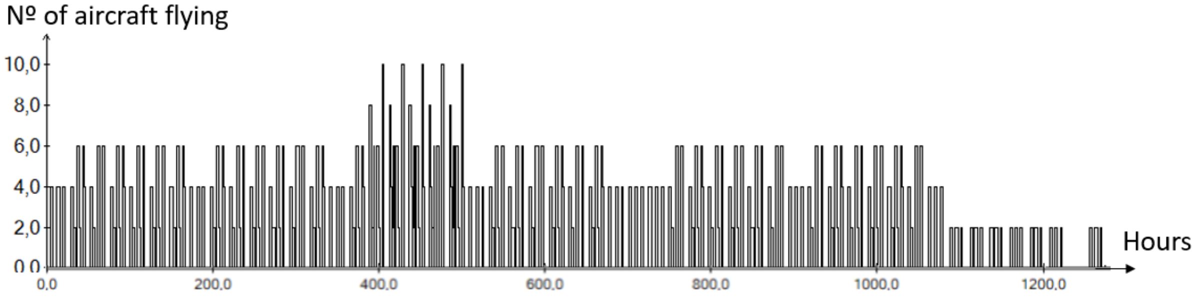

Figure 19: Nº of aircraft flying according to demonstrative scenario

For the supportability modeling, a basic structure of one operating base and one maintenance base will be considered, according to Figure 20.

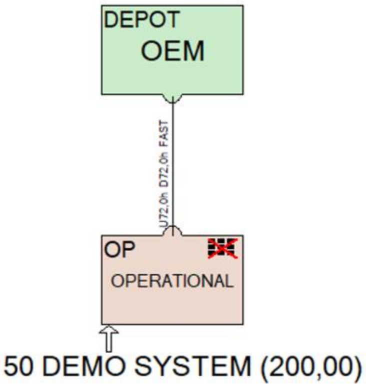

Figure 20: Demonstrative support structure

And then, others parameters necessary to run the simulation can be seen in Table 6:

Table 6: Parameters assumed in the demonstrative model

Parameter	**Value**
Replace component cost	US$ 1.000,00
Replace component time	36 hours
Repair component cost	US$ 70.000,00
Repair component time	2 months
Repair consumable cost	US$ 100,00/repair
Storage annual cost	5%/price item
Transport cost	US$ 1.000,00
Transport time	72 hours
Aircraft quantity	50
Utilization profile	200 FH / year
Scenario length	10 years

Since this model is a simplified version, it has the same maintenance time for all components, although the repair cost varies for each component. Additionally, the scheduled maintenance is according to Table 7.

Table 7: Demonstrative model scheduled maintenance

Maint. Interval	**Maintenance Downtime**	**Maintenance Cost (US$)**
20 days	2 hours	---
100 FH	190 hours	4.099,00
1200 FH	730 hours	31.539,00
1 year	504 hours	13.365,00
4 years	800 hours	27.416,00

The first line of Table 7 refers to preventive maintenance of a specific aircraft item, which due to a design mistake must be carried out with a high frequency (every 20 days) and which, due to the error, the costs are paid by the manufacturer, so that for the operator there is no cost. After implementing the data described above, the cost-effectiveness graph in Figure 21 was obtained:

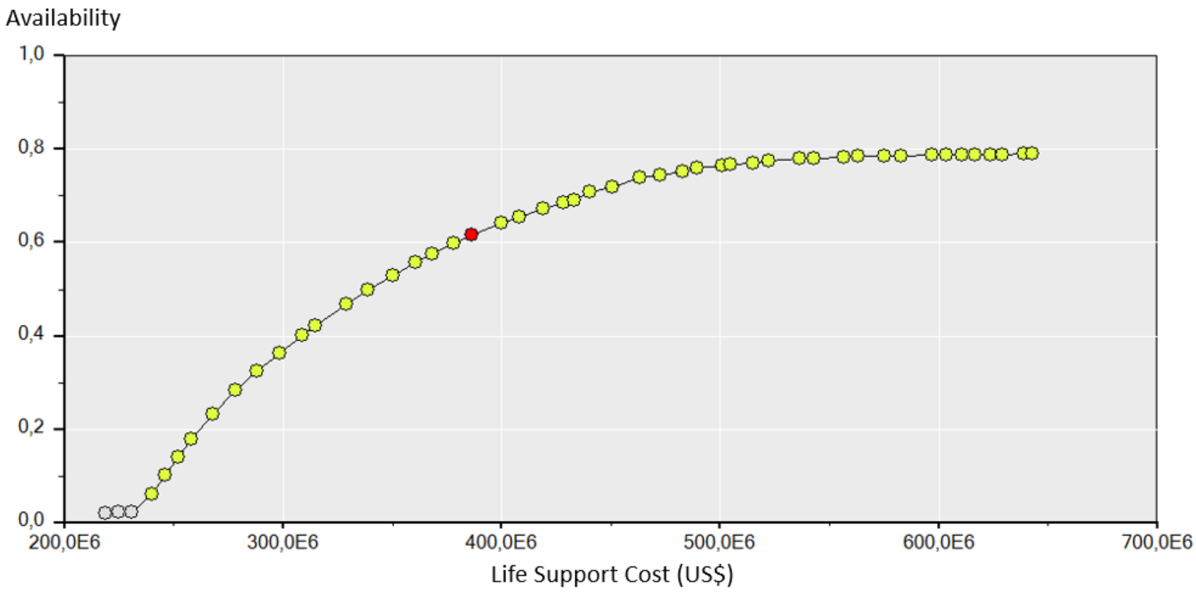

Figure 21: Demonstrative model – Opus availability

The graph shows operational availability on the “y” axis and Life Support Cost (LSC) on the “x” axis. In this way, the fleet manager has a clear view of the performance his fleet is capable of achieving, as well as how each point shows different levels of investment and the availability achieved with it.

In Figure 21, each point corresponds to an optimum level of spare parts to be purchased in order for the fleet to reach the determined availability. The quantity of spare parts in stock for the 40%, 50%, 60% and 70% availabilities is shown in Annex A.

Another characteristic seen in Figure 21 is the gray points at the beginning of the curve. These points mean that the number of spare parts in stock is so low that the fleet was not able to reach the required flight hours. If the utilization rate of the aircraft is increased, the number of gray dots on the curve increases too.

However, this is the result obtained by the Opus10 software, which assumes a “steady-state” scenario, where there are no utilization spikes. In order to make the model more representative, the Simlox software were used, where the events become time dependent, and the operating profile described in Figure 19 is added. The closer point with 60% availability on Opus were chosen, with its related inventory level. The result of the simulation considering the time dependent scenario gave an operational availability of 61,73%. Additionally, the system states over time can be seen in Figure 22.

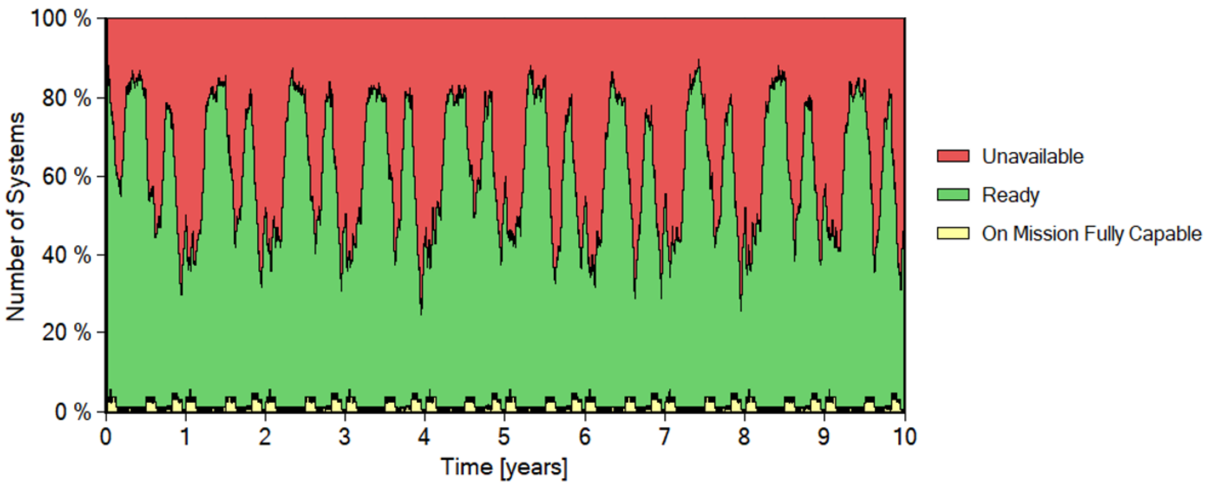

Figure 22: System states over time

Figure 22 shows the cyclical behavior of the fleet availability throughout the years. This is because the aircraft utilization profile varies throughout the year, but the annual operating profile is repeated over the 10-year simulation period.

Another important information to be taken from this analysis is the breakdown of the unavailability causes of the simulated period. Figure 23 shows the segregation of the "unavailable" period.

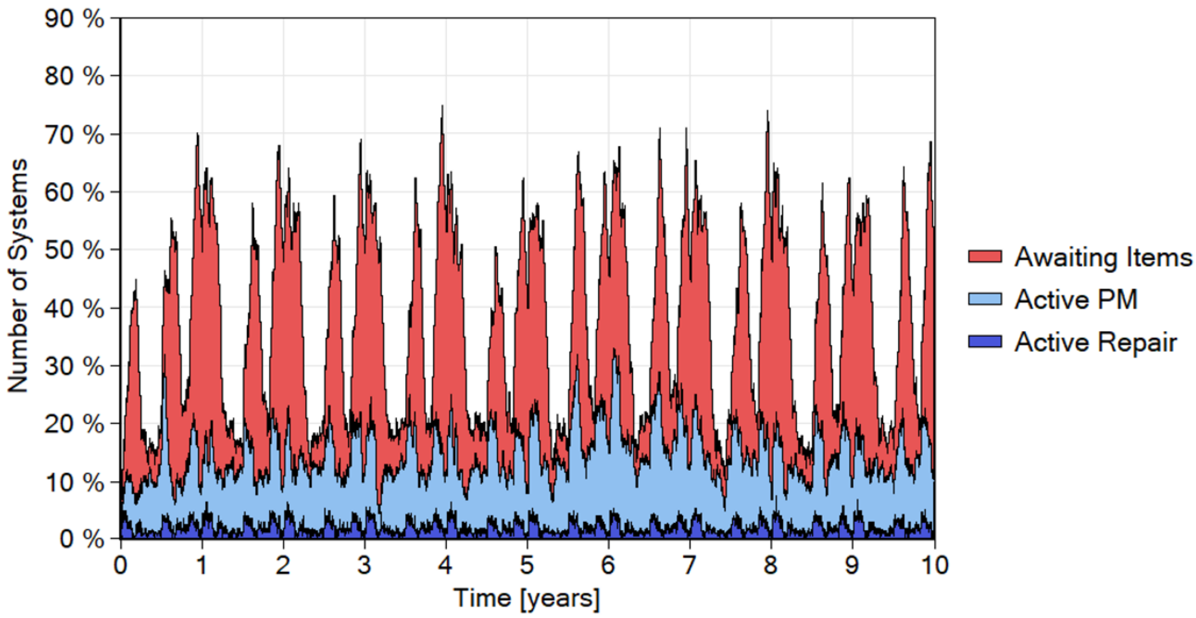

Figure 23: System unavailability over time

Figure 23 also shows the system unavailability over time. The "Active Repair" is the time required for items removal and/or installation, the "Active PM" is the time required to perform the scheduled maintenance, and the "Awaiting Items" is the time that an aircraft is downtime waiting for an item to be shipped and/or to be repaired.

In sequence, the supportability costs related to the 60% availability inventory level are shown in Table 8:

Table 8: Demonstrative model cost breakdown

Costs proportion	Cost description
45%	Corrective Maintenance
25%	Components Investments (acquisition)
12%	Storage Costs
12%	Components Depreciation
4%	Preventive Maintenance
< 2%	Transportation
< 1%	Removals and installations

These results were taken from the CATLOC software, that shows both the total composition of costs, which is also shown in OPUS10, but also shows its composition by categories, spending by year as well as spending by different items. In this way it is possible to plan not only global factors, such as desirable operational availability and the total cost of supportability, but also to trace and monitor sub-groups of expenditure.

3.7.1 Sensitivity Analysis

After the development of the demonstration model, the sensitivity analysis were executed. To do this, some variations were made in order to check how the model would behave to these variations, and then determine the impact on operational availability and the total cost of supportability.

Therefore, the following variations were made:

a) Increase the failure rate in 20% and 50%
b) Increase the MTTR (repair and PM) in 20% and 50%
c) Increase Repair Cost in 20% and 50%
d) Increase transport time in 20% and 50%
e) Increase transport and storage cost in 20% and 50%

The results for the first variation mentioned above, followed by some comments can be seen in Figure 24:

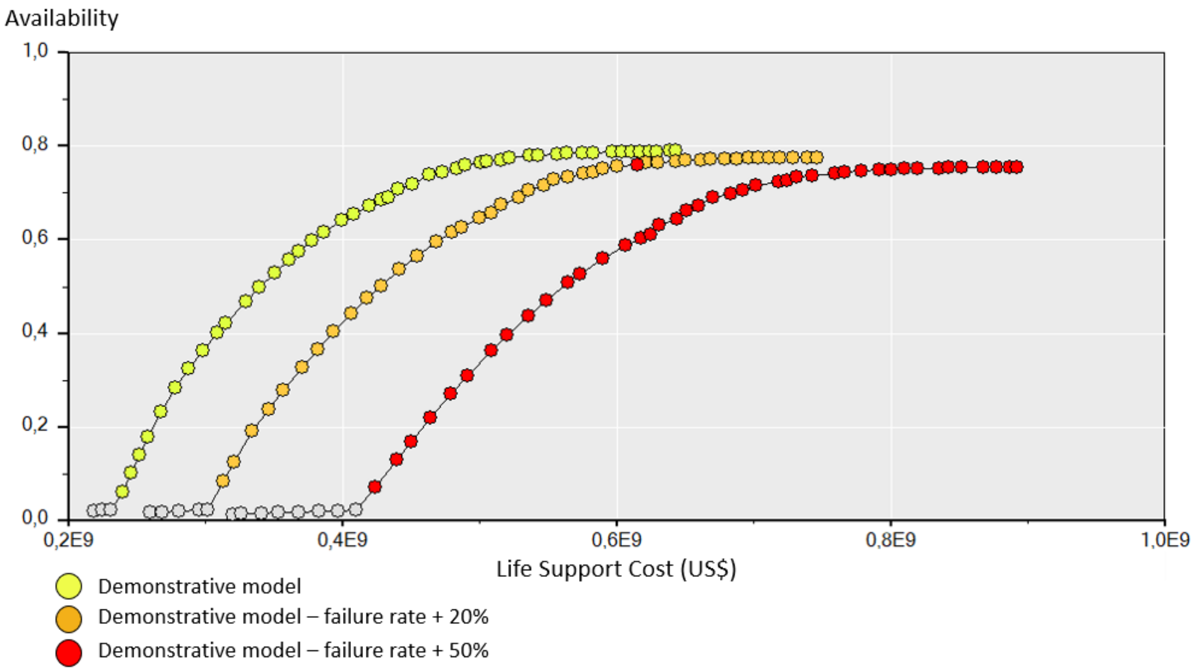

Figure 24: Demonstrative model – Opus availability with increased failure rate

As can be seen, the increase in the failure rate of components worsened the cost-effectiveness of supportability. As a result, in order to obtain the same level of availability, it would be necessary an increase in costs compared to the previous model. This result is quite logical, since having a system that fails more (with worse reliability) would result in total cost increase.

Another important observation of this variation is that although the curves are quite different, for a high level of inventory investment (the points towards the right of the curves), they reach practically the same "availability plateau", around 80% on the graph. This is because for these high levels of inventory investment the stock is large enough to cover almost all faults, so that there are practically no unavailable aircraft waiting for a component to be repaired. Therefore, for these levels of investment, when a failure occurs the downtime will be the time needed to remove, transport and install the components, which is considerably lower than the repair time. This explains why they reached almost the same "availability plateau", with the models with the highest failure rate being slightly lower, due to the higher number of occasions that components will have to be removed, transported and installed.

The next variation is to increase the mean time to repair (MTTR) in 20% and 50%. In this case, the time for all maintenance tasks (repair, scheduled maintenance and removal and installation) were increased, and the result is shown in Figure 25:

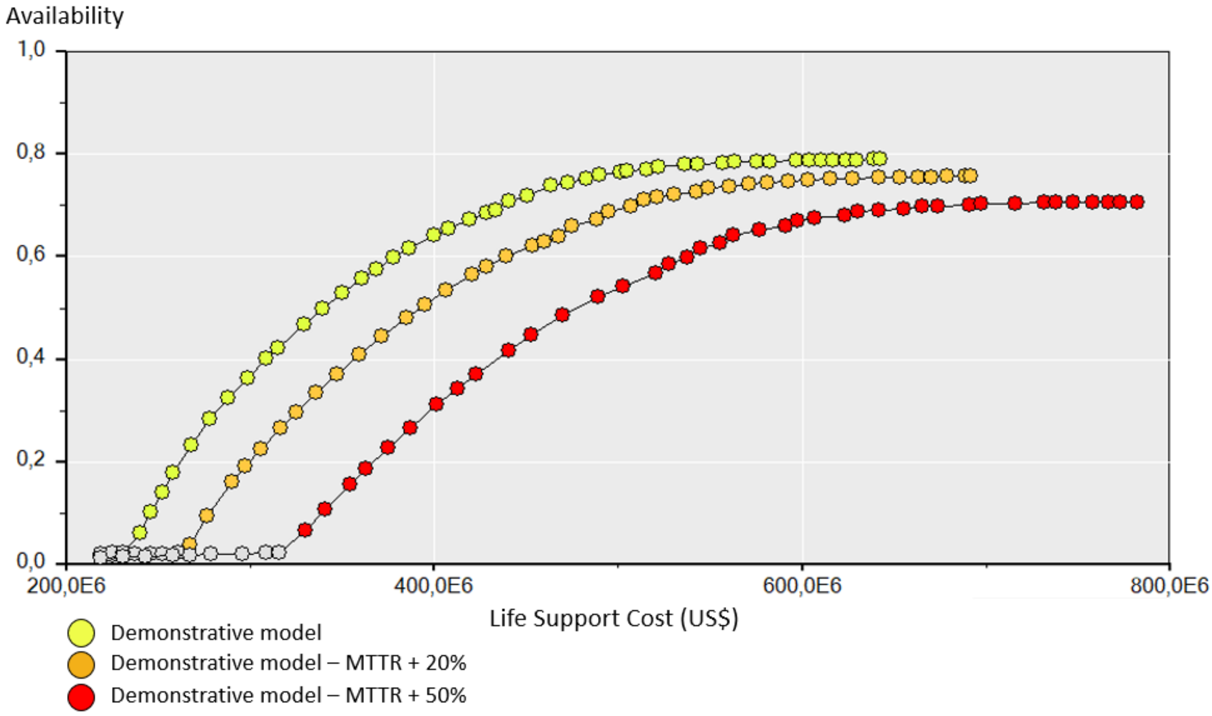

Figure 25: Demonstrative model – Opus availability – increased mean time to repair

As can be seen, the increase in task execution time deteriorated the cost-effectiveness ratio, as it was expected. In this scenario, the number of failures were the same, but the reaction time to the failure were longer, in other words. the supportability latency had increased.

The next variation is to increase maintenance costs by 20% and 50%. The cost increment was applied in the repair tasks, scheduled maintenance tasks and component removal and installation. Figure 26 shows the result of these variations.

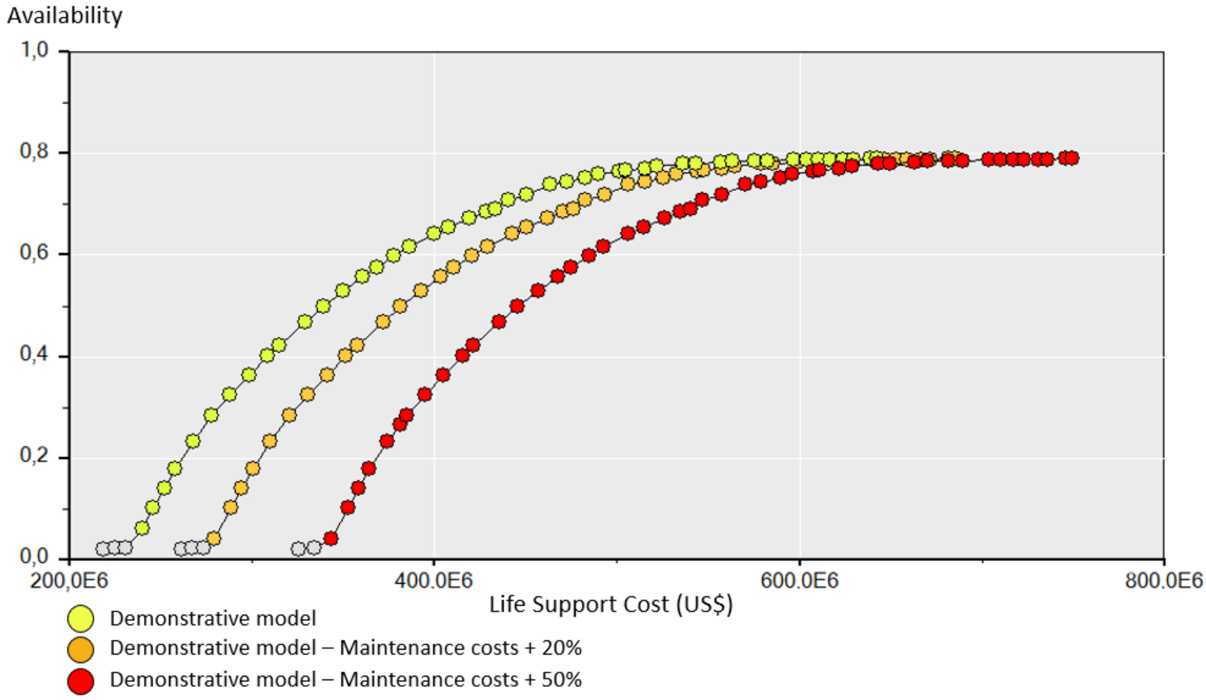

Figure 26: Demonstrative model – Opus availability – Increase maintenance costs

As can be seen, the increase in costs had the predictable result of worsening the fleet's cost-effectiveness ratio, since it's necessary to spend more to maintain the same availability.

Another relevant observation of this variation is the shape of the curves. Since only the maintenance costs were varied, without changing any aspect that impacts the number of failures or reaction times due to failure or PM tasks, in all three cases the total downtime was the same, the only change was the costs of carrying out the tasks. Therefore, it was like if the curves were shifted to the right. They have similar shapes, such as the "availability plateau", which are the same, the only difference was basically the cost to achieve a certain availability.

Following the analysis, Figure 27 shows the variation in the transportation time of the components by 20% and 50%.

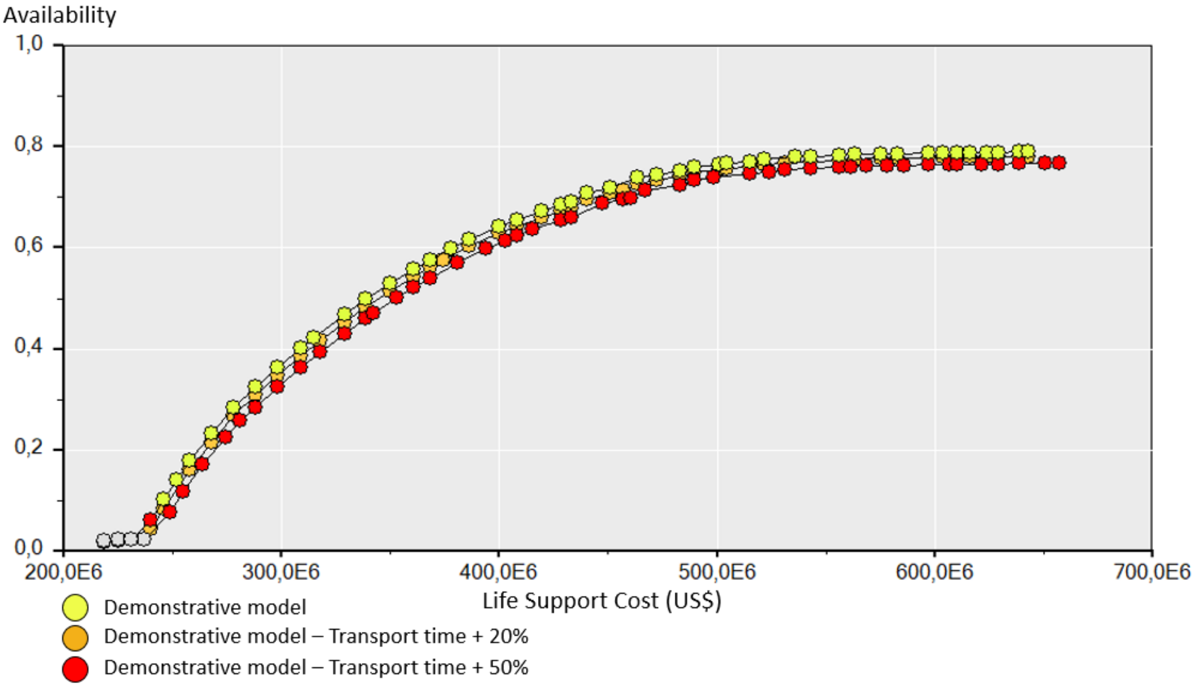

Figure 27: Demonstrative model – Opus availability – Transport time increase

As can be seen, the increase in transportation time had a very low impact on the cost-effectiveness ratio, which leads to the conclusion that for this model transportation time has a small impact on fleet availability. This statement can be reinforced when comparing transportation time with scheduled maintenance or repair time, which are 1 to 2 orders of magnitude higher.

From Figure 28, it can be seen that the increase in transportation and storage costs also had a small impact on the cost-effectiveness ratio.

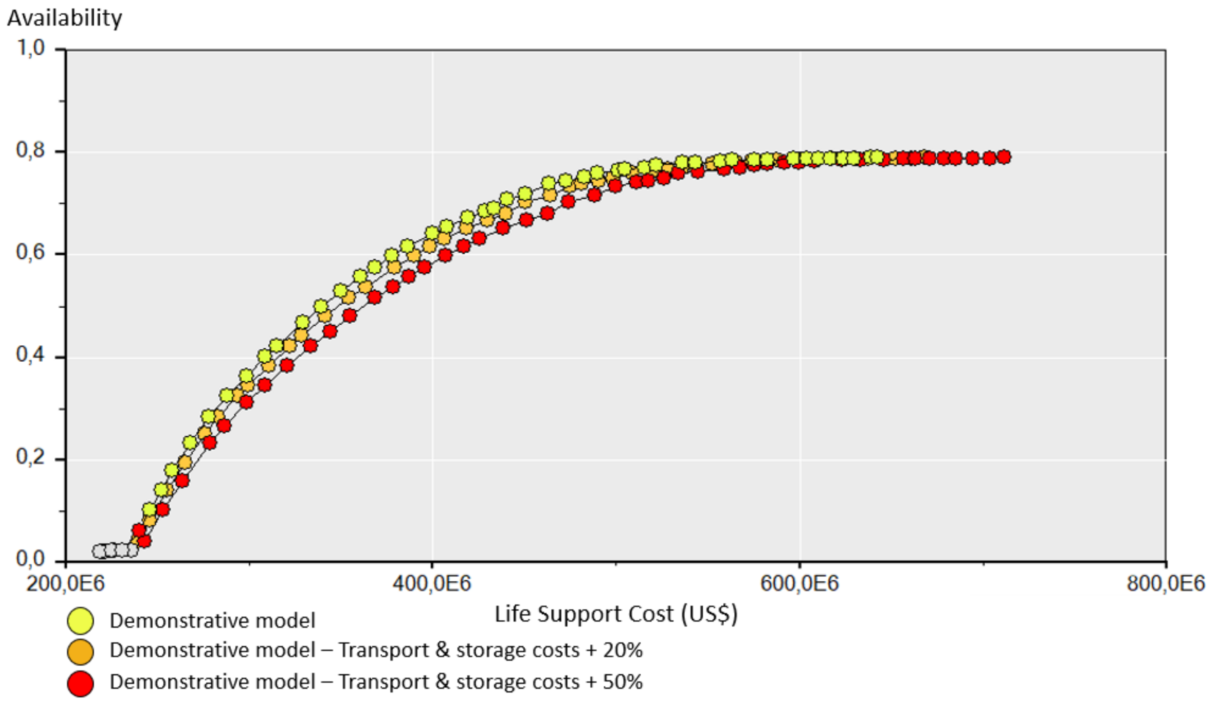

Figure 28: Demonstrative model – Opus availability – Transport & cost increase

After all the variations proposed, Figure 29 presents some of them on the same graph.

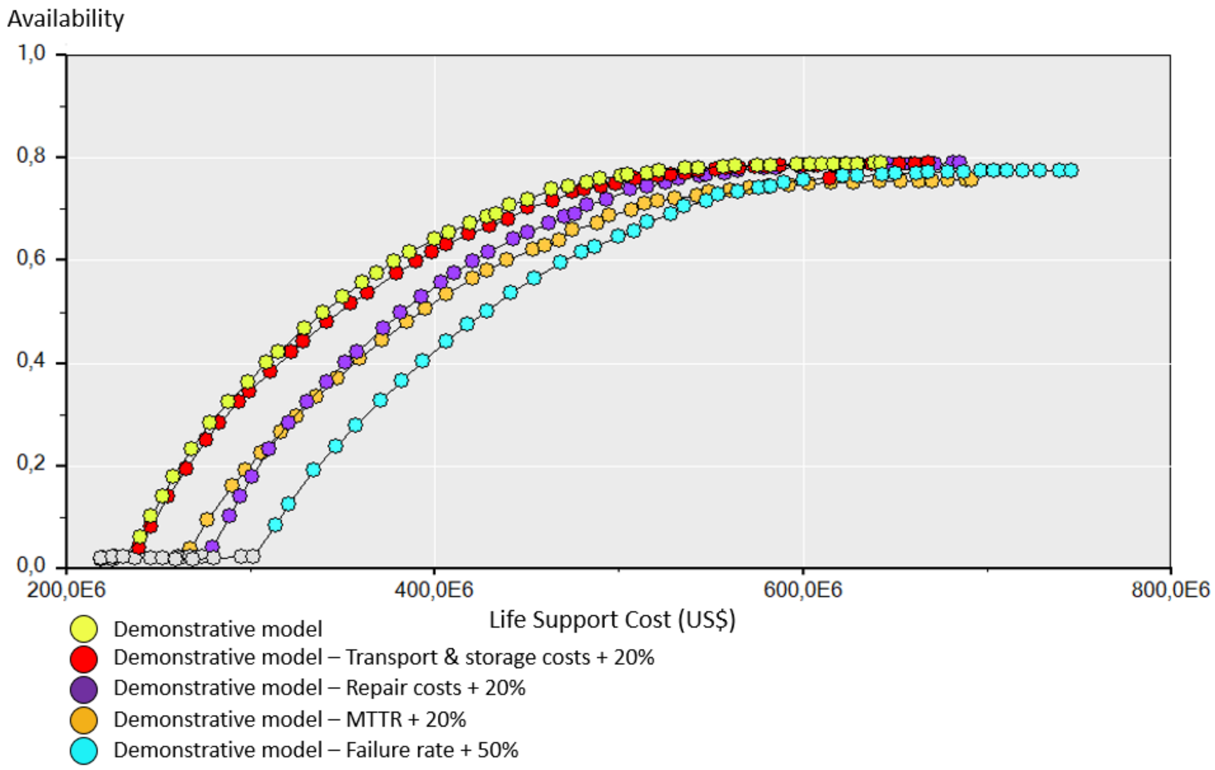

Figure 29: Compiled of sensitivity analysis performed

As could be seem, the model's responses were all within expectations, based on each individual variation. Another important factor in demonstrating the model's ability to reliably represent the data input was that, given the scheduled maintenance of 1 and 4 years, in which the aircraft spend 504 and 800 hours of downtime respectively, in order to intersperse the scheduled maintenance over time , the simulation considered that the aircraft had different entry into service dates, which made the aircraft stop to preventive maintenance at different periods, as could be seem in Figure 22. But, if the model considered that all aircraft had the same entry into service at the beginning of the simulation, the fleet availability would look like Figure 30:

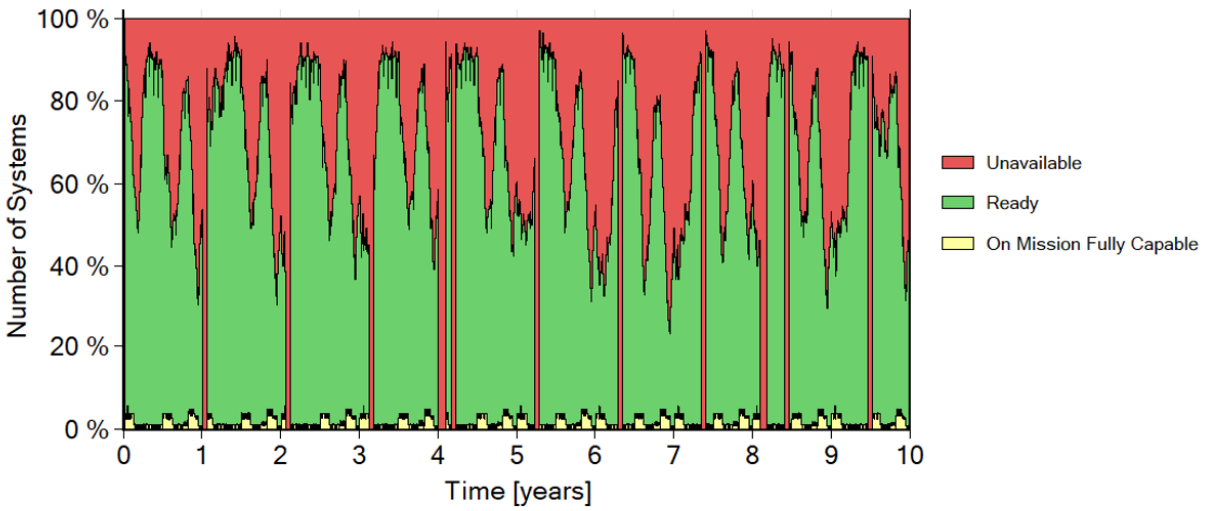

Figure 30: Fleet availability with the same entry into service

As can be seen, there is a peak in unavailability every year, due to the yearly scheduled maintenance. Also, there is another peak in unavailability every 4 years, due to the 4-year scheduled maintenance. This behavior did not happen in Figure 22, where the entry into service were at different dates, and the scheduled maintenance were spread over time.

3.7.2 Conclusion:

According to the variations proposed in the previous sub-topic, it was possible to observe that the model presented consistent outputs with the variations imposed. In this way, the model proved to be adequate in ensuring a reliable simulation of the supportability of an aircraft fleet, and in this way be a useful tool to assist the decision-making process of fleet managers.

3.8 Final Considerations

As possible limitations and restrictions of the model, it is important to mention that a model is a simplification of reality, and its use in concrete cases must be adjusted for each case. In addition, its results will be impacted by the availability of the data to be input, as well as the assumptions that were adopted that may vary in specific cases.

4 Methodology Application, Results and Discussions

This chapter describes how the methodology was applied, presenting the results achieved and ends up with a discussion about the results, its assumptions and limitations, and also the feasibility of the variations analyzed.

4.1 Literature Adherence

In this stage a correlation analysis between the model and existing literature and papers was made. This phase is important to ensure the model's robustness and validity. Given that, a literature adherence was performed in order to conclude if weather or not the model covers the main aspects of the supportability in analysis. This step helps to mitigate the risk of underfitting or even overfitting the model, ensuring that it captures the most relevant factors of an aircraft fleet supportability related to the decision of outsourcing its maintenance activities.

Considering that, the follow aspects were confronted with the literature existing.

- The model computes the operational availability, one of the main supportability metrics, since it covers design requirements of the system, the operational environment that the system has being used, and also the support structure adopted (BLANCHARD, 2014). Given that, the operational availability is a good ruler to be adopted on this model.
- The model applies a cost-effectiveness approach, computing the operational availability versus its cost for each scenario analyzed and for each level of investment desirable. According to Blanchard and Blyler (2016), to design and develop a system that will meet customer requirements effectively and efficiently is necessary to maximize system effectiveness and maximize its cost-effective.
- The model should be able to cover the IPS elements, which can guarantee that it covers the supportability issues.
- The model uses as input the insertion of aircraft data, usage profile data, maintenance data and data of the logistics chain for the supportability of the system, increasing the significance level of its results.
- The model allows a comprehensive analyzes of the costs, computing how much is being spent according to different cost categories. According to ASD/AIA, a Life Cycle Cost analysis is mandatory in order to determine the most cost-effective option among

different competing support alternatives, as well as shows the cost sensitivity of each possible alternative.

Therefore, in order to analyze different alternatives in relation to outsourcing fleet supportability, the adoption of metrics such as operational availability and a cost-effectiveness analysis, as well as the adoption of the IPS elements in the proposed model, it is concluded that the model addresses the most relevant factors for supportability according to the present literature.

4.2 Case Study

4.2.1 Introduction

Once the demonstrative model have been developed and the method has been validated through a sensitivity analysis, the case study model were developed at this stage. To do this, the first question that was answered is which system/aircraft would be analyzed, and it was chosen to study the Brazilian Navy's fleet of H225 Super-Puma aircraft. The main reason for choosing this aircraft were that they are used by all three Brazilian forces, which in theory makes it easier to obtain the field data. Also, another reason is the quite new fleet age, in which the delivers happened between 2011 and 2022 for the Brazilian Navy.

The H225 Super Puma is an Airbus Helicopters project and it is manufactured by Helibras, a Brazilian helicopter manufacturer. It was delivered 15 H-225 for the Brazilian Navy. It is an aircraft characterized by its capability to carry heavy payloads with a high flight range, in addition to operating in severe weather conditions. It is used in commercial, government and defense operations and has more than 6 million hours flown, a capacity of 28 seats, 600 nm and a payload of 4,750 kg (Airbus, n.d.).

In the Brazilian Navy, the H225 are multi-mission helicopters. The basic version (UH-15) is used for tasks associated with supporting special operations, naval land operations, as well as benign activities and limited use of force, such as aeromedical evacuation, search and rescue, logistical airlift and firefighting. The UH-15A version carries out Combat SAR (C-SAR), Search and Rescue (SAR), Amphibious Operations support and Special Operations missions. The AH-15B version, on the other hand, besides carries out the mission mentioned above, it also executes clarification and attack missions (Brazilian Navy). Figure 31 presents a Brazilian Navy H225 in operation.

Figure 31: Brazilian Navy Super Puma (Brazilian Navy, n.d.)

Once the aircraft has been chosen, the next step is to obtain the data to be included in the model. To do this, operational and supportability data was obtained from officers of the Brazilian Navy and the Brazilian Air Force, as well as manufacturer’s member.

4.2.2 General Information on Aircraft Supportability

While obtaining data from the aircraft, one point that caught the eye was the virtually unanimous comment among operators and maintainers that the aircraft requires intense downtime for preventive maintenance. In addition, it was reported that a study group with different operators carried out an analysis and concluded that the aircraft requires approximately 40% of its time just to carry out preventive maintenance, a factor that has a significant impact on the aircraft's availability.

In addition to the above, a history of the availability condition of the H225 aircraft of all the 3 Brazilian forces in 2024 was obtained. The result is shown in Figure 32.

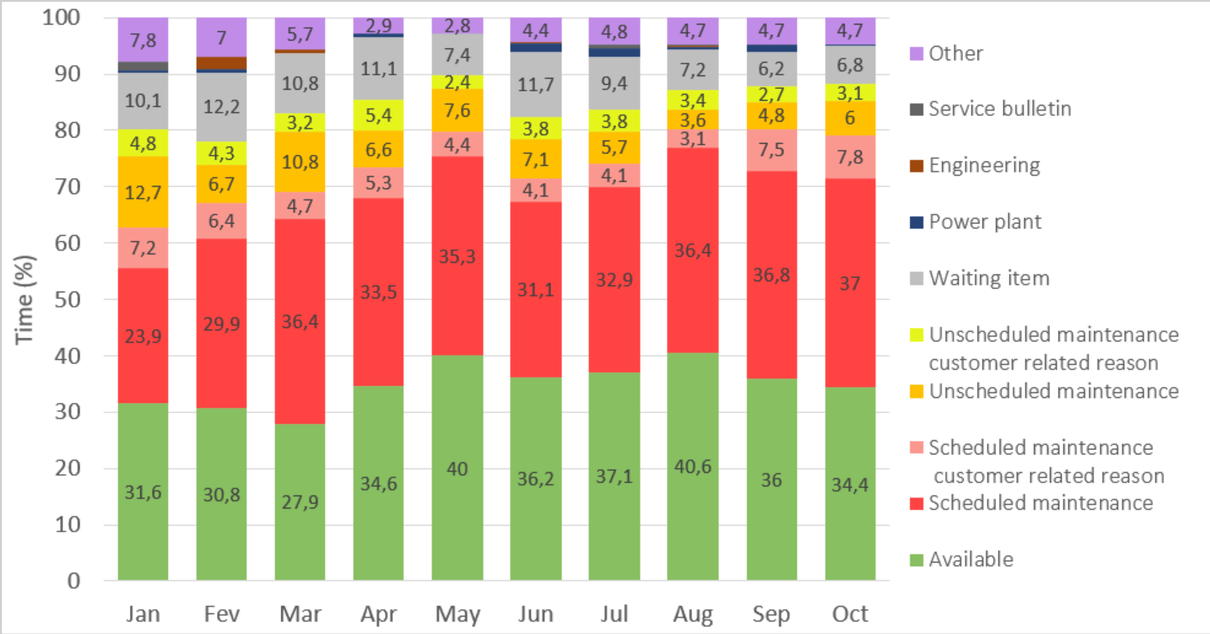

Figure 32: H225 availability states (Source: Data from manufacturer)

Since the data has several classifications that are not the aim of this modeling, they were grouped in order to obtain the classifications that are of interest to this study, which are: "available", "waiting item", "scheduled maintenance" and "unscheduled maintenance". After these groupings, the values shown in Figure 33 were obtained.

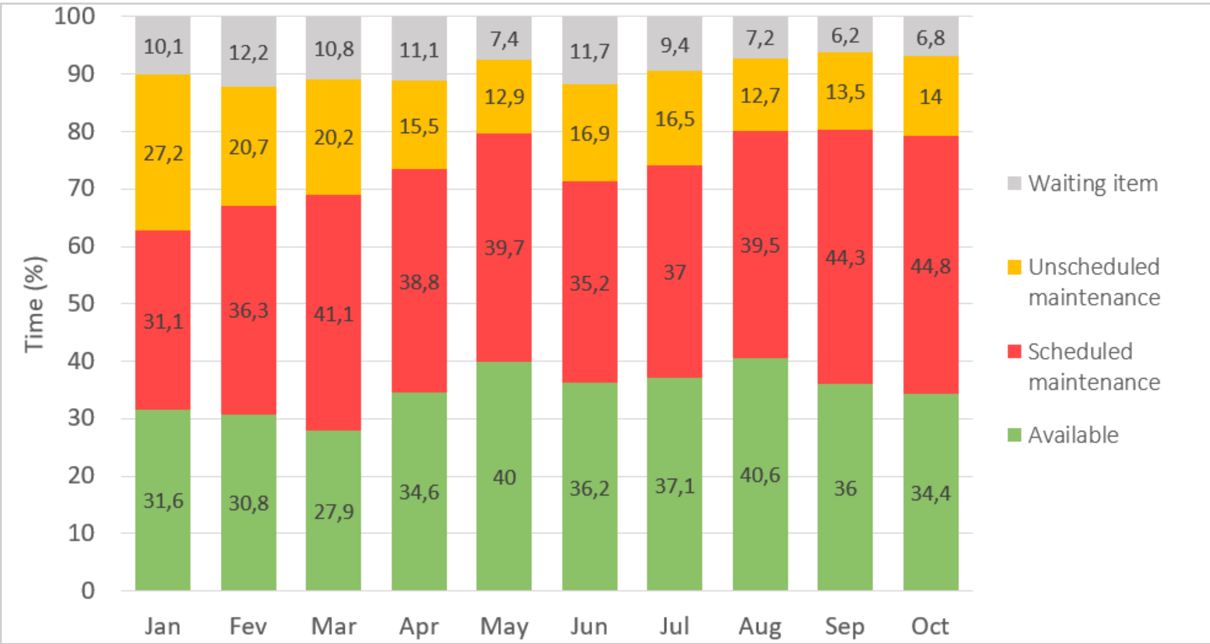

Figure 33: H225 availability states adapted

As can be seen from the graphs above and the operators' reports, the aircraft takes a considerable amount of time to carry out scheduled maintenance. In addition, it was observed that the time taken to carry out scheduled maintenance estimated by the study group was approximately similar to the value found in the field by the manufacturer's data. Finally, the average availability value was slightly below 40%. According to officers, the contract target is 50% availability, and this is going to be the availability target to be used on this model.

4.2.3 Scheduled Maintenance Analysis

After the general analysis of supportability in the previous sub-topic, in which it was observed that it is strongly impacted by scheduled maintenance, this phase focused on the scheduled maintenance and determine how it would be modeled.

The H225 aircraft has more than 30 different scheduled maintenance intervals, with more than 800 tasks in total. Figure 34 shows a graph of the number of tasks planned for each scheduled maintenance interval.

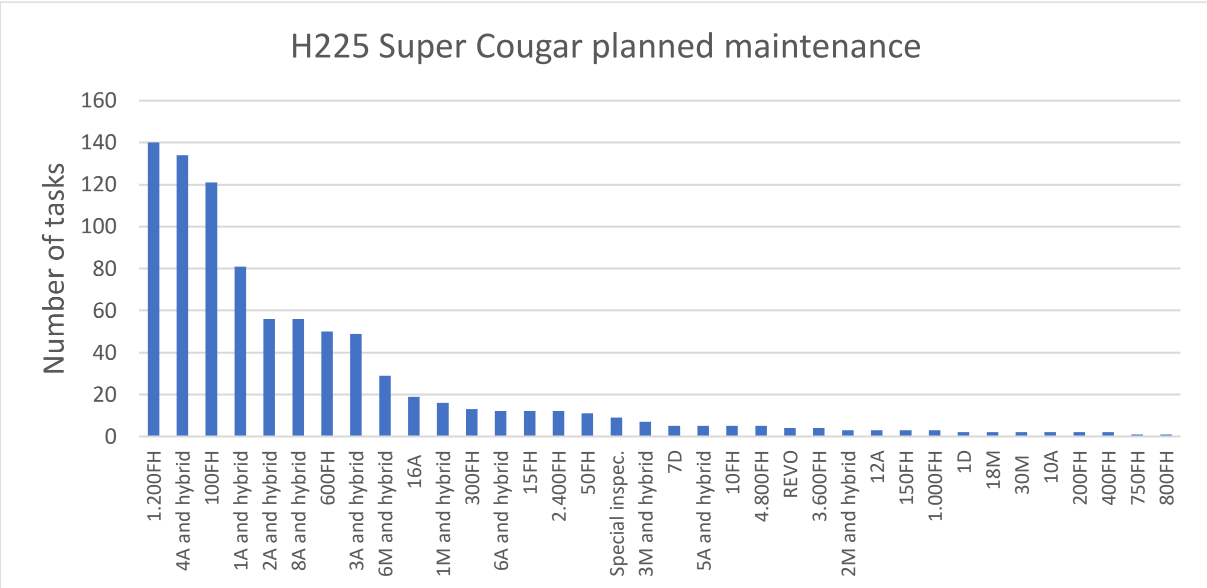

Figure 34: H225 planned maintenance interval tasks (Source: Author)

As can be seen, there are a large number of planned maintenance intervals to be executed, which increases the complexity for the fleet operator to manage along with their particular operating profile. Because of this, the anticipation of tasks ends up being necessary in some cases, which has a negative impact on total fleet availability.

To model the aircraft, the 8 largest maintenance intervals in number of tasks to be performed were considered. These tasks correspond to 78% of the aircraft's total number of planned maintenance tasks. In this way, the model represents the aircraft needs for maintenance with a good degree of representativeness. Figure 35 shows the tasks chosen to be modeled.

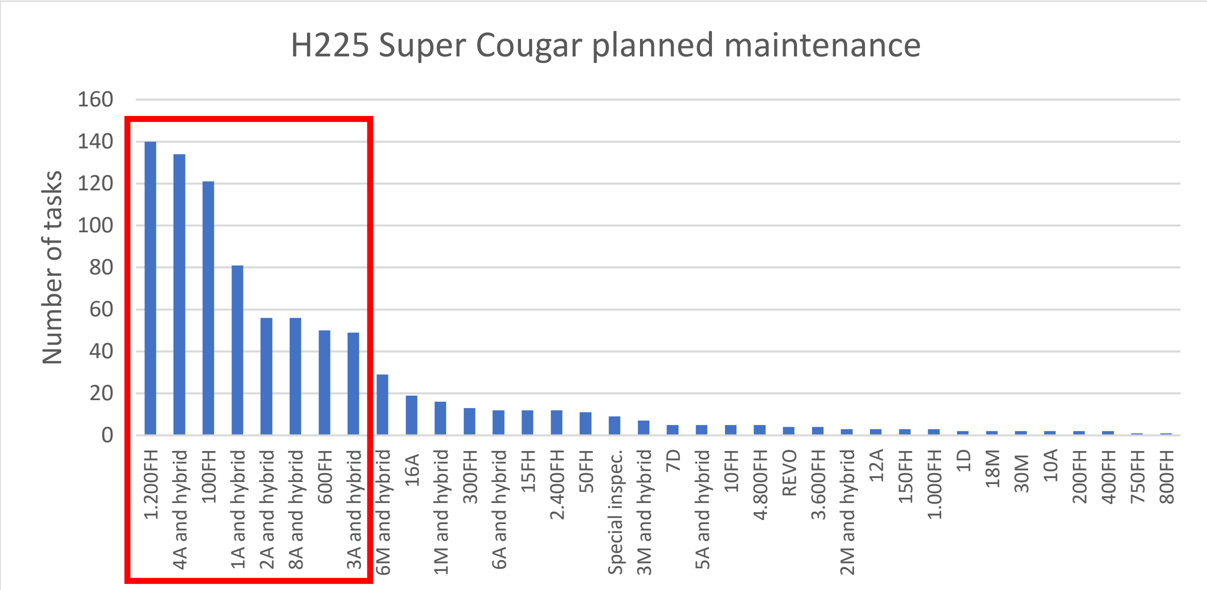

Figure 35: Maintenance intervals chosen to be modeled

Next, a questionnaire was sent to the operators/maintainers, asking them to answer the time and man hours used for each task individually. The summary of the information from the questionnaire is shown in Table 8.

Table 9: Operators/maintainers questionnaire

Maint. Interval	**Number of tasks**	**Average task execution time**	**Average man-hour/task (MH)**
1.200 FH	140	2 hrs and 45 min	1.6
4A and hybrid	134	3 hrs and 5 min	1.5
100 FH	121	48 min	1.1
1A and hybrid	81	3 hrs and 19 min	1.5
2A and hybrid	56	2 hrs and 50 min	1.5
8A and hybrid	56	7 hrs and 25 min	1.9
600 FH	50	1 hr and 58 min	1.3
3A and hybrid	49	5 hrs and 41 min	1.4

Based on this data, some calculations were made to arrive at total downtime for maintenance, man hours and downtime costs. The values are shown in Table 10:

Table 10: Scheduled Maintenance Information

Maint. Interval	**Elapsed time considering idleness (hours)**	**Total man-hour (MH)**	**Total maintenance cost (US$)**
1.200 FH	1.164	616	32.524,80
4A and hybrid	1.252	620	32.722,80
100 FH	291	106	5.622,15
1A and hybrid	810	403	24.673,85
2A and hybrid	475	238	12.566,40
8A and hybrid	1.252	789	41.666,23
600 FH	302	128	6.749,59
3A and hybrid	842	390	20.585,48
20 days	4	---	---

The information on Table 9 were added on the simulation model. To arrive at these, it was made the followed assumptions:

- The costs were based on man hour and consumable answered in the survey questionnaire with operators.
- It was assumed that each working day corresponds to 8 hours of actual maintenance.
- The total man-hour time was calculated by multiplying the average man-hour of each task times the number of tasks in each interval.
- For the man-hour cost, it was considered an average gross salary of R$10,000.00 for the aviation mechanic. It was assumed that the mechanic works on effective maintenance an average of 15 days a month, with each day actually working on maintenance for 5 hours. With an approximate dollar exchange rate of R$6.00/US$1.00 (December 2024), the net hourly cost of an aviation mechanic on a military maintenance base was estimated at around US$22.00.
- No differentiation in sub-specializations was considered among mechanics, e.g.: avionics, engines, airframe, structures, electronics, hydraulics.
- With the man hour cost, the total labor cost of the checks was calculated by multiplying the man hour cost by the total man hour of each check.

- The total cost of the planned maintenance checks was the cost of the labor plus an additional 130% to cover direct expenses such as consumables, mandatory replacement items and other expenses related to the maintenance tasks.

Finally, a last maintenance task was added for eddy current inspection of swashplates. According to the manufacturer, this inspection should take place after the component reaches 13 years of manufacture, and should occur every 100 FH or 20 calendar days, whichever comes first. Due to the low utilization rate, this task was simulated every 20 calendar days. As has been noted, the majority of aircraft already have triggered operating hours to start performing this task.

Although the manufacturer has assumed all the costs of carrying out this task, possibly due a design failure, its short interval between inspections became a relevant factor for fleet managers to take into account when managing the aircraft. As reported, the manufacturer inspector goes to the aircraft's location, it does not require any prior activity and the inspection is quick. Therefore, in the modeling, it will happen every 20 days, it will not require any prior activity, the manufacturer will pay for all the costs, and it requires a 4 hours duration, covering occasional administrative delay and/or time loss.

4.2.4 Aircraft Components

After detailing the scheduled maintenance, this sub-topic discusses the components that were used in the modeling. The components were chosen based on the ABC analysis presented in Chapter 2. The system is represented by 52 LRU (Line Replaceable Unit) type repairable items, which are covered by 1 contract with the manufacturer. Four major groups were selected: “propulsion”, “landing gear”, “avionics” and “other components”, and the list of the items can be found at Annex B.

4.2.5 Operational Profile

For the simulation of the aircraft's operational profile, which mainly provides information on the aircraft's utilization rate, 3 types of mission were adopted: “maritime patrol”, “squad mission” and “extraordinary mission”, according to the data in Table 11.

Table 11: Operating profile

Type of mission	**Operator**	**Nominal nº of A/C**	**Minimum nº of A/C**
Maritime Patrol	Main Operator	1	1
Squad Mission	Main Operator	2	1
Extraordinary Mission	Operational Far	2	1

Maritime patrol missions take place from Monday to Friday, from 9am to 11am, and in the afternoon from 2pm to 5pm. They take place in January, February, March, April and May. Squad missions take place from Monday to Friday, from 9am to 11am, and in the afternoon from 2pm to 5pm. They take place in January, February, March, April and May. Finally, extraordinary missions take place from Monday to Friday, from 9am to 11am, and in the afternoon from 2pm to 5pm. They take place in January, February, March, April and May. This usage profile is repeated for all the years of the simulation.

After the description of the missions above, the profile with the number of aircraft being used throughout the year can be seen in Figure 36.

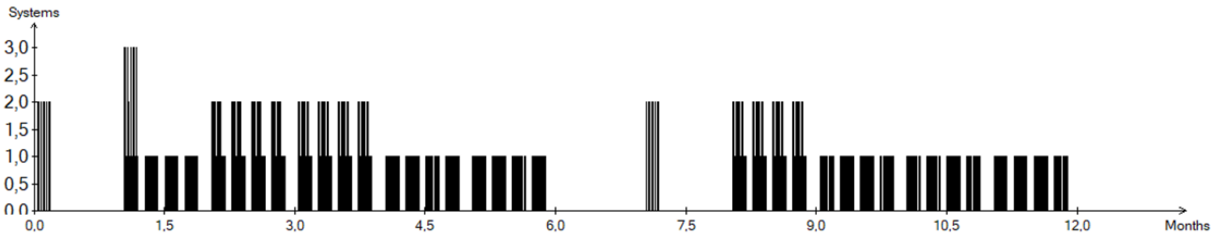

Figure 36: Yearly Operating Profile

The idea to create the operating profile is to input variability to the model, avoiding constant or almost constant usage rates. In Figure 36 can be seen that some periods has no utilization at all (e.g. between months 6 and 7), while others have quite constant usage rates (between months 9 and 12), and others have a considerably variable usage rate (e.g. between months 1 and 4). A closer view of the operating profile considering a 2 weeks horizon can be seen in Figure 37:

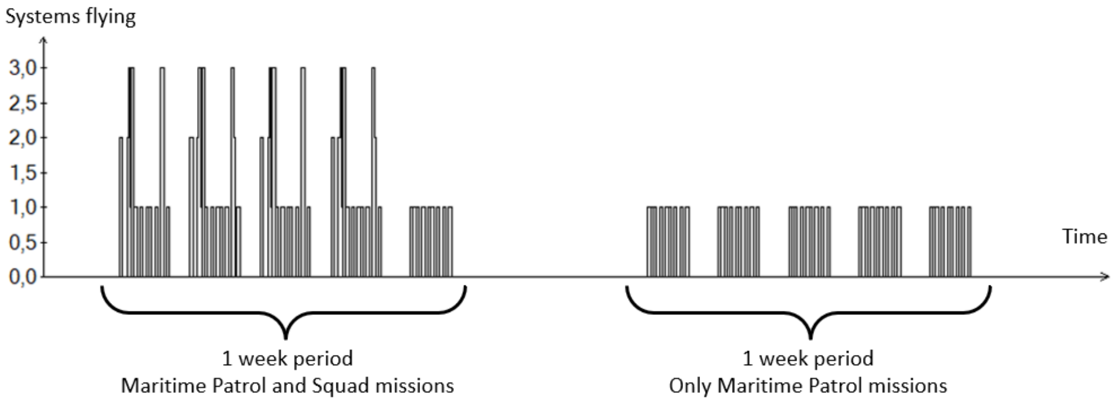

Figure 37: 2 week period of operating profile

These missions were chosen to meet two requirements: firstly, that the average utilization rate of all the aircraft was approximately 150 flight hours/year, and secondly, that the missions showed significant variability in the way the aircraft were used, in order to avoid constant or approximately constant utilization rates.

4.2.6 Support Structure

The support structure adopted in this simulation was based on field observations, and can be summarized as:

- With regard to the support structure, there is one current contract with the aircraft manufacturer (Helibras) that covers the repair of all components.
- There are 2 operational bases, one with 10 aircraft (Main Operator) and the other with 5 (Far Operator). They do not store any components and are supported by a central base.
- The central base serves as a hub for the logistical demands of all the fleets and different operating vehicles. The contract with the manufacturer is executed with this base. In this way, it receives the demand and/or item from the operational bases and makes the service request to the manufacturer.
- The last support base is the manufacturer. The spare parts storage is made at this base, as well as the repairs of the faulty components. The support structure can be seen in Figure 38.
- The cost of storing items is 5% per year of the item's value, including insurance.

- The average transit time between the Main Operator and the Central is 72 hours for both directions, and cost US$ 500.00 to go from Central to Main Operator, and cost US$ 1.000,00 to go for the opposite direction. The average transit time and cost between Far Operator and Central is 108 hours, while the cost is US$ 1.500,00 from Central to Far Operator, and US$ 3.000,00 to go for the opposite direction. For last, the transit time between Central and the manufacturer is 24 hours, while the cost is US$ 300,00 from the manufacturer to the Central, and US$ 600,00 to go to the opposite direction. All these times have administrative delay included.
- When a failure happens, the faulty component is removed from the aircraft, send to Central, and Central sends to manufacturer for repair. If there is an available component on stock, it is directly sent to fulfill the component vacancy, and the aircraft will be available again. If there is no available stock item, the aircraft will be unavailable while the repair of one of this component finishes (not necessarily the same than was installed before).
- For the replace tasks (remove and installation), the engine, the main gear box (MGB) and the main motor head (MMH) replace take 24 hours and 3 mechanics, the avionics replace takes 6 hours and 1 mechanic, and the other items take 12 hours and 2 mechanics. These times already accounts for administrative delay. The mechanic man hour is US$22,00 (as estimated previously) and these tasks have also a fixed cost of US$ 1,000.00 for avionics, US$3,000.00 for engine, MGB and MRH, and US$2,000.00 for the other items.
- There is no cannibalization and item discard, which means that the repairable items can always be repaired.
- The repair cost by the manufacturer already includes all the operator's obligation costs. No other fees or expenses will be charged.
- The modeling did not consider consumable items such as screws, nuts, washers, oils, greases, among others, due to their low cost and significance in the model. Their prices are included directly on the task cost.
- The model described has three echelons. The first, the operators, are the ones who actually use the aircraft, and they are also where scheduled maintenance is performed. The second echelon is the Central, which is a logistics center to concentrate all the demands of the maintenance contract with the manufacturer. And the third echelon is

the manufacturer, who stocks the items and has the capacity to perform the corrective maintenance.

- The failure rate of components is not affected by the utilization rate or even the aircraft aging.
- The failures are independent. There are no conditional faults. The failure of one component does not affect the probability of failure of another component in the same or another aircraft system.
- Items are handled individually, that is, repaired, ordered and transported as individual units. In other words, since a failure happens, the item is immediately sent to repair, there is no waiting to accumulate items to be transported in batches.
- The model does not take into account the occurrence of "findings" during scheduled maintenance or inspections.
- Atmospheric conditions such as operating in a saline environment, landing on helicopter carriers (for Brazilian Navy ships) or unpaved runways do not alter the probability of component failure.

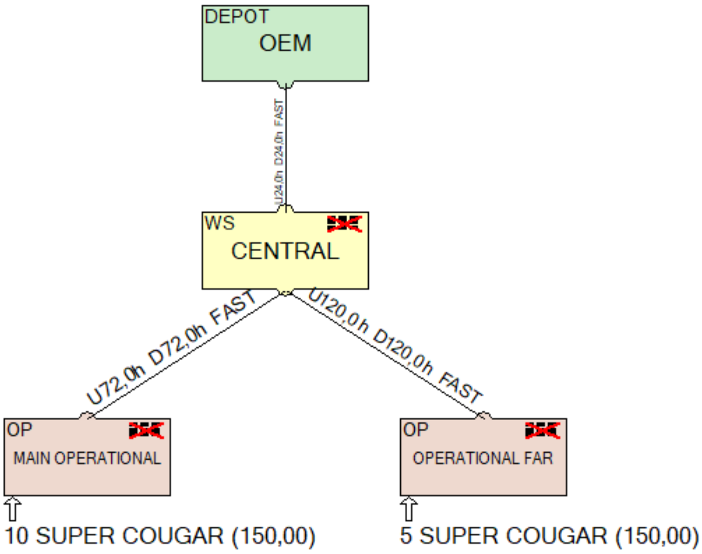

Figure 38: Support Structure for Default Scenario

4.2.7 Default Model

After processing the information to build the "default model", it was obtained the operational availability x Life Support Cost (LSC) curve according to Figure 39:

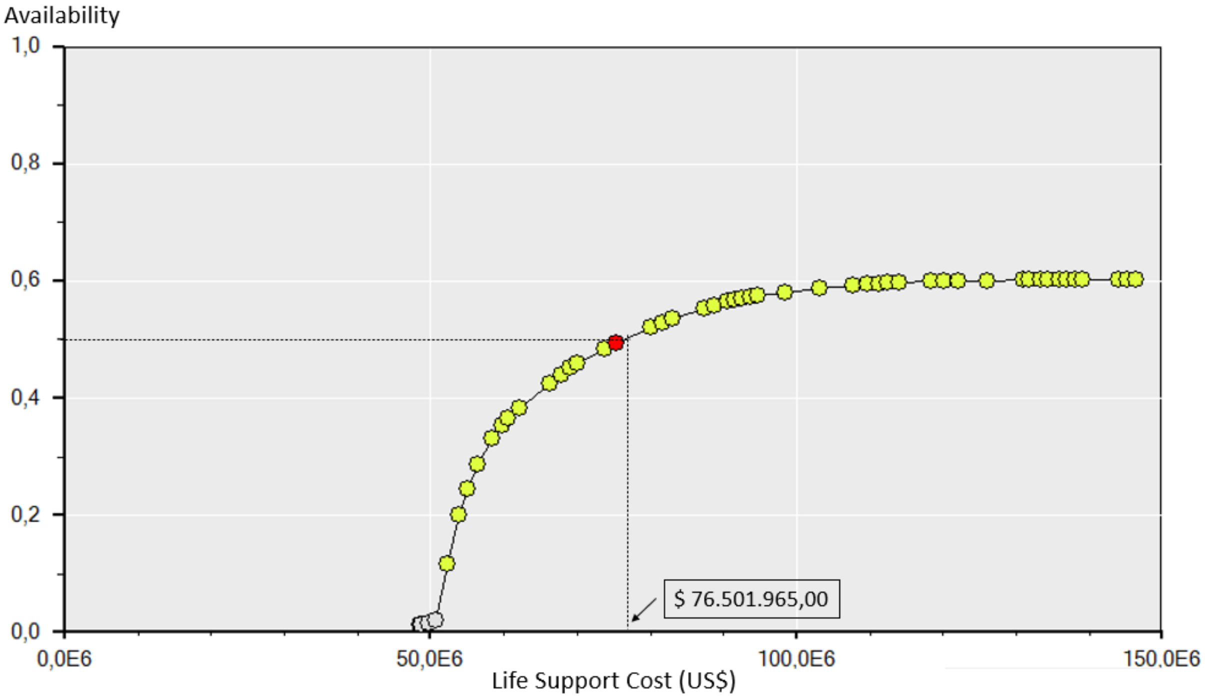

Figure 39: Cost effectiveness ratio for Study case

It's important to note some details from the previous figure. Firstly, it provides a list of points for operational availability and the respective costs given the support structure modeled. It can be seen from the curve that in order to obtain greater operational availability, it is necessary to increase the total support costs. Variations in the support structure (improvements or degradations) will have an impact on this curve, altering the cost-effectiveness ratio. In other words, if the curve shifts to the left or upwards, it improves the cost-effectiveness ratio, while if it shifts to the right or downwards, it worsens the ratio.

Another important detail to note is that the curve shows an availability "ceiling" around 60%. At this point, no matter how much more investment is made in the fleet, it would not have a significant impact on availability. The main factor responsible for this "ceiling" is the scheduled maintenance routines, which must be carried out and will take the same amount of time regardless of the level of spare parts stock.

It was chosen the Opus point 18, which has a 49,37% availability to continue the simulation, since it is the closest to the project target availability of 50%. For this point, the spare parts stock level is described in Annex C.

However, Opus presents a static scenario, which takes into account average demand rates per time and per aircraft, such as the utilization rate and maintenance. As such, this simulation does not consider peaks or batches. For the simulation of a more realistic scenario, which takes into account the mission scenario presented above, with demands variation and seasonality, using the stock level chosen previously, it was found an operational availability of 53,62%. Additionally, the system status throughout the years are presented in Figure 40.

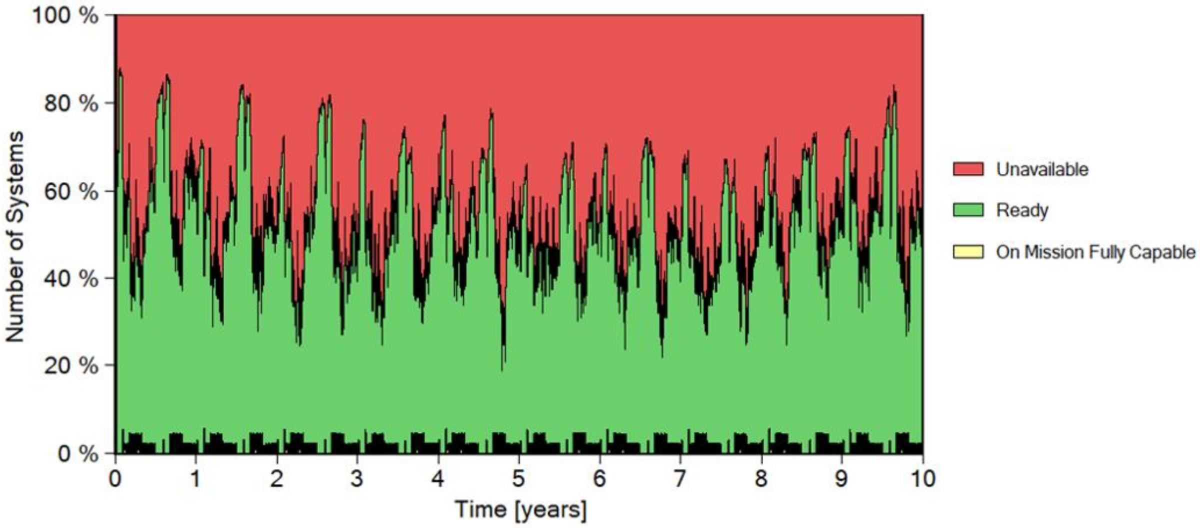

Figure 40: Fleet states profile throughout the years

Additionally, the SIMLOX also gives the unavailability breakdown, that can be seen in Table 12. This information is useful to find the drivers for fleet unavailability.

Table 12: Unavailability breakdown average for Default Model

Percentage	**Unavailability classification**
28,1%	Scheduled maintenance
17,1%	Corrective maintenance/Waiting items
1,1%	Removal and installation

In Table 12 the time for corrective maintenance and waiting items were compiled. An important observation during the simulation was to adequate these downtime periods with the real values observed. After performing this "calibration phase", the model is a good representation of reality in terms of downtime proportions as well as the relationship between availability and downtime.

Continuing, the costs breakdown for this scenario are described in Table 13:

Table 13: Costs breakdown for Default Model

Cost percentage	**Cost description**
38%	Corrective maintenance
21%	Inventory acquisition
12%	Scheduled maintenance
11%	Storage cost
11%	Depreciation
5%	Items transportation
2%	Removal and installation

As can be seen, the main driver is the corrective maintenance, which is outsourced in this model, followed by the inventory costs, and then scheduled maintenance (which is done in-house), the depreciation, which in this model were considered a 20 years of technical life length, and then the storage costs, and transportation costs, respectively.

4.3 Alternative Scenarios

According to the default scenario, the scheduled maintenance is performed in house by the operator, while the corrective maintenance is done by the manufacturer. Additionally, the items are shipped from the operators to a central base, and from there to the manufacturer. This pathway is done the same way for both sides. Moreover, the spare parts warehouse is on the manufacturer location.

At this point of the research it was developed the alternative scenarios, as described in Chapter 3. The scenarios to be analyzed are pointed below.

- Case A: Fully outsourced. The scheduled maintenance will be performed by the manufacturer.
- Case B: Fully in-house. The corrective maintenance will be performed in house.
- Case C: Unsuccessful repair. The manufacturer occasionally sub-contracts another company to perform some repairs.
- Case D: Specified company oversea, hired for high complex equipment.
- Case E: Variation in the dollar exchange rate.

4.3.1 Case A: Fully outsourced

To run this simulation it was used data from the current support contract between the Helibras, the manufacturer, and Brazilian Forces. The maintenance tasks that will be altered were presented in Table 10, and the new values are presented in Table 14.

The contract has information for the major stops, which are: 1,200 FH, 4 years and 8 years. But these services cover the smaller tasks considered in the simulation (e.g. if the 1.200 FH scheduled maintenance is requested for the manufacturer, it will be performed the tasks related to the 1.200 FH, but also the sub multiples will be executed, like the tasks related to 100 FH, 600 FH). The same pattern happens if the task related to the 4 years is requested, in this case the tasks related to the 1 and 2 years will also be executed. Due to that, the cost per task was weighted in order to not overpricing the services performed by the manufacturer.

Table 14 shows the comparison between the Default Model and the Case A (preventive maintenance performed by the manufacturer).

Table 14: Scheduled maintenance by manufacturer

	Default Scenario		**Case A: PM by manufacturer**	
Task ID	**Cost (US$)**	**Downtime (hours)**	**Cost (US$)**	**Downtime (hours)**
20 D	0,00	4	0,0	4
1 A	24.673,85	810	42.201,2	400
2 A	12.566,40	475	21.493,1	235
3 A	20.585,48	842	35.208,6	416
4 A	32.524,80	1252	55.967,8	619
8 A	34.721,86	1252	71.264,3	619
100 FH	5.622,15	291	24.395,5	338
600 FH	6.749,59	302	29.287,7	350
1.200 FH	32.524,80	1164	141.130,7	1352

As can be seen, some tasks have become more expensive and are performed with a reduced downtime, while other tasks have become more expensive and more time-consuming.

The result of these variations is presented in Figure 41:

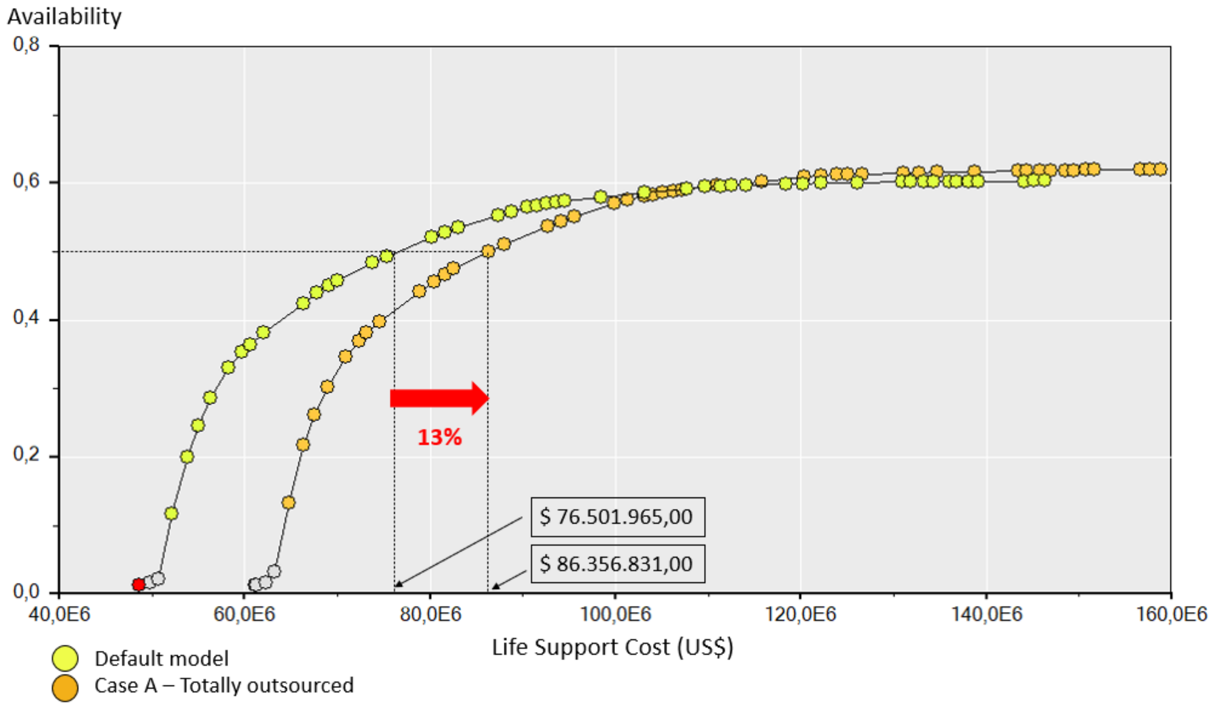

Figure 41: Default Scenario x Case A (totally outsourced)

As can be seen, for an availability of 50%, the Default Scenario has a Life Support Cost (LSC) of US$ 76.5 million while Case A has US$ 86.3 million of LSC for the same availability, a 12.9% increase in cost.

Another observation from this analysis was that, for higher availability values, the disparity between the costs for both scenarios is reduced. Additionally, around 60% availability the costs for both scenarios are the same, and above 60% availability Case A is slightly better than the Default Scenario, as it delivers higher availability. For example, the last point in Case A has 61,95% availability, compared to 60,33% availability for the Default Model. Therefore, choosing the best alternative is not trivial and depends on the requirements/performance expected by the fleet, which for the example of 50% availability target the Default Scenario is more appropriate.

Another observation was the simplifications made in this analysis, which took into account the time and direct costs of performing the tasks. In this way, costs such as commissioning and decommissioning of hangar and/or special tools are already included in the costs, as well as that in Case A the tasks would be performed by manufacturer at the operator's facilities, so there would be no need to move the aircraft to carry out these tasks.

4.3.2 Case B: Totally in-house

In order to simulate the execution of the repair in-house, it was necessary to make some adjustments to the model. The first adjustment was the support structure. While the Default Scenario has 2 operational bases connected to a central base, and the central base connected to the manufacturer, for Case B this last connection (Central Base - Manufacturer) was suppressed.

Figure 42 presents the support structure for this analysis.

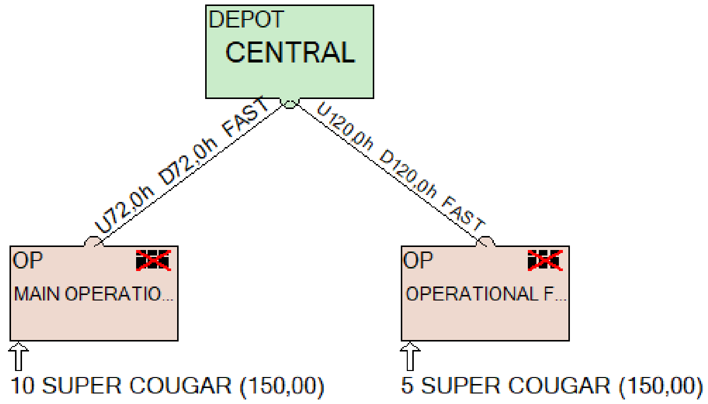

Figure 42: Case B – Support Structure adopted

In addition to removing the manufacturer from the support structure, the central base received the capacity to perform the corrective maintenance, and also received the capacity to store spare parts, at the same cost as the manufacturer (5% per year of the item's price).

Next, the resources needed to carry out the repair tasks were modeled. The resources included in the model were: Acquisition of Ground Support Equipment (GSE); acquisition of technical publications; investment in facilities; and training costs.

For this simulation, an initial GSE acquisition cost of 20 million dollars was considered, as well as a recurring update and calibration cost of 5 million dollars over 10 years. For technical publications, an initial cost of 40 million dollars was considered, along with a recurring update cost of 7 million over 10 years. For facilities, an initial cost of 10 million dollars was considered, as well as a recurring cost of 4 million over 10 years. Finally, for training costs, an initial cost of 4 million dollars was considered, as well as a recurring cost for retraining and new classes of 10 million dollars over 10 years. As a result, the total cost of the resources needed to carry out the repair tasks was 100 million dollars over 10 years. A summary of the values used can be seen in Table 12.

Table 15: Resource costs

Resource	**Initial cost (US$)**	**Recurrent cost (US$/year)**
GSE	20.000.000,00	500.000,00
Technical Publication	40.000.000,00	700.000,00
Facilities	10.000.000,00	400.000,00
Training	4.000.000,00	1.000.000,00

The numbers used above were estimated considering various criteria. Firstly, it took into account the order of magnitude of the values of the items included in the model, which in total add up to US$28 million for each aircraft. Secondly, an internal Embraer case study was used, in which the costs of resources to internalize maintenance tasks for an equipment on board of a military aircraft were analyzed. Third, it was used general information of aeronautic sector, such as the “GE Celma” report, which invested US$ 50 million in GSE and facilities to build an aero-engine test bench (available in: https://www.aeroflap.com.br/ge-celma-inaugura-um-dos-maiores-e-mais-modernos-bancos-de-testes-de-motores-do-mundo/, accessed November, 17, 2024). Further on, the resources costs were evaluated considering an increase and reduction of 50%.

Next, it was modeled the costs of carrying out the repair tasks. To do that, it was used the repair cost for the Default Scenario as a baseline. It was considered that the repair cost had a profit margin of 50% for the manufacturer. Of the remaining amount, it was estimated that 60% would be labor costs and 40% would be consumable costs. Additionally, it was considered that the cost of consumables would be the same whether the repair was carried out by the manufacturer or internalized. Regarding labor costs, the current contract charges R$660.00 man/hour if the customer requests any service. Considering a R$ 6.00 / US$ 1.00 exchange ratio (December, 2024), the manufacturer's man-hour cost was US$ 110,00, while for the armed forces the cost was estimated at US$ 22.00. Thus, while the consumable materials were the same for both cases, the labor cost to carry out the repair in-house was significantly lower than the same cost for the manufacturer.

After the considerations mentioned above, the Table 16 indicates the direct costs for carrying out the repair tasks.

Table 16: Direct cost per repair task performed

Repair task	Cost by manufacturer (US$/repair)	Cost doing internally (US$/repair)
Repair Engine	201,872.41	52,890.57
Repair Gear Box	176,401.27	46,217.13
Repair Main Rotor Head	222,928.04	58,407.15
Repair Propulsion Items	20,169.67	5,284.45
Repair Motor Pump	2,511.52	658.01
Repair Landing Gear Items	13,135.82	3,441.58
Repair Avionic Items	16,664.93	4,366.22
Repair “Remaining” Items	24,268.19	6,358.27

These costs are computed each time an item fails and the repair task is performed. As can be seen, the option to internalize the repair actions has a lower recurrent cost, but also has a fixed resource cost. After these assumptions have been made, the result of the simulation is shown in Figure 43.

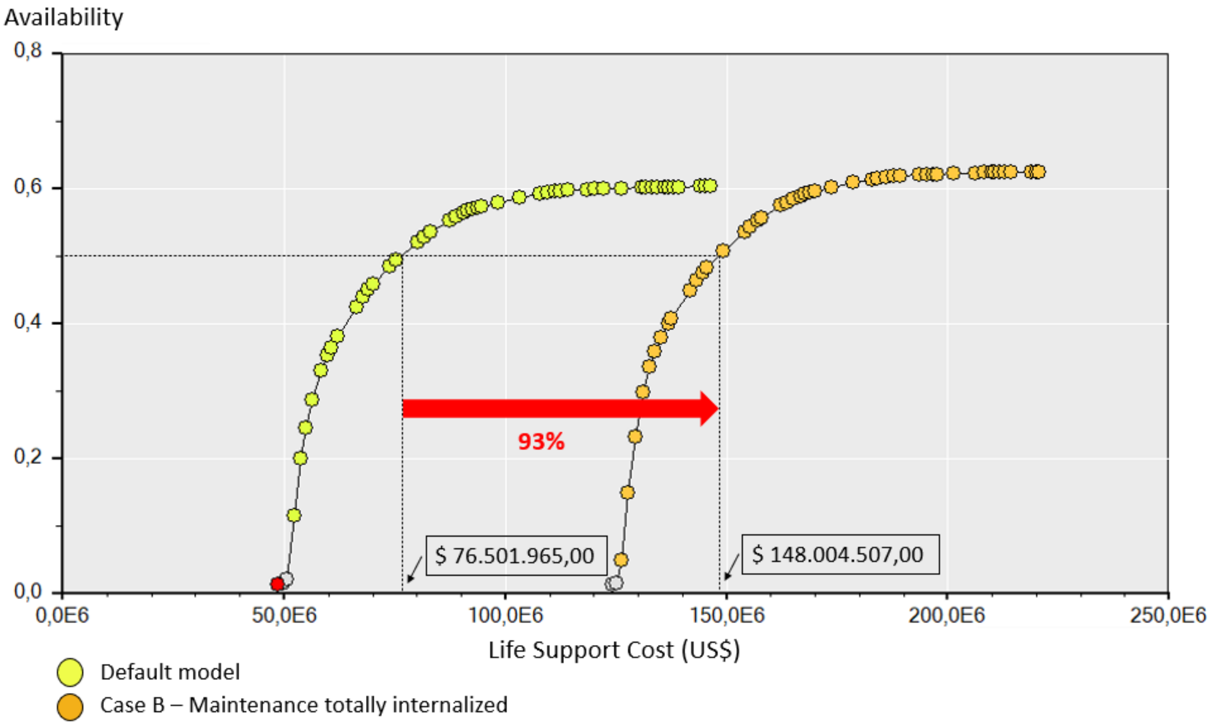

Figure 43: Cost effectiveness of repair tasks performed internally

As can be seen, the option to repair in house was very costly, with a much higher Life Support Cost (LSC) than the option to contract the repair from the manufacturer (Default

Model) for any availability requirement, which means that the option to perform corrective maintenance with the manufacturer has a better cost-benefit ratio over the entire spectrum. For the 50% availability, the Case B (corrective maintenance in house) had a LSC nearly US$ 150 million, compared to US$ 76 million for repair by manufacturer (Default Model), an increase of 93%.

The cost breakdown for both cases can be seen in Table 17.

Table 17: Cost breakdown for Default Model and Case B – Maintenance fully internalized

Cost Description	**Default Model**	**Case B – Fully internalized**
Items Investment	$ 17,8 M	$ 16,8 M
Preventive Maintenance	$ 9,8 M	$ 9,8 M
Item Storage	$ 8,9 M	$ 8,4 M
Item Transportation	$ 4,0 M	$ 2,9 M
System Replacement Costs	3,0 M	$ 3,0 M
Item Direct Repair Cost	**33,0M**	**$ 2,0 M**
Consumable - Item Repair	**---**	**$ 6,3 M**
Resource Initial Investment	**---**	**$ 74,0 M**
Resource Recurrent Cost	**---**	**$ 26,0 M**
TOTAL	**$ 76,5 M**	**$ 149,2 M**

As can be seen, the discrepancy was mainly due to the high resource's costs needed to acquiring maintenance capacity, combined with the fact that the fleet is relatively small, with only 15 aircraft. Additionally from Table 17, the "item direct repair cost" for Default Model is the cost actually paid for the contractor to perform the repairs, while this same cost for Case B is the incomes costs for the own mechanics to perform the repair internally.

Because of the high resource's costs, a new simulation was executed, considering a variation in the number of aircraft on the fleet, in order to check if the resource costs can be diluted for a larger fleet. As could be seen in the simulation, an increase in the number of aircraft at the fleet reduces the cost discrepancy. To point that, it was ran several simulation increasing the number of aircraft, until the simulation for 54 was performed, and for that the Case B presented costs quite similar to the Default Model. These results are shown in Figure 44.

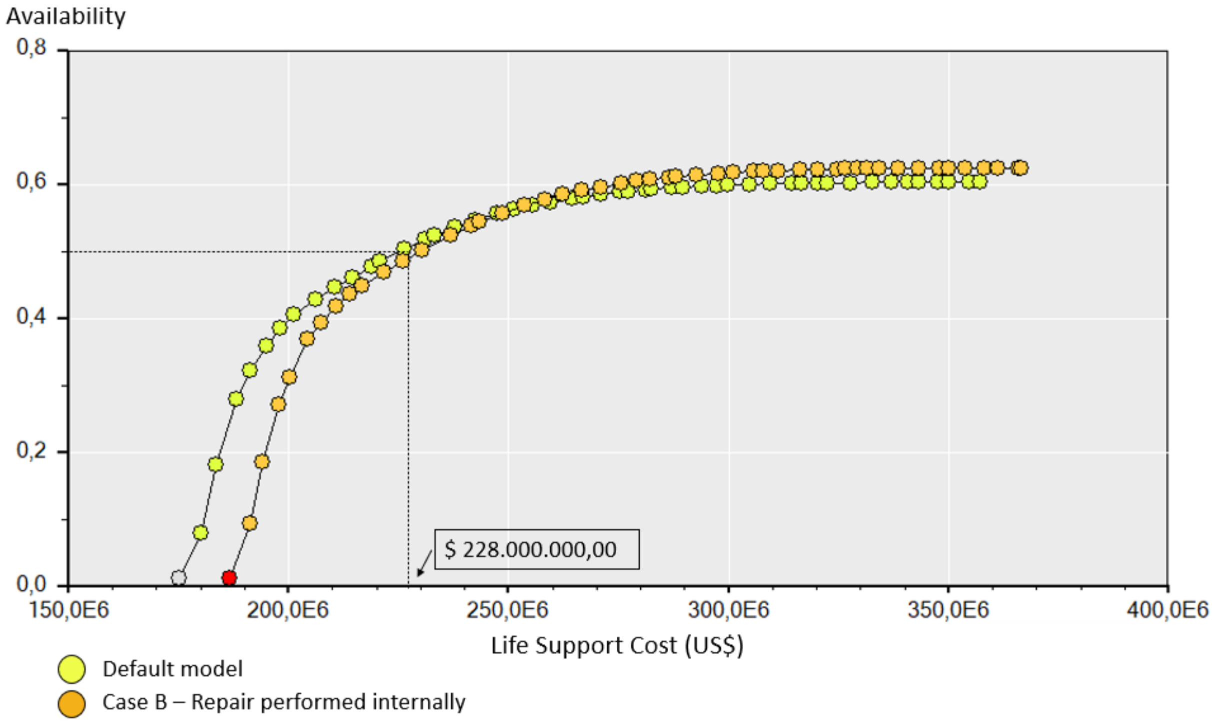

Figure 44: Default model x Case B considering a fleet of 54 aircraft

As can be seen, for a fleet of 54 aircraft the LSC for 50% availability is practically the same for both cases, proving that fleet size is a major factor in deciding where to carry out repair tasks.

Another observation in Figure 44 is the profile of the curves, which for Case B start out more expensive, then reach the same value, and afterwards Case B is more advantageous compared to the Default Scenario. This behavior can be explained by the fact that Case B has a higher fixed cost and a lower variable cost compared to the Default Scenario, so the "slope" of the curve is greater for Case B.

Moreover, it can also be seen that for high quantities of spare parts available (the end points of the curves), Case B showed slightly higher availability than the Default Scenario. This is because the support structure for Case B has a faster transportation time, since there is only transportation from the operational bases to the central base, while for manufacturer repairs there is also transportation from the central base to the manufacturer. In other words, given a fault, the support structure reacts more quickly, resulting in the aircraft being unavailable for less time.

Additionally, the cost breakdown for the fleet of 54 aircraft for Default Scenario and Case B is presented in Figure 45.

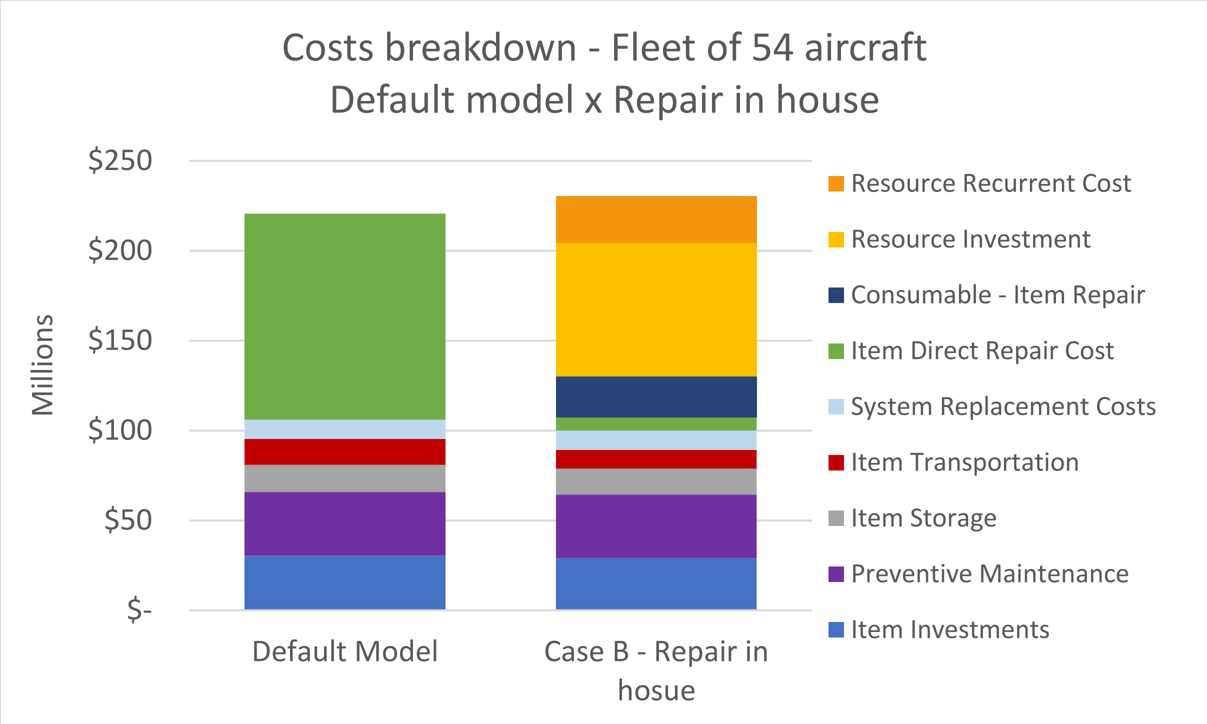

Figure 45: Cost breakdown for a fleet of 54 aircraft

As can be seem, although some costs were quite similar, like Item Investments, Preventive Maintenance, Item Storage, Item Transportation and System Replacement Costs, the remaining Costs were considerably different, but the summation of them were almost the same, proving the fleet of 54 aircraft were the breakeven fleet size for this model.

Continuing with the fleet size analysis, Figure 46 compiles the results for a fleet of 15, 54 and 90 aircraft. The yellow marks are related to the Default model, while the orange marks are related to the Case B. Additionally, the circle marks are related to a fleet of 15 aircraft, while the squares marks are related to a fleet of 54 aircraft, and the triangle marks are related to a fleet of 90 aircraft.

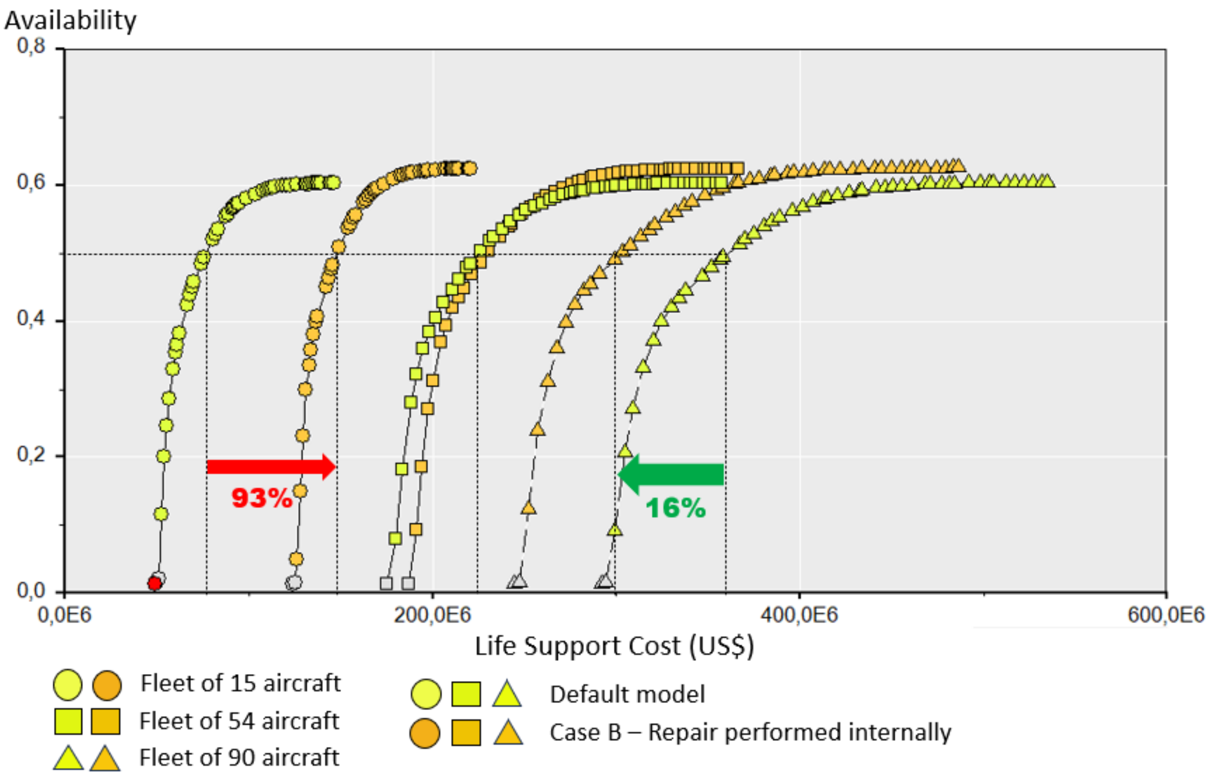

Figure 46: Default model x Case B considering a fleet of 15, 54 and 90 aircraft

As can be seen, for 15 aircraft, in-house repair is highly discouraged, as it had an increase of 93% compared to repair by the manufacturer, for an availability of 50%. For a fleet of 54 aircraft, however, there was a technical tie, with approximately the same values for 50% availability. For a fleet of 90 aircraft, however, in-house repair was more advantageous, with a 16% reduction in cost (US$ 299 million against US$ 358 million) compared to the option of having the repair carried out by the manufacturer.

4.3.2.1 Repair decision and its relationship to resource costs

Throughout the above analysis, it became clear that the decision is highly influenced by the size of the fleet, but also it was impacted by the cost of the resources needed to carry out corrective maintenance. Therefore, the next analyses considered a 50% reduction in the total cost of resources, while a second variation considered a 50% increase in the total cost of resources. As the initial analysis considered a total cost of US$ 100 million, in this analysis the resource costs were US$ 50 million and US$ 150 million respectively. Additionally, the initial and recurring costs are as shown in Table 18.

Table 18: Resource cost variations

Resource	Initial Cost (US$)	Annual Cost (US$)	Initial Cost (US$)	Annual Cost (US$)	Initial Cost (US$)	Annual Cost (US$)
GSE	10.000.000	250.000	20.000.000	500.000	30.000.000	750.000
Tech Pubs	20.000.000	350.000	40.000.000	700.000	60.000.000	1.050.000
Facilities	5.000.000	200.000	10.000.000	400.000	15.000.000	600.000
Training	2.000.000	500.000	4.000.000	1.000.000	6.000.000	1.500.000
Total cost	**US$ 50 million**		**US$ 100 million**		**US$ 150 million**	

Considering a 50% reduction in resource cost, it was performed the simulation for the Default model and Case B considering a fleet of 15 aircraft, and then it was runned several simulations increasing the number of aircraft on the fleet, until the fleet reach 27 aircraft. Figure 47 compiles the data with a fleet of 15 aircraft (the circle marks) and also the fleet of 27 aircraft (the square marks).

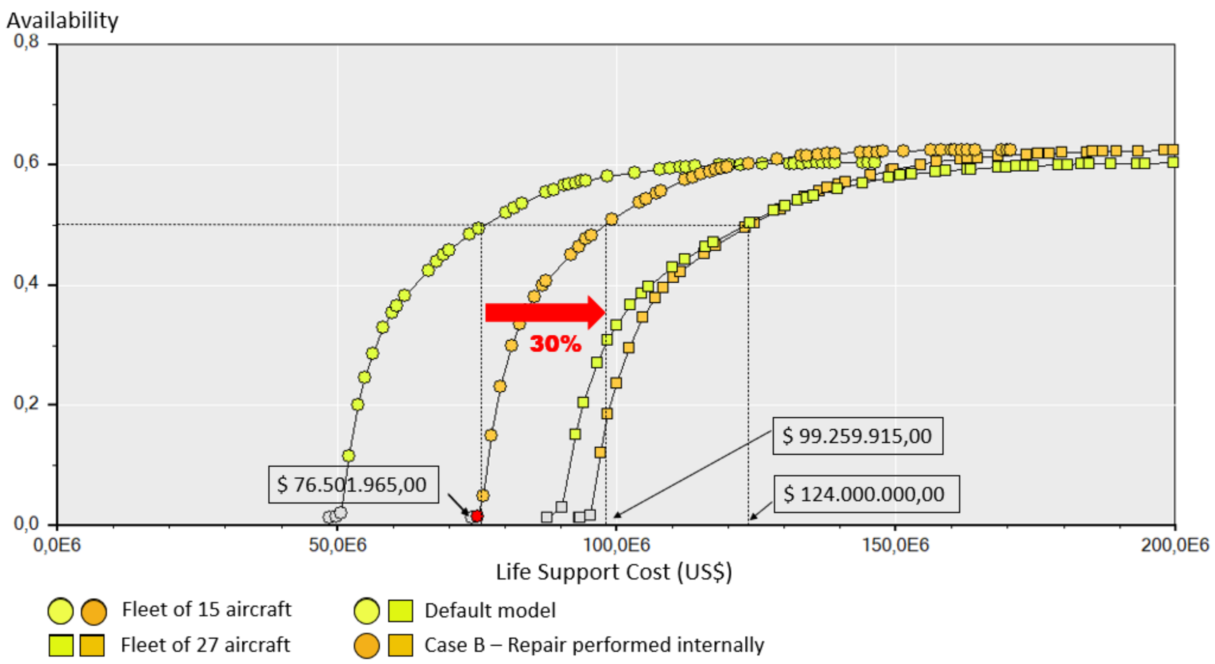

Figure 47: Cost effectiveness considering US$ 50 million of total resource cost

From Figure 47, it can be seen that, for a total resource cost of US$50 million, the choice to repair in-house would have a Life Support Cost 30% higher than the Default Model option for the actual fleet. It is a considerable reduction in the discrepancy, considering that for US$

100 million resource investment the difference was 93% higher. In addition, for a US$ 50 million resource cost, the breakeven for the fleet size was 27 aircraft, much lower than the 54 aircraft for a resource cost of $100 million seen earlier.

Continuing the analysis, it was now considered a US$ 150 million investment in resource, that can be seen in Figure 48. Again, it was compiled the results for the fleet of 15 aircraft (circle marks) and for the breakeven, that for this case was a fleet of 85 aircraft (the square marks).

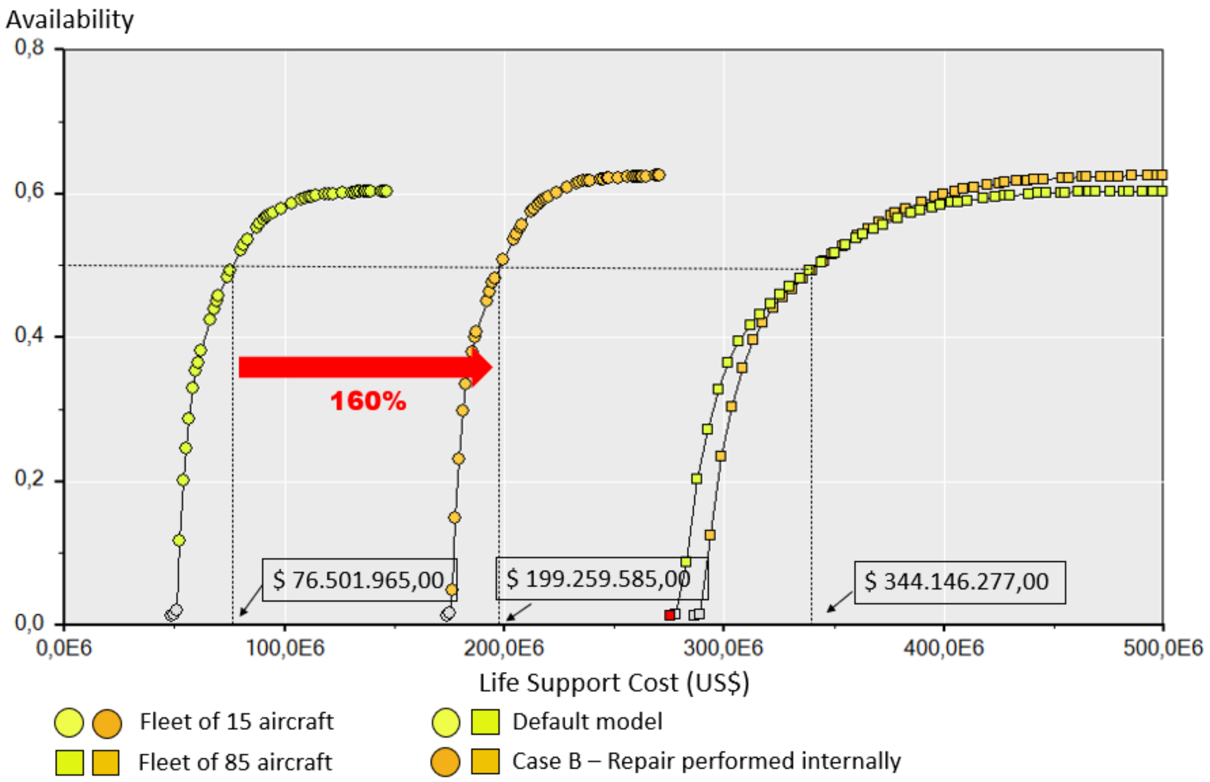

Figure 48: Cost effectiveness considering US$ 150 million of total resource cost

From Figure 48, it can also be seen that with a resource cost of US$150 million over 10 years, there was a 160% increase in the Life Support Cost of the in-house repair option compared to the Default Model, for the current fleet of 15 aircraft. In addition, the breakeven fleet size between the two options was 85 aircraft, with an LSC of US$ 344,1 million. Therefore, for a fleet of more than 85 aircraft, the option of internalizing the repair is more advantageous, while for a fleet of less than 85 aircraft, the option of repairing with the manufacturer, which is the default option, is more cost-effective.

With regard to the cost of the resources needed to acquire the capacity to carry out repairs, as well as the size of the fleet, it was possible to observe that the higher the cost of the resources, the larger the size of the fleet must be to compensate the investment. Table 19 summarizes the results obtained above.

Table 19: Relationship between resource cost and fleet size threshold

Total resource cost	**Fleet size threshold (units)**
US$ 50 million	27
US$ 100 million	54
US$ 150 million	85

The above result can be seen graphically in Figure 49.

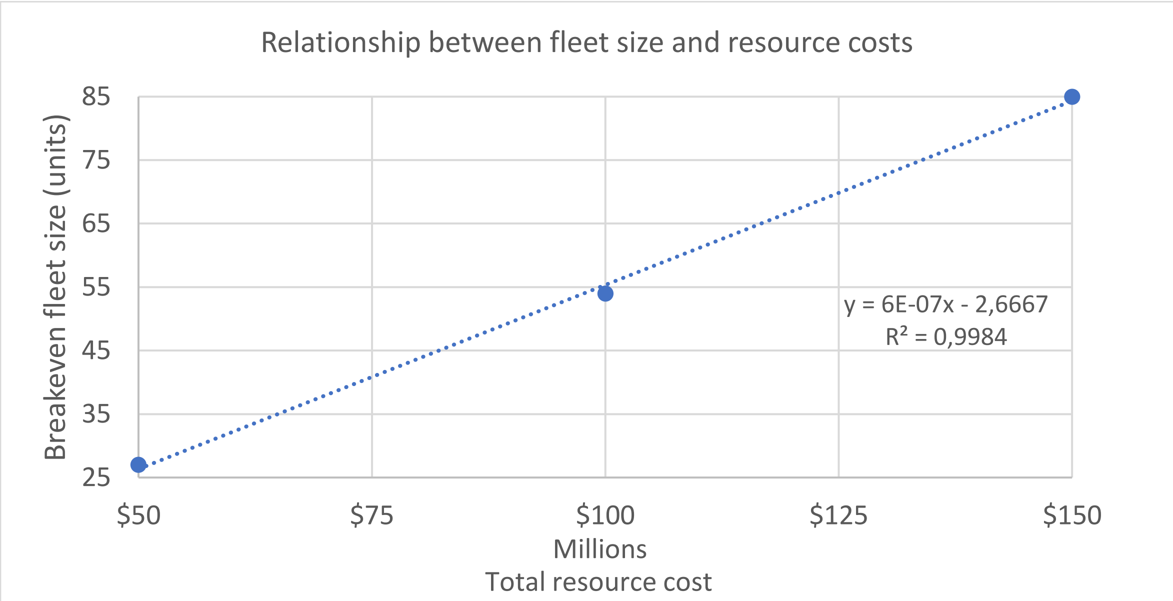

Figure 49: Relationship between resource cost and the breakeven fleet size

As can be seen, a linear approximation provides a good fit for these results, with an R^2 of 0.9984. In this way, in the case that the resource costs is different of the analyzed values, they can be estimated using the equation from Figure 49.

It should be emphasized that these results are variable and highly dependent on the assumptions applied initially, so their use in real cases should be made taking into account the particularities of each case.

4.3.2.2 Number of repairs being performed simultaneously

Another important point in the decision to internalize or outsource the corrective maintenance is “how large the internal repair structure has to be to handle the demand for the repairs that will come?” While the option of outsourcing to the manufacturer itself has some benefits, such as know-how, or even facilities already installed and working properly, the manufacturer offers this service to other customers too, so that they have installed capacity able to meet individual customer demands. In other words, when a repair is requested to the manufacturer it is started immediately.

However, for the decision to internalize repair services, the volume of repairs that can be carried out simultaneously is a factor that needs to be considered. The volume of repair performed simultaneously is highly dependent on the amount of investment made for that supportability structure. Due to a variety of restrictions, such as the number of test/repair benches, or the number of specialist mechanics, or the number of special tools available, if one of these resources isn't available, the repair can't be carried out, and the failed item will have to wait for all the necessary resources to be released before it can be repaired. So, in one hand there is a high costly structure, with abundant resources, that always that a failure happens the repair will initiate immediately, and on the other hands there is a low-cost structure, with limited resources, and occasionally when a failure happens there will be not all the necessary resources available, so the faulty item will have to wait to be repaired.

In this way, a resource called “Repair Bench” was created on the model, and each repair requires 1 bench. Thus, a bench will be occupied for the entire repair time of a specific item. Next, it was runned some simulations in which the number of benches was restricted. Therefore, when all the benches were being used, if another failed item arrived, it could not be repaired, and it had to wait for a bench to be vacated so that the repair could be carried out.

In these cases, the main indicator to observe is SIMLOX's “Awaiting Item”, since the aircraft will be waiting for the item to be repaired. However, “Availability” and “Mission completed” was also observed. Finally, a simulation was carried out considering the capacity to repair 20 and 10 items simultaneously, and the results of these three indicators can be seen in Figure 50. For this didactic example, the case with 20 simultaneous repairs simulates a large maintenance structure, with high costs incurred, while the case with 10 simultaneous repairs simulates a small/medium maintenance structure, where it is expected that occasionally could happen an waiting list for repairs.

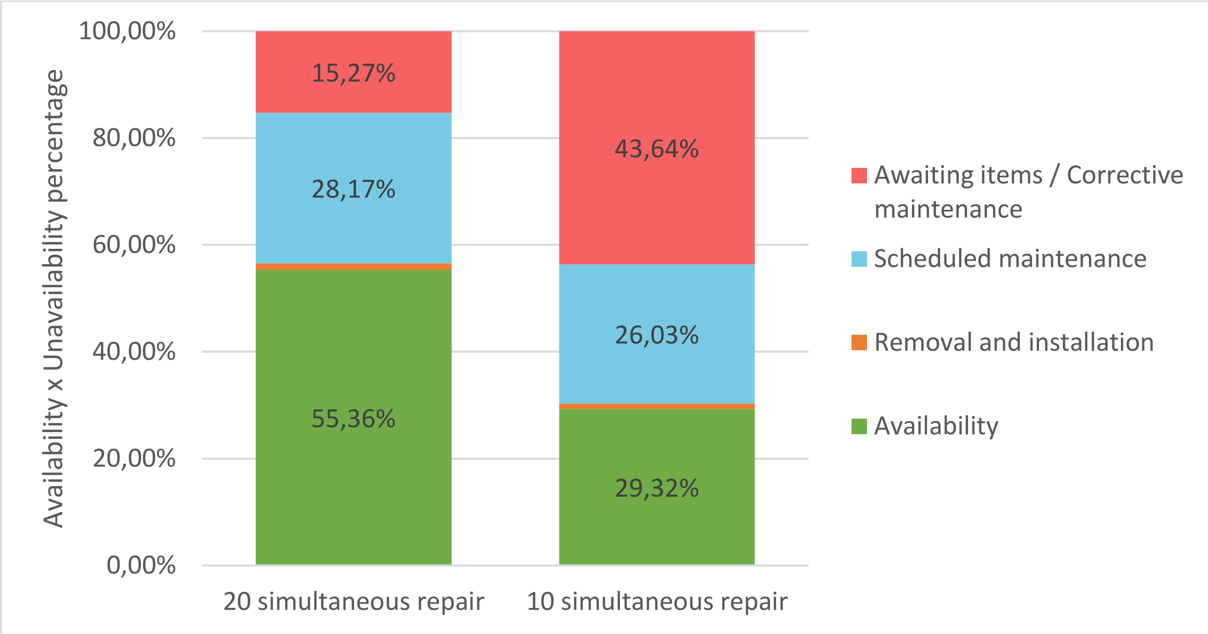

Figure 50: System status for 20 and 10 simultaneous repair

As can be seen, when the simultaneous repair capacity was reduced from 20 to 10, there was an increase in unavailability due to “Awaiting Item” from 15% to 43%. In addition, it can be seen too the impact in the availability for both cases, that was reduced from 55% for the 20 simultaneous repairs option to 29% for the 10 simultaneous repairs option. This indicates that, as previously proposed, the number of simultaneous repairs has an important effect on the decision to internalize or outsource corrective maintenance tasks.

Finally, the fulfillment rate of the requested missions was analyzed, which can be seen in Figure 51.

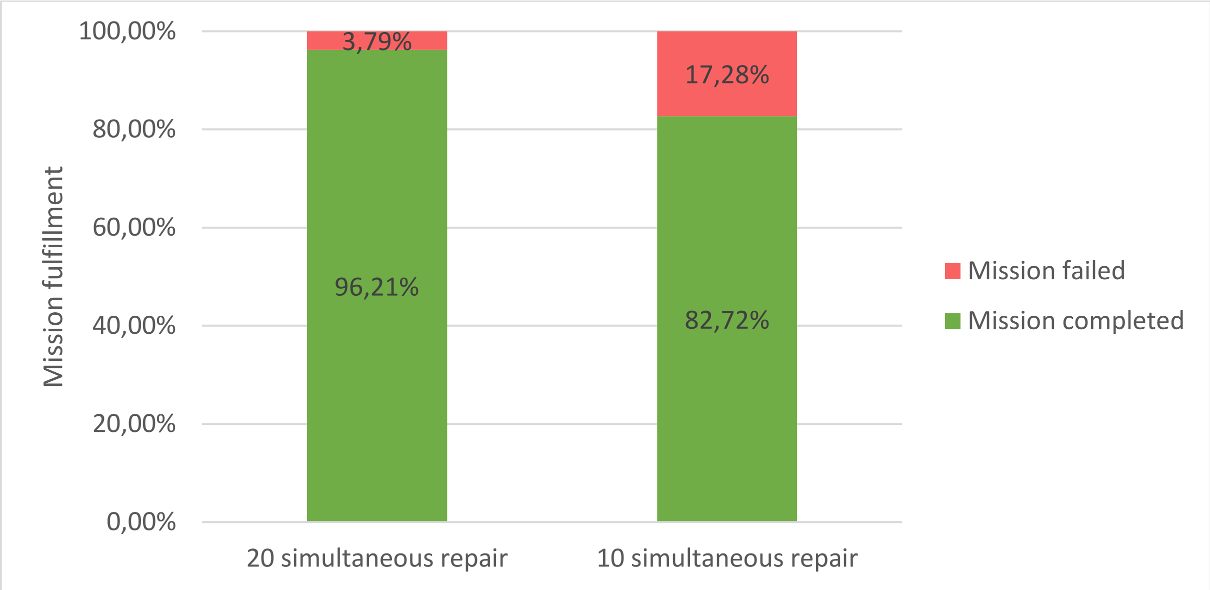

Figure 51: Mission completed rate for 20 and 10 simultaneous repair

As can be seen, the reduction from 20 to 10 in the number of simultaneous repairs resulted in a degradation of the fleet, increasing aircraft downtime due to waiting time for items, reducing aircraft availability, and also reducing the capacity to fulfill the required missions.

Due to that, it was performed a simulation considering various numbers of simultaneous repair, that can be seen in Figure 52, which compiles the 3 main indicators on the same graph.

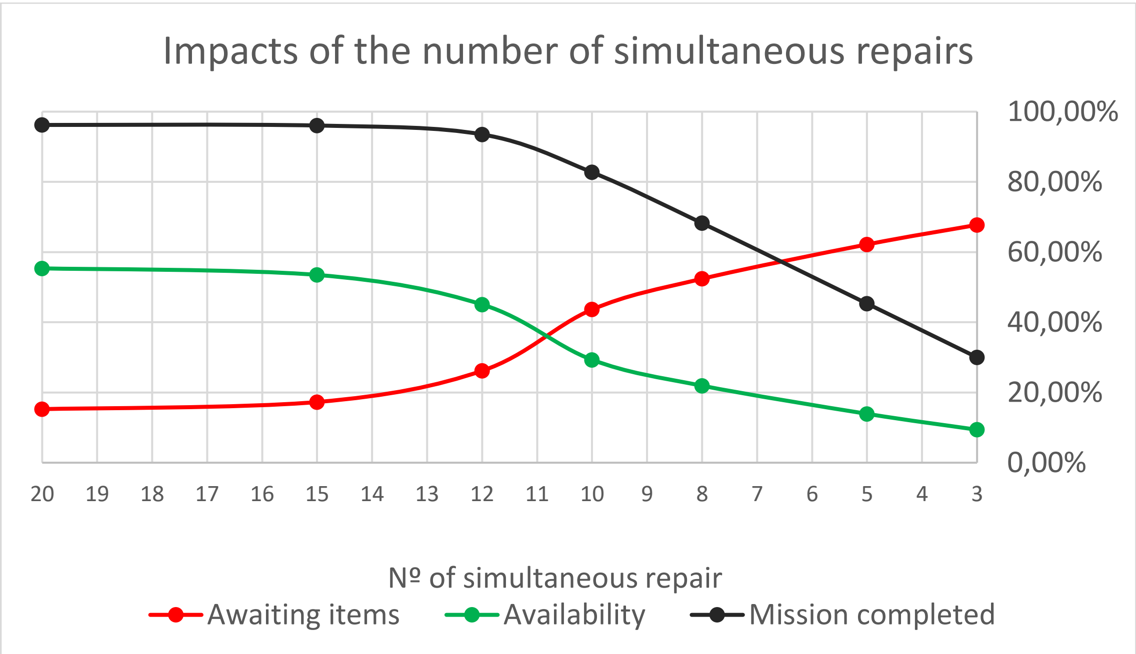

Figure 52: Impact of the number of simultaneous repairs

From Figure 52 it can be seen that for 15 or more simultaneous repairs there is no degradation in the fleet's supportability. However, below 15 simultaneous repairs, the fleet begins to suffer negative impacts, either through an increase in the number of aircraft waiting for an item to be repaired (since there is waiting list for repairs now), causing a reduction in availability, and also reducing the number of missions completed.

Thus, for the simulation model used, the organization must design a structure (with qualified personnel, including planning for vacations and other unavailability, equipment and tools, working area, etc.) that is capable of carrying out 15 simultaneous repairs. Any number above this value increases costs and does not bring an effective gain to the fleet, and values below 15 compromise the fleet's supportabilities.

4.3.3 Case C: Unsuccessful repair

This scenario deals with situations in which, for different reasons, the contractor can not successfully repair the failed component and then sub-contracts another company to perform the repair services. A typical case of this assumption is when the contracted company has difficulties and is unable to carry out the repair following the normal procedures and processes, so they turn to other companies, with more expertise in the specific issue they are unable to resolve. This situation is typical in products launched at a low level of maturity, or in products with low testability, or in highly complex products where the manufacturing company has several suppliers of high complex components.

Due to its unusual situation, this type of subcontracting occurs sporadically. Therefore, the model assumed that 20% of the time the repair would require subcontracting, while the remaining 80% would not. In addition, in cases where subcontracting was necessary, there would be a transit time of 1 day both to and from the item, there would be an additional time for the subcontracted of 20% of the time contracted with the manufacturer, and there would be an additional cost of 50% of the amount contracted with the manufacturer.

Due to the facts presented, the support structure for this case is simulated according to Figure 53.

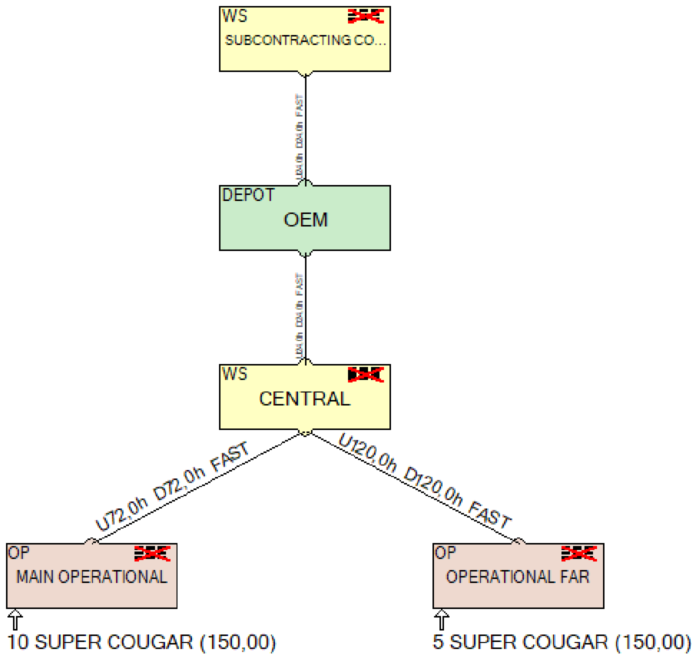

Figure 53: Support Structure for Case C – Unsuccessful Repair

And the result of the simulation of this scenario is shown in Figure 54.

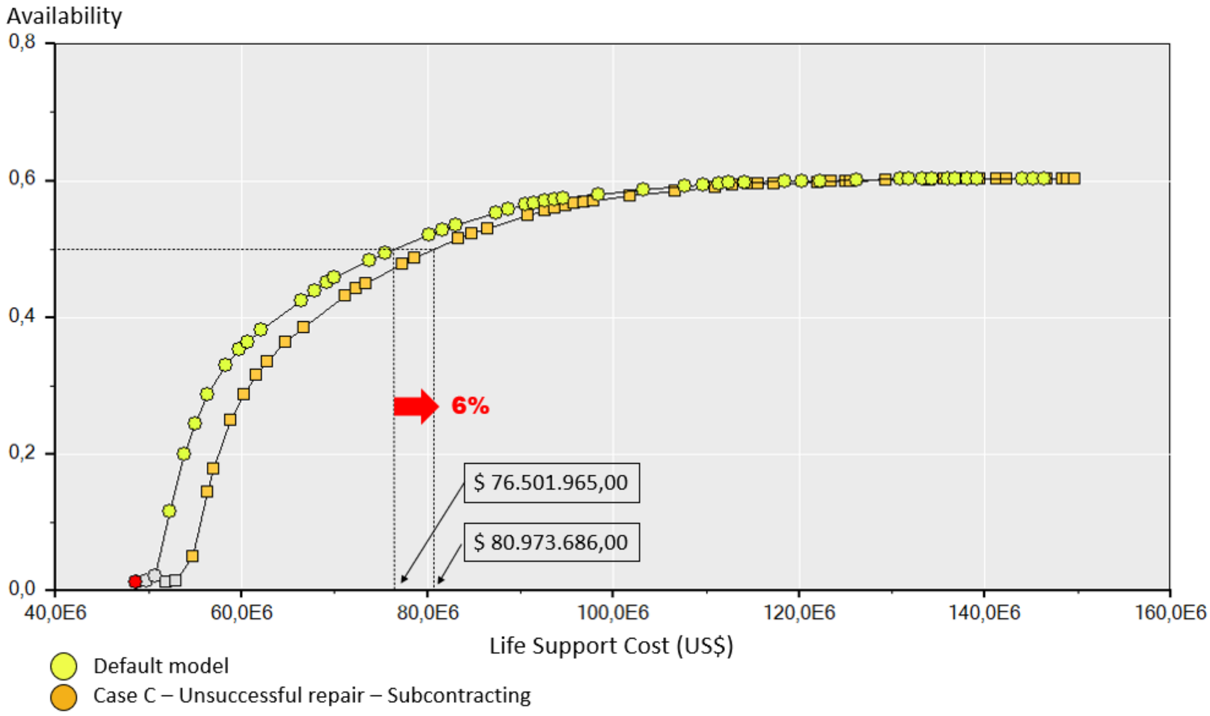

Figure 54: Case C – Unsuccessful repair and subcontracting

As can be seen, subcontracting the execution of repair services led to a worsening in the cost-effectiveness of fleet support, increasing the Life Support Cost by approximately 6% for an availability of 50%. About the stock items, they were the same for both scenarios.

Despite knowing in advance that this solution would be worse than the Default Model, since it was basically increased the repairs time and cost in 20% of the cases, the aim of this analysis was to quantify how much this isolated action could impact on the total cost of fleet supportability.

4.3.4 Case D: General x Specific Contracts

This analysis considers the case in which there is a general contract for the aircraft with its manufacturer, while there is a specific contract for a particular subsystem with its own developer, and this company is based overseas. This analysis aims to estimate the impact of geographically dispersed maintenance contracts.

This scenario was chosen for two main reasons. First, it addresses real-world challenge that organizations have to deal with: managing maintenance contracts for complex and specialized components that are often sourced from overseas manufacturers. By isolating the impact of geographic distance, this research aims to provide insights into the trade-offs involved in such arrangements. Second, the analysis highlights the strategic implications of supply chain decisions in the aviation industry. The choice to outsource maintenance for specific components to distant suppliers can have significant effects on overall operational efficiency and costs. By quantifying these effects, this research aims to contribute to a more comprehensive understanding of these factors.

The reasons for operators to proceed in this way can be varied, such as the legal reserve of certain equipment, ongoing patents, lack of qualified labor, or even previous experiences that indicate that certain equipment should be treated differently. Engines/propulsion systems are often treated in this particular way, which there are few developers' companies around the world, either because of the high costs involved in developing these projects, or because of their high complexity.

Due to that, the support structure modeled is showed in Figure 55.

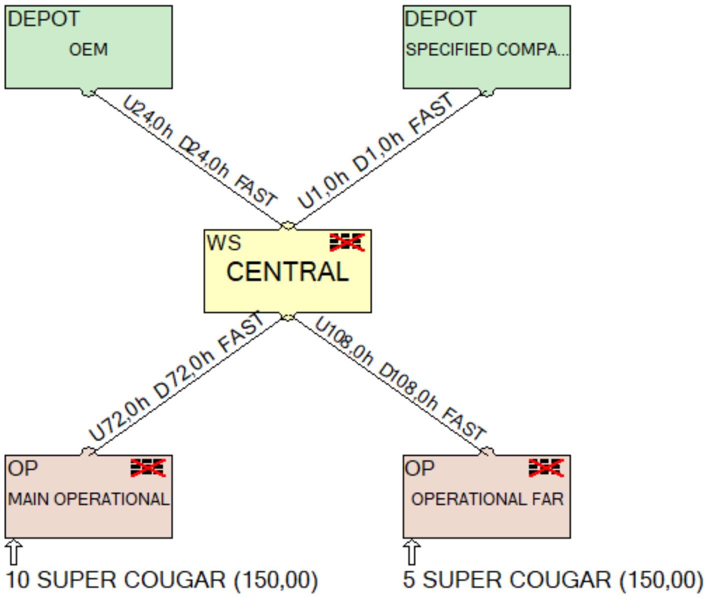

Figure 55: Support Structure for Case D – Specific contract oversea

In this support architecture, the propulsive system components are delivered to the "Specified Company", while the rest of the items are normally delivered to the aircraft manufacturer (OEM). As said before, it was considered that the "Specified Company" (the one that manufactures the propulsive system) is based in a long geographical distance (e.g. Europe or the United States), while the OEM has a base in Brazil. Due to that, the transportation time were increased from 1 day (between Central and OEM) to 10 days (between Central and Specified Company), while the transportation cost was increased to an average of US$ 3.000,00 to export (from Central to Specified Company) and US$ 6.000,00 to import (from Specified Company to Central). These prices considered that the spare parts have 25 kilograms in average, and the cost to export is US$120,00/kg and to import is US$240/kg, due to import fees. The cost and time to repair has been kept the same as the Default model, in order to isolate just the contribution of geographical disperse of maintenance contracts.

Given the considerations above, the result of this simulation is showed in Figure 56.

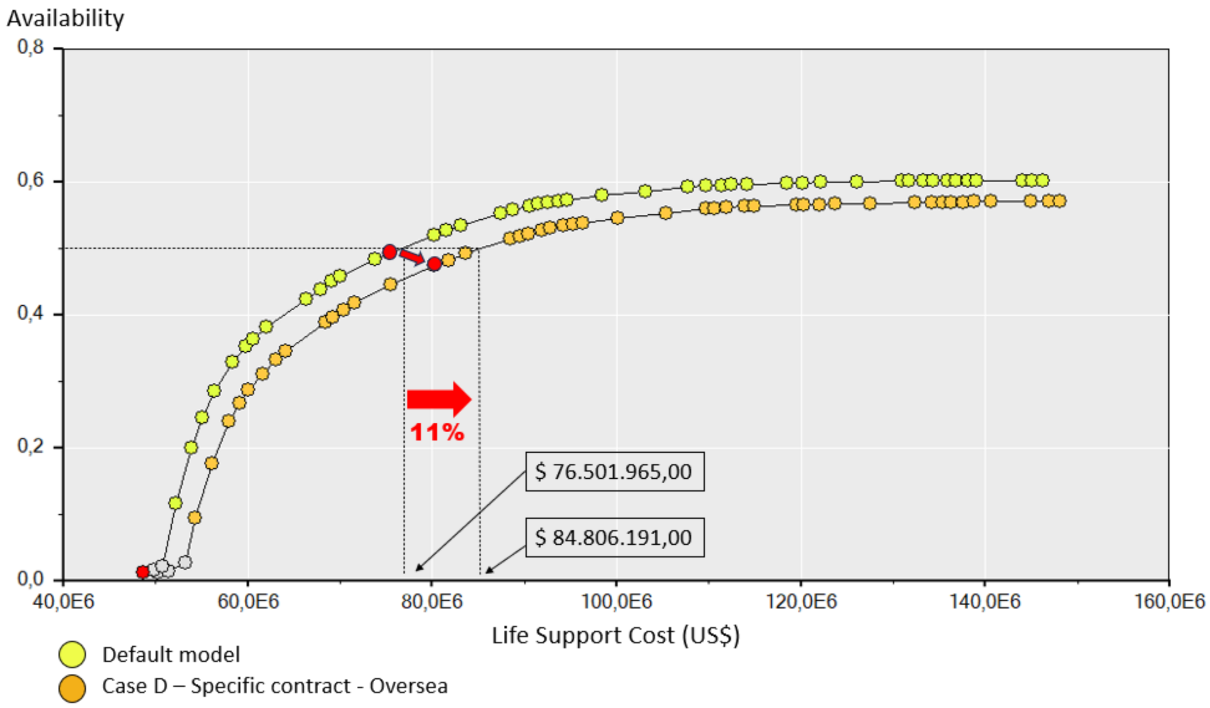

Figure 56: Cost-Effectiveness ratio for Case D – Specific contract oversea

From Figure 56, 2 factors should be observed. First, the red circles in both curves represent the same inventory level. This is the inventory that delivers a 50% availability for Default Model. Considering the same inventory for the Case D (specific contract oversea), the availability has decreased to 47,46%, while the cost has increased to US$ 80.260.000,00. Second, in order to reach a 50% availability, it is necessary to have a greater inventory level, and, at the end, the Life Support Cost has increased from US$ 76 million to US$ 84 million (11% increase) considering the case of specific contract oversea. Additionally, the list of the spare parts to be purchased for both Default Model and Case D is detailed in Annex D. From this list, it can be concluded that for the Default Model there are 74 items on the list to be purchased, while for the Case D has an additional of 4 items to be required, 2 of them were propulsive system items (PROP-05 and PROP-06), and 2 items from the list of other repairable (REP-09 and REP-18).

However, this simulation considered that all propulsive system items would be shipped and repaired abroad by the specified company, including peripheral items such as fuel pumps, fairing, and exhaust, which can be repaired using the general contract with the OEM. Therefore, a new simulation was realized, considering that only the most complex items would be supported by the specified contract. The items considered were: the engines, the gearboxes (main and intermediate), the main rotor head and the swashplate.

The result of this simulation, as well as the previous one, can be seen in Figure 57.

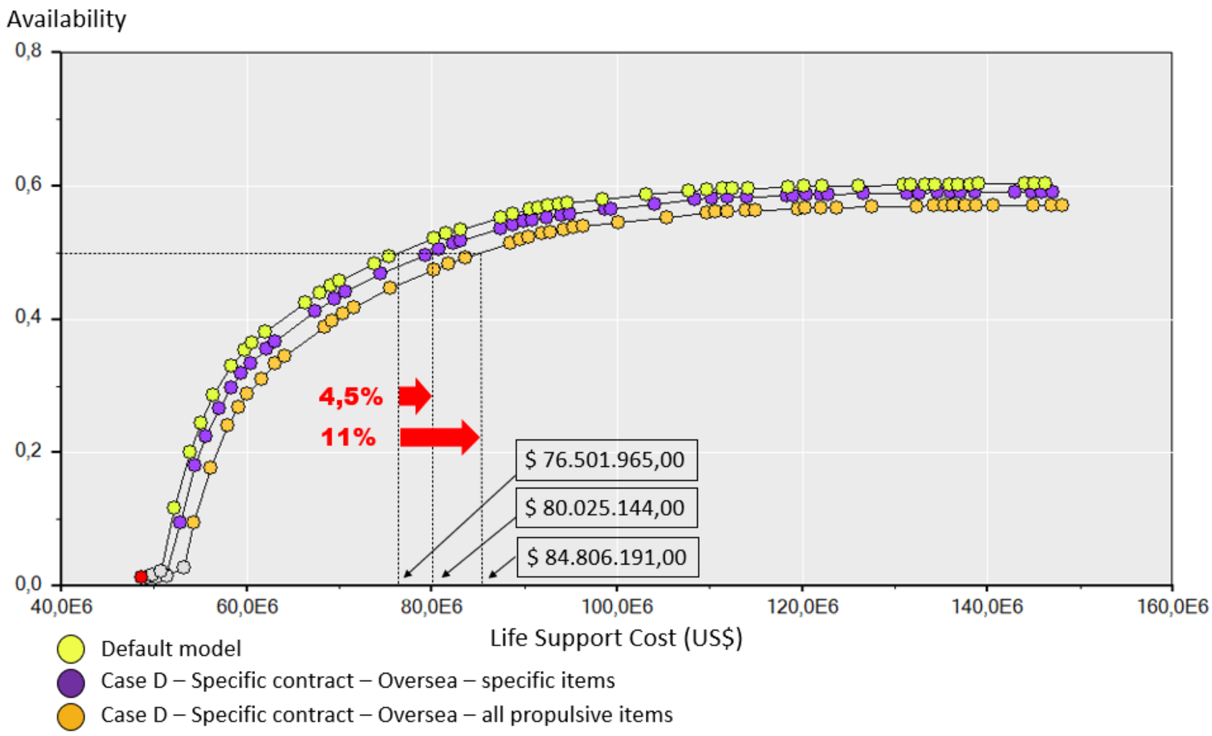

Figure 57: Cost-Effectiveness ratio for Case D in different configurations

Therefore, considering only the most complex items in the propulsion system, the LSC increased by 4.5% compared to the Default Model.

4.3.5 Case E – Exchange rate fluctuations

This analysis considers the impact of exchange rate fluctuations on the Life Support Cost. This study has its relevance due to the increasing globalized market, specially the aeronautical, which most of the manufacturers are foreign companies, and even the national ones usually have their accounting currency in exchange currency, usually the dollar. Given that, this study aims to address this significant risk faced by the organizations when they are planning and operating their fleets. And, by isolating the exchange rate fluctuation impact, this study aims to provide insights of the risks associated to currency variations.

Based on the life cycle costs of a fleet, it is to be expected that some are strongly linked to variations in foreign currencies, while others do not have a strong link to foreign currencies.

Because of this, the first step in this study was to separate the costs that would be impacted by variations in the dollar from those that would not.

Given the main costs, those that did not change with external currency variations were the cost of (internal) labor, the cost of transportation, as well as the cost of storage. The costs that did change were the cost of spare parts, the cost of consumables (necessary for preventive maintenance tasks), and the cost of corrective maintenance. It's worth noting that some costs correlate with each other, such as the cost of spare parts, which, if it changes, also alters the cost of storage, as well as the cost of depreciation. Another example is consumables, which also affect the cost of preventive maintenance.

Afterwards, the result of a 20% exchange variation (increase and decrease) caused an impact on the LSC that can be seen in Figure 58.

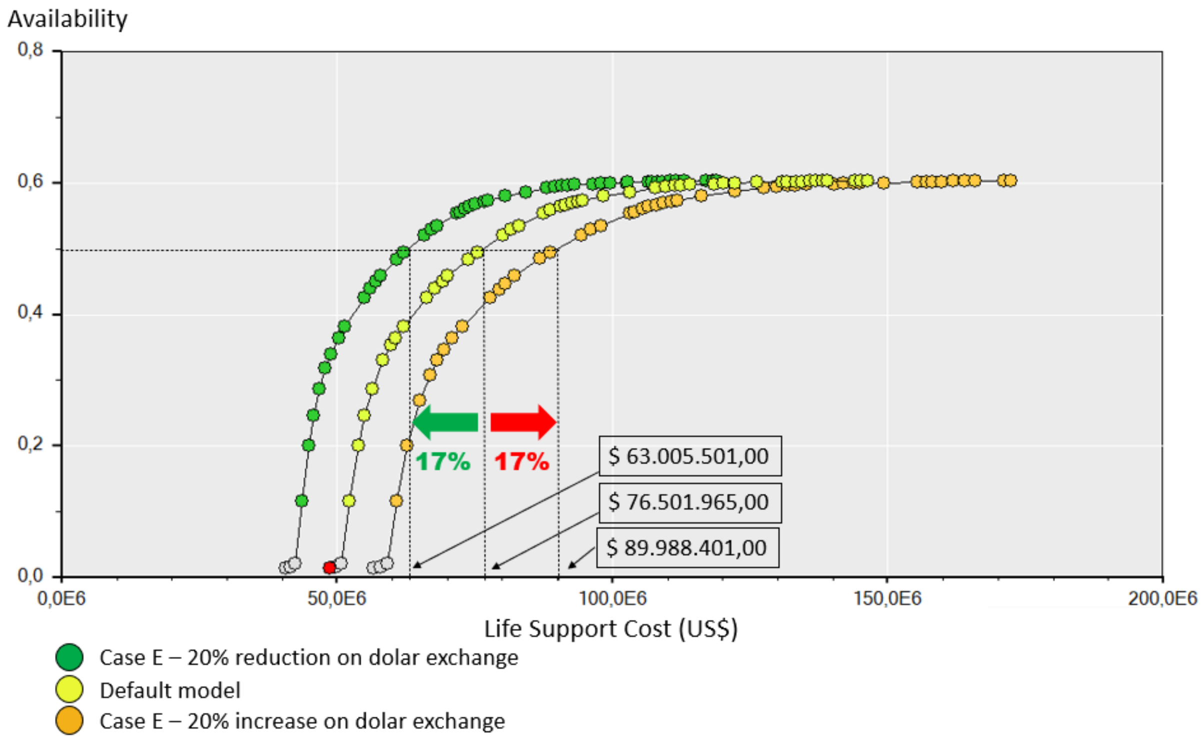

Figure 58: Case E – Currency exchange fluctuation

As can be seem, considering a fleet already in operation, a 20% fluctuation in currency exchange (increase or decrease) caused a 17% variation on the Life Support Cost.

Another simulation was performed to analyze the impact of currency fluctuations with the fleet already in operation, where the entire support structure has already been installed. This analyzes is relevant due to the fact that when a fleet is already in operation some costs has been totally incurred before the exchange, and does not suffer oscillations. One example is the cost of spare parts, that has a large fraction of the total cost, and also impacts also the cost of storage and depreciation expenses. Once the spare parts are purchased at the beginning of the operation, they would not be affected for future exchange oscillations, as well as the costs aggregated to it. Continuing, the currency fluctuation would fully impact the costs of corrective maintenance (assuming the contract prices would be recomputed), and would impact partially the cost of consumable materials (assuming that some of them had been purchased in advance also). The other costs were not affected. The result of the simulation considering the exchange fluctuation with a fleet already in operation can be seen in Figure 59.

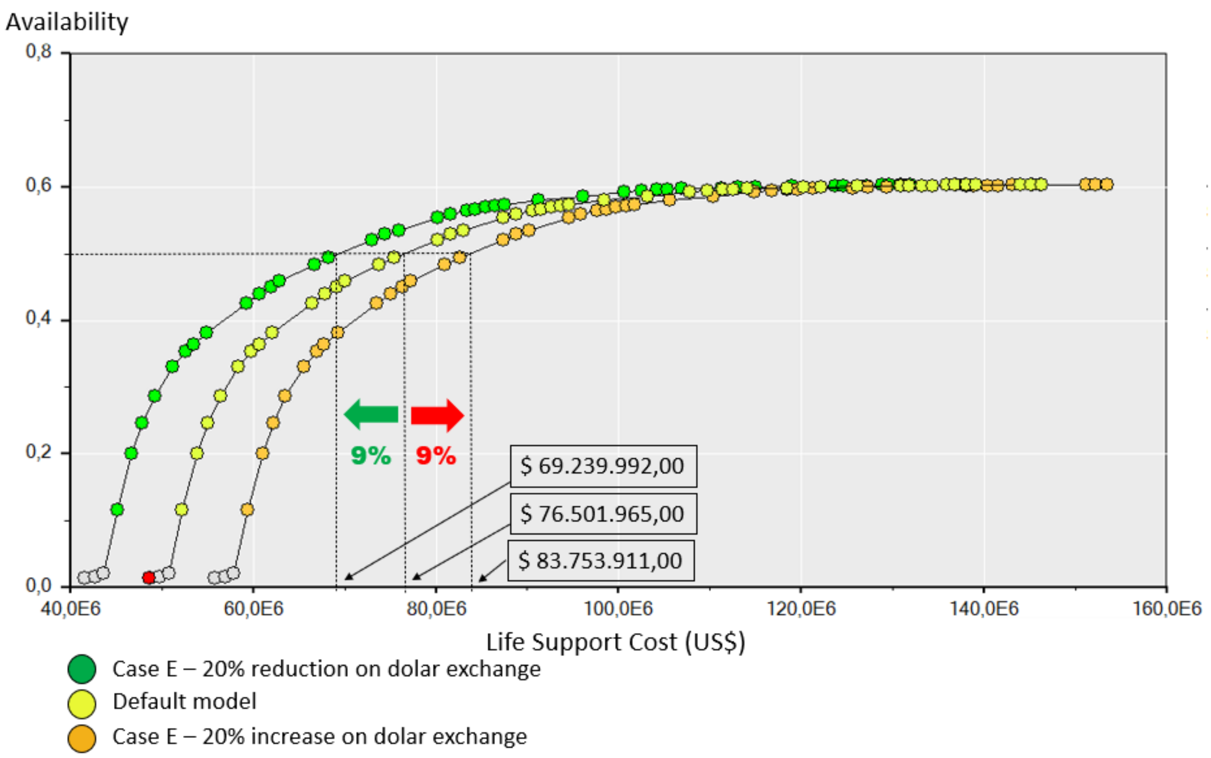

Figure 59: Case E – Currency exchange fluctuation for a fleet already in operation

As can be seem, considering a fleet already in operation, a 20% fluctuation in currency exchange (increase or decrease) caused a 9,5% variation on the Life Support Cost.

After all the scenarios have been described, Table 20 shows a summary of the results of the variation in the life support cost (LSC) of each scenario while maintaining an operational availability of 50%.

Table 20: Result summary of the simulations performed

Scenario	**Life Support Cost impact**
Default Model	---
Case A – Totally outsourced	Increase of 13%
Case B – US$ 50 million resource investment	Increase of 30%
Case B – US$ 100 million resource investment	Increase of 93%
Case C – Unsuccessful repair	Increase of 6%
Case D – Specific contract	Increase of 11%
Case E – Exchange fluctuation in early project phase	Increase/decrease of 17%
Case E – Exchange fluctuation in operating & support phase	Increase/decrease of 9%

As can be seem, it was observed that the Default Model was the best option in terms of cost saving for a 50% availability. The only exception for this statement is for Case E, if there is an appreciation of the local currency against the foreign currency and prices would be revised, as assumed in the model. Although the Default Model (with a partially outsourced and a partially internalized maintenance strategy) offers the best support structure solution compared to the other options, in order to compare the results obtained in this research with previous works in the literature, Figure 60 shows a comparison between the results obtained by Massoud Bazargan (2015) and the results of this research.

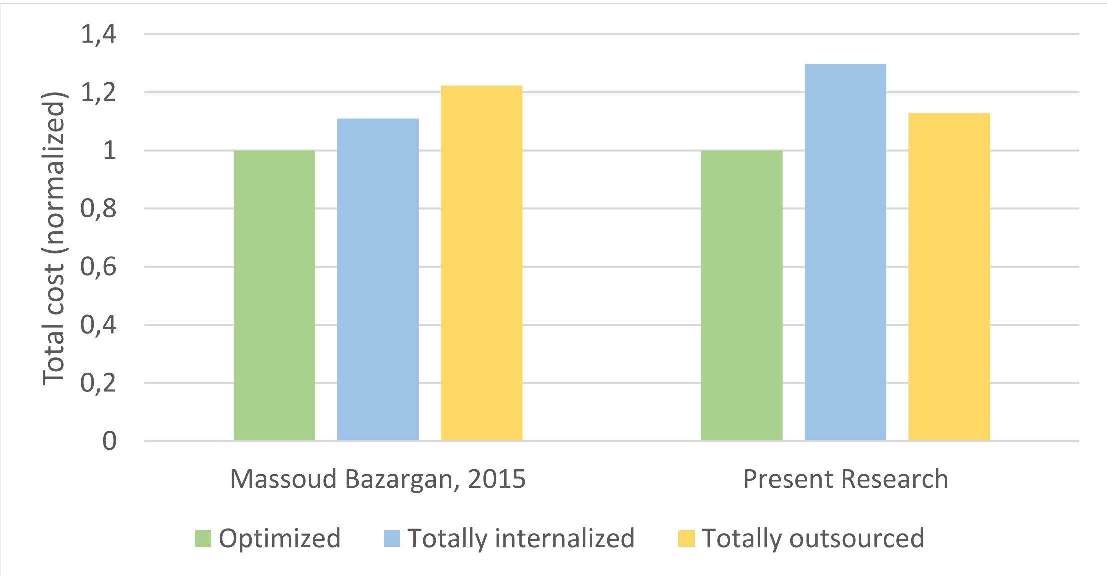

Figure 60: Cost comparison for different researches

Although there are differences between the methods, the main results were compared for illustrative purposes. As can be seen, in both cases the optimum result was a hybrid maintenance option with part being outsourced and part internalized, with the difference being that Bazargan's work showed the highest cost for the outsourced option, while the present work showed the highest cost for the fully internal option. This is probably due to the small fleet size.

5 Conclusion

During the research problem, different methods for managing aircraft maintenance services were discussed, ranging from one extreme (fully in-house) to the other extreme (fully outsourced). Furthermore, the choice between the different methods is not trivial, and depends on various factors, some based on economic analysis, and others based on the strategic alignment of the organizations. Since this research aimed to conduct a cost-benefit analysis of maintenance decisions, the main economic factors discussed in the literature were analyzed in this research.

With this, we conclude that the general and the specific objectives were satisfactorily achieved. With regard to the general objective, a quantitative model was developed for a fleet of defense aircraft that carried out a cost-benefit analysis for different outsourcing options.

With regard to the specific objectives, objective #1 was achieved by establishing a standard support structure based on field data acquisition. Objective #2 was achieved by simulating the fully outsourced condition using data from the current contract. Although this model has the potential to provide a small gain in the maximum operational availability that can be achieved, this maintenance model presented a considerably higher cost for practically all the investment levels simulated, including for the 50% operational availability, the most relevant in this research. Objective #3 was achieved by simulating the fully internalized condition, taking into account the size of the fleet and the costs of the resources required. In this analysis, the organizations would have to invest in a variety of resources in order to acquire the capacity to perform corrective maintenance. This model presented a highly disadvantageous result compared to the Default model, since that to maintaining the operational availability requirement it was necessary a considerably higher cost. Investment in resources was the main driver of this cost's increase. Additionally, it was estimated the fleet size and the cost of the resources that would equalize both scenarios (default model and fully in-house).

Objective #4 was achieved by analyzing the capacity to carry out simultaneous repairs (which indicates how large the support structure should be) and its impact on the indicators: operational availability; unavailability due to item waiting; and mission completion rate. It was observed that having a very large structure, with high costs and capable of meeting the demand for services (a structure capable of carrying out several simultaneous repairs) does not “improve the product”, delivering indicators in line with those expected for the product and the logistical support structure involved. However, as the capacity to execute simultaneous repair was reduced, there was a point at which the fleet's performance indicators began to be negatively impacted, until for a small support structure (capable of executing few simultaneous repairs) the fleet's performance was highly degraded. Therefore, the size of the support structure is an important factor to take into account.

Objective #5 was achieved by comparing the Default Model with the other scenarios analyzed, and concluding that the Default Model presented the best cost-benefit ratio. Thus, it can be concluded that the “partially outsourced” supportability model represents the best choice for the fleet analyzed. This conclusion is in line with the understanding of some authors, such as Bazargan (2016), who, after analyzing various factors relating to outsourcing aircraft maintenance, concludes that “a combination of in-house and outsourced maintenance is recommended”.

Objective #6 was achieved by analyzing the impact of “unsuccessful repair” on availability and support costs. Objective #7 was achieved by analyzing the consequences of having a specific contract for a particular equipment or system, focusing on the impact of having a contract with a company with a large geographical distance. Finally, objective #8 was achieved by analyzing the impact of exchange rate variations on the cost of supportability, both for programs in the initial phase and for programs in the operation and support phase.

Despite the Default Model was the best alternative, it was noted that there are possible inefficiencies that could become improvement opportunities. One clue of this is that the current fleet availability is below the expected value. As an example of possible improvement could be if the manufacturer would be able to deal direct with the operational bases, thus eliminating intermediaries between the operator and the maintainer. Another possibility could be to allocate the inventory closer to the operating sites, which tends to reduce the latency to a fault occurrence. However, these would be proposals to improve the status quo of the current support structure. But, once this research aimed to model the way the fleet is currently supported, and to analyze alternative scenarios more specifically related to outsourcing, improvements in the current support structure were not analyzed in order to avoid the risk of deviating from the theme.

Despite the fact that the scope of this work focused on the economic aspects of a support structure, there are non-economic aspects that should also be taken into account. For example, as this is a fleet of national defense aircraft, efficiency in the use of resources is not the only determining criteria. Sometimes, the need to maintain a greater degree of control over operations, as well as to respond quickly to specific demands, can override the economic aspects. In addition, there is the risk of political influences forcing a discontinuation of services at times of political instability, as has been observed historically.

Another relevant factor is the risk of losing internal expertise. Excessive outsourcing can lead to a gradual loss of in-house execution capacity. It is being seen sometimes that organizations with a history of manufacturing and maintaining complex products that, as outsourcing progressed, lost the ability to execute and manufacture products themselves, even products that had already been made. Allied to this process is the need for knowledge management, which, if not carried out properly, contributes even more to the loss of capacity.

Due to the arguments presented above, the final decision of which support structure will be chosen depends not only of economical factors, but it is a multidisciplinary decision that should consider the needs of different teams, within their pros and cons of each possible solution.

Finally, it is clear that the application of modeling and simulation techniques to a real case of logistical support for a fleet of defense aircraft contributes to a better understanding of the condition of the fleet, as well as the expected results (through indicators) for different support policy options.

5.1 Suggestions for future work

With regard to suggestions for future work, an analysis could be regarding the option of a fully in-house structure, analyzing the use of special tools/structures, where there is a limited quantity to serve the entire fleet, with the possibility of generating a waiting list and its impact on the indicators.

Another variation can analyze the impact of keeping repairs at a central base compared to another condition in which operators have the capability to carry out the repairs themselves. In this situation, analyzing the optimal stock location also becomes relevant.

Another analysis could be made in relation to scheduled maintenance, in which the size of the hangar would be taken into account, in order to observe the number of aircraft that would be undergoing scheduled maintenance simultaneously, as well as the impact on the indicators if there is a limit on the size of the hangar available.

Finally, another possibility for future work would be to take into account the ageing of the fleet and its impact on decisions to internalize or outsource repair tasks.

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Annex A – Demonstrative Model Inventory

This annex shows the quantity of each spare part to be purchased in the demonstrative model in order the fleet reaches 40%, 50%, 60% and 70% availability.

ITEM	**AVAILABILITY**			
	40%	**50%**	**60%**	**70%**
LRU 1	0	0	2	4
LRU 2	0	0	0	1
LRU 3	0	3	5	7
LRU 4	4	5	6	9
LRU 5	12	12	13	13
LRU 6	4	5	6	7
LRU 7	18	19	20	23

Annex B – Aircraft Components

This annex contains the aircraft components used for the case study in Chapter 4. They were divided into 4 groups: “propulsion”, “landing gear”, “avionics”, “other repairable”.

Item	Aircraft system	Quantity per A/C	Failure rate (1/10^6 FH)	MTTR (days)	Acquisition price (US$)
PROP - 01	Propulsion	2	445	182	2.883.891,54
PROP - 02	Propulsion	1	428	182	2.520.018,19
PROP - 03	Propulsion	1	883	60	224.431,05
PROP – 04	Propulsion	5	375	60	617.400,59
PROP – 05	Propulsion	1	460	182	3.184.686,29
PROP – 06	Propulsion	1	497	60	168.701,90
PROP – 07	Propulsion	1	573	60	107.613,53
PROP – 08	Propulsion	1	434	60	322.543,71
PROP – 09	Propulsion	2	489	30	35.878,83
PROP – 10	Propulsion	2	394	60	151.097,10
PROP – 11	Propulsion	2	402	60	118.339,50
LG-01	Landing gear	2	851	30	100.590,26
LG-02	Landing gear	1	694	30	113.081,30
LG-03	Landing gear	3	787	30	262.651,29
LG-04	Landing gear	1	794	30	274.295,49
LG-05	Landing gear	2	736	30	180.643,82
LG-06	Landing gear	1	691	30	107.648,31
AVI-01	Avionic	1	252	15	439.549,75
AVI-02	Avionic	1	293	15	348.772,58
AVI-03	Avionic	1	294	15	336.896,33
AVI-04	Avionic	1	314	15	211.083,27
AVI-05	Avionic	1	319	15	194.127,06
AVI-06	Avionic	1	349	15	128.802,08
AVI-07	Avionic	1	349	15	127.957,79
AVI-08	Avionic	1	358	15	117.374,68
AVI-09	Avionic	1	287	15	431.364,40
AVI-10	Avionic	1	288	15	413.096,50
AVI-11	Avionic	1	321	15	186.548,94
AVI-12	Avionic	1	341	15	141.502,60
AVI-13	Avionic	2	356	15	119.105,47
REP-01	Repairable	1	494	30	764.754,81
REP-02	Repairable	1	591	30	561.604,48
REP-03	Repairable	1	634	30	346.923,13
REP-04	Repairable	1	653	30	298.612,65
REP-05	Repairable	1	695	30	227.675,63

REP-06	Repairable	1	701	30	218.937,87
REP-07	Repairable	1	741	30	179.983,65
REP-08	Repairable	1	748	30	175.015,41
REP-09	Repairable	1	563	30	930.431,78
REP-11	Repairable	1	594	30	536.903,63
REP-12	Repairable	1	723	30	195.396,97
REP-13	Repairable	2	759	30	166.722,90
REP-14	Repairable	1	763	30	163.524,88
REP-15	Repairable	2	775	30	155.995,46
REP-16	Repairable	1	801	30	141.534,37
REP-17	Repairable	2	808	30	138.146,35
REP-18	Repairable	1	833	30	126.937,58
REP-19	Repairable	1	867	30	114.504,01
REP-20	Repairable	1	869	30	113.999,82
REP-21	Repairable	1	932	30	96.432,17
REP-22	Repairable	1	937	30	95.411,14
REP-23	Repairable	4	1022	30	79.184,63
REP-24	Repairable	2	2050	30	132.508,17
REP-25	Repairable	2	1764	30	31.962,26
REP-26	Repairable	1	1780	30	31.568,54

Annex C – Default Model 50% availability inventory

This annex contains the spare parts for 50% availability.

Item	Store Local	Quantity
PROP-01	OEM	1
PROP-02	OEM	1
PROP-03	OEM	2
PROP-04	OEM	2
PROP-06	OEM	1
PROP-07	OEM	2
PROP-08	OEM	1
PROP-09	OEM	2
PROP-10	OEM	2
PROP-11	OEM	2
LG-01	OEM	2
LG-02	OEM	1
LG-03	OEM	2
LG-04	OEM	1
LG-05	OEM	2
LG-06	OEM	1
REP-01	OEM	1
REP-02	OEM	1
REP-03	OEM	1
REP-04	OEM	1
REP-05	OEM	1
REP-06	OEM	1
REP-07	OEM	1
REP-08	OEM	1
REP-11	OEM	1
REP-12	OEM	1
REP-13	OEM	2
REP-14	OEM	1
REP-15	OEM	2
REP-16	OEM	1
REP-17	OEM	2
REP-18	OEM	1
REP-19	OEM	2
REP-20	OEM	2
REP-21	OEM	2
REP-22	OEM	2
REP-23	OEM	4
REP-24	OEM	3
REP-25	OEM	4

REP-26	OEM	3
AVI-04	OEM	1
AVI-05	OEM	1
AVI-06	OEM	1
AVI-07	OEM	1
AVI-08	OEM	1
AVI-12	OEM	1
AVI-13	OEM	1
AVI-14	OEM	1

Annex D – 50% availability inventory for Case D – Specific contract overseas

This annex contains the inventory comparison between default model and Case D, which there is a specific contract oversea to repair the propulsive items. In the case, to reach the 50% availability, it was necessary to acquire 4 more items in comparison to Default Model, they are: PROP-05, PROP-06, REP-09 and REP-18.

	Default model			**Case D – Specific contract oversea**	
Item	**Store place**	**Qty**		**Store place**	**Qty**
PROP-01	OEM	1		SPECIFIED COMPANY	1
PROP-02	OEM	1		SPECIFIED COMPANY	1
PROP-03	OEM	2		SPECIFIED COMPANY	2
PROP-04	OEM	2		SPECIFIED COMPANY	2
PROP-05*	----	---		SPECIFIED COMPANY	1
PROP-06*	OEM	1		SPECIFIED COMPANY	2
PROP-07	OEM	2		SPECIFIED COMPANY	2
PROP-08	OEM	1		SPECIFIED COMPANY	1
PROP-09	OEM	2		SPECIFIED COMPANY	2
PROP-10	OEM	2		SPECIFIED COMPANY	2
PROP-11	OEM	2		SPECIFIED COMPANY	2
LG-01	OEM	2		OEM	2
LG-02	OEM	1		OEM	1
LG-03	OEM	2		OEM	2
LG-04	OEM	1		OEM	1
LG-05	OEM	2		OEM	2
LG-06	OEM	1		OEM	1
REP-01	OEM	1		OEM	1
REP-02	OEM	1		OEM	1
REP-03	OEM	1		OEM	1
REP-04	OEM	1		OEM	1
REP-05	OEM	1		OEM	1
REP-06	OEM	1		OEM	1
REP-07	OEM	1		OEM	1
REP-08	OEM	1		OEM	1
REP-09*	---	---		OEM	1
REP-11	OEM	1		OEM	1

REP-12	OEM	1		OEM	1
REP-13	OEM	2		OEM	2
REP-14	OEM	1		OEM	1
REP-15	OEM	2		OEM	2
REP-16	OEM	1		OEM	1
REP-17	OEM	2		OEM	2
REP-18*	OEM	1		OEM	2
REP-19	OEM	2		OEM	2
REP-20	OEM	2		OEM	2
REP-21	OEM	2		OEM	2
REP-22	OEM	2		OEM	2
REP-23	OEM	4		OEM	4
REP-24	OEM	3		OEM	3
REP-25	OEM	4		OEM	4
REP-26	OEM	3		OEM	3
AVI-04	OEM	1		OEM	1
AVI-05	OEM	1		OEM	1
AVI-06	OEM	1		OEM	1
AVI-07	OEM	1		OEM	1
AVI-08	OEM	1		OEM	1
AVI-12	OEM	1		OEM	1
AVI-13	OEM	1		OEM	1
AVI-14	OEM	1		OEM	1

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6. AUTOR(ES):

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11. RESUMO:

The decision to keep the maintenance services of an aircraft fleet in-house or outsource is a dilemma that has a direct impact on costs, aircraft availability and the ability to fulfill the missions that the fleet is assigned. To answer this question, this research developed a model that simulates various maintenance configurations, from totally in-house maintenance to totally outsourced maintenance, as well as considered other constrains. To do this, a standard supportability model was first developed. After developing and calibrating the standard model, alternative scenarios were developed to be compared with the initial (standard) model, which takes into account how the fleet has been supported, including technical and commercial data. For these alternative scenarios, it was considered not only the cases of fully internalized and fully outsourced maintenance, but it was also analyzed the impact of significant factors on this decision, such as the size of the fleet, the cost of the resources to be acquired (for internalization), the size of the maintenance structure required (which indicates the volume of services that can be carried out in a given period of time), it also considered cases of unsuccessful repairs, as well as the impact of specific contracts with suppliers based in different continents, and even the impact of exchange rate variations considering the current support structure. In this way, this work performed a cost-benefit analysis that considered several factors regarding the outsourcing of repair services, as well as the impact of these factors on the main fleet indicators. Ultimately, this work aims to be a guide to support decision-making for fleet managers and other professionals in the aviation sector.

12. GRAU DE SIGILO:

(X) OSTENSIVO **( ) RESERVADO** **( ) SECRETO**